

Modeling and Control of A Hybrid Sustainable Energy System

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CERTIFICATE

This is to certify that the thesis entitled “**Modeling and Control of A Hybrid Sustainable Energy System**” being submitted by Mr. Amit Kumar Roy to the Department of Electrical & Instrumentation Engineering, Thapar Institute of Engineering & Technology (Deemed to be University), Patiala, Punjab, India for the award of the degree of **Doctor of Philosophy**, is a record of bonafide research work carried out by him under our guidance and supervision and has fulfilled the requirements for the submission of this thesis, which to our knowledge has reached the requisite standard.

The results embodied in the thesis have not been submitted in part or full to any other Institute or University for the award of any diploma or degree.


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ABSTRACT

Harnessing of power from non-conventional energy generators such as wind energy conversion system or photovoltaic system is a proven choice for power generation. Some convincing features like zero emission of greenhouse gases, their availability in abundance, and requirement of low maintenance cost are offered by renewable generators. Though generation of power from such sources faces challenge of intermittency due to dependency on variable climatic conditions. Thus, integration of backup sources like fuel cell-electrolyzer, super-capacitors, and battery are inevitable in order to enhance the overall system reliability, efficiency and sustainability of the system. A combination of a renewable energy generator along with back up sources leads to the formation of hybrid sustainable energy system (HSES). If such systems can share a considerable quantum of energy in a geographical area then grid integration of such system is a viable option. Grid integration of HSES enhances the reliability of the utility grid, and such integration attributes to a successful grid support. Yet, the grid integration of such renewable generation-based hybrid energy system faces the challenge of uncertain power system dynamics due the different characteristics of integrated renewable energy resources. Occurrence of faults at the utility end and variation in the load demand at the point of common coupling can affect the operation of HSES. In addition, unpredictable change in climatic conditions may affect the power generation from the sustainable energy generators.

In order to solve such challenges, this research work considers design and modeling modalities, fault ride through (FRT) capability enhancement strategies, and power management control strategies in renewable energy-based hybrid energy systems. This thesis majorly considers three distinct configurations of grid-connected hybrid energy systems. The first configuration considers a permanent magnet synchronous generator (PMSG) based wind energy conversion system and a fuel cell (FC) system interconnected at a common dc bus. The second configuration considers a PMSG/Battery/FC-Electrolyzer based hybrid system, while; the third configuration considers doubly-fed induction generator (DFIG)/supercapacitor (SC)/FC-Electrolyzer based hybrid system. In all the considered configurations, an effort is made to enhance the FRT capability of various active FRT schemes for dc-dc converter control and inverter control system. Specifically, a new feed-forward based FRT control scheme for the inverter current control is recommended where, new current references of the dq -axis frame are derived by tracking the positive sequence power. The regulation of current references is

performed by the application of artificial intelligence techniques in order to achieve an enhanced ride through control in the first and third configuration.

In order to solve the problem of generation intermittency and variations in the load demand, power management control is essential. Therefore, this thesis also proposes two new power management algorithms that are based on use of reduced-rules by monitoring state of charge of battery and net power of the hybrid system. The request made by the grid operator is kept on priority in all the power management schemes. Further, integrated power management strategy and low-voltage ride through (LVRT) control schemes are also proposed in the second and third configurations. The same is realised by adoption of mode selection-based control between grid feeding mode and LVRT mode in the inverter control structure. The LVRT capability is enhanced through multi-dimensional control approaches in the third hybrid energy system configuration. New control techniques, namely, OFF-MPPT control for the rotor side converter is performed for torque ripple nullification in DFIG during grid voltage sag. Mode selection-based switching control for the dc-dc converter interfaced with SC is adopted for smoothening the dc-link voltage transients under voltage sag scenario. This research work also suggests the adaption of a feed-forward control based adaptive neuro-fuzzy inference system-based control for the grid side converter of DFIG in order to effectively perform LVRT control functionalities. In all the considered hybrid energy system, the proposed power management algorithms and FRT control algorithms are validated by detailing relevant mathematical models. Simultaneously, various case studies such as variable wind speed, load demand, grid power request and occurrence of balanced and unbalanced grid voltage sags are undertaken. The extensive simulation and analysis works are performed using standard MATLAB/Simulink platform. The simulation results obtained from the testbed have validated the design, modeling and control of the proposed HSES architectures.

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LIST OF ABBREVIATIONS

AI	Artificial Intelligence
ANFIS	Adaptive Neuro Fuzzy Inference System
ANN	Artificial Neural Network
CEA	Central Electricity Authority
DER	Distributed Energy Resources
DFIG	Doubly Fed Induction Generator
DG	Distributed Generation
DPC	Direct Power Control
dq	direct axis and quadrature axis
ELZ.	Electrolyzer
FC	Fuel Cell
FF	Feed Forward
FLC	Fuzzy Logic Control
FRT	Fault Ride Through
GC	Grid Connected
GSC	Grid Side Converter
H ₂	Hydrogen
HES	Hybrid Energy System
HSES	Hybrid Sustainable Energy System
HV	High Voltage
IGBT	Insulated Gate Bipolar Transistor
IPS	Input Power Sensing
KCL	Kirchhoff's Current Law
KVL	Kirchhoff's Voltage Law
LVRT	Low Voltage Ride Through
MF	Membership Function
MPPT	Maximum Power Point Tracking
NM	Negative Medium
NS	Negative Small
NS	Negative Small
O ₂	Oxygen

OPR	Output Power Reference
P. U	Per Unit
PB	Positive Big
PCC	Point of Common Coupling
PEMFC	Proton Exchange Membrane Fuel Cell
PI	Proportional Integral
PLF	Plant Load Factor
PLL	Phase Locked Loop
PM	Positive Medium
PMC	Power Management Controller
PMS	Power Management Strategy
PMSG	Permanent Magnet Synchronous Generator
PR	Proportional Resonant
PS	Positive Small
PV	Photo-Voltaic
PWM	Pulse Width Modulation
RSC	Rotor Side Converter
SC	Super Capacitor
SDBR	Series Dynamic Breaking Resistor
SLG	Single Line to Ground
SMES	Super Conducting Magnetic Energy Storage
SOC	State of Charge
SOFC	Solid Oxide Fuel Cell
SRF	Synchronous Reference Frame
TS	Toggle Switch
UC	Ultra-Capacitor
VOC	Voltage Oriented Control
VSC	Voltage Source Converter
VSI	Voltage Source Inverter
WECS	Wind Energy Conversion System
ZE	Zero Error

Introduction and Literature Review

1.1 Introduction to Hybrid Sustainable Energy Systems

The global energy demand is rising at an exponential rate, leading to construction of new power plants, new transmission lines and new auxiliary equipment. It is essential that power production, its distribution and its utilization is done in an efficient manner, but at the same time the standards for environmental norms must be maintained by the power utility companies. On account of above challenges, power generation from renewable energy resources is a promising solution to overcome the energy crisis in developing countries. These sources are environmentally friendly and are available in abundance [1]. Harness of energy from wind and solar photo-voltaic (PV) is of utmost interest due to the emergence of power electronic technology and favourable commercial policies. However, the biggest limitation of these technology is the challenge of intermittency due to dependency on variable climatic conditions [2]. If storage devices such as batteries, super-capacitors (SCs), fuel cell (FC)-electrolyzer based hydrogen (H_2) storage systems are also integrated with the non-conventional energy generators, then the redundancy and reliability of renewable power generation system can be improved [3]. Such a resultant system is termed as hybrid sustainable energy system (HSES) which offers the benefits of high reliability, sustainability and flexibility. HSES possess convincing feature of meeting the ever-growing energy demands of the present and future electric power systems [4]. Along with the benefit of sustainability, the environmental, economic and social benefits make HSES a popular choice for power harnessing. Hybrid generation systems can be installed via a suitable manner to serve the required load demand of the local area or its power can be used to feed the utility grid. HSES architectures are majorly classified as islanded mode and grid connected mode [5]. The islanded mode is also referred as off-grid mode, isolated mode or stand-alone mode where the power generated from HSES is utilized to meet the load demands of a remote area where access to the utility grid is difficult or it is not feasible to lay out transmission lines. These systems are designed and sized to meet the load demand of a particular geographical location. Whereas, a grid connected HSES is connected in parallel to the utility grid, providing the flexibility to export its surplus power to the power deficit regions. The renewable energy generators and the backup sources generate its power either in form of dc or ac, while; the nature of electrical loads could be of ac-type or dc-type. In this regard, power conditioning devices using power electronic converters are a

necessary interface between the energy sources and loads [6]. Based on the interconnection of power converters, a hybrid energy system is established by following the common ac bus architecture, common dc bus architecture and hybrid dc-ac bus architecture either for standalone or in grid connected mode [7]-[8].

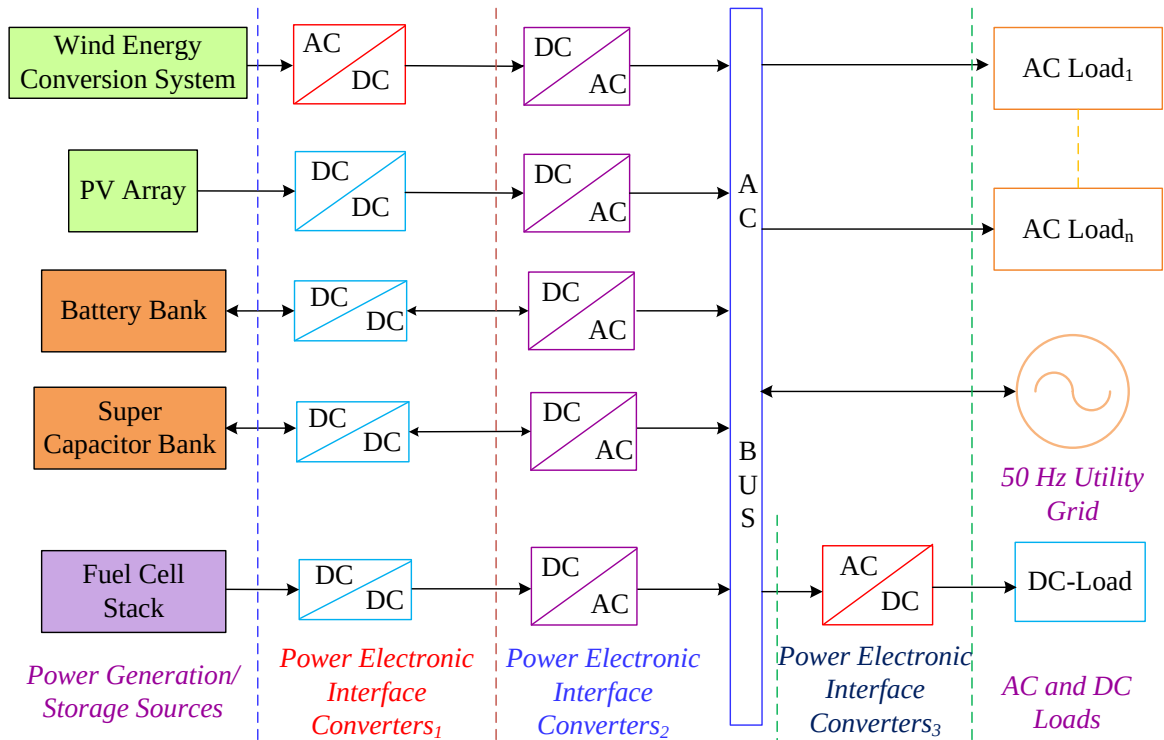


Fig. 1.1. Centralized ac bus configuration.

In the *centralized ac-bus* layout shown as per Fig. 1.1, all the energy sources and loads are connected to an ac bus. The dc sources need to have inverters to convert dc to ac before connecting to the ac bus. It is a modular configuration hence; the ever-changing surge of energy needs is accommodated via this configuration. However, this configuration offers some limitations; firstly, there is the need of synchronization of several inverters with the rated and centralized ac voltage and frequency of the system. Secondly, the injection of undesired harmonics introduced into the system by the use of inverters increases the power quality problems. Lastly, if it is desired to connect a dc load at the tail end of the configuration, then there is a necessary of 3-stage power conversion with the requirement of power electronic interface converters viz. converters₁₋₃ respectively. Therefore, this configuration will lead to a higher energy conversion loss. In *centralized dc-bus* layout shown as per Fig. 1.2, the energy sources are integrated to a common dc-bus. The sources which generate ac power requires rectifier to convert ac power to dc before connecting to the dc bus. While the dc loads are

connected directly to the central dc-bus. This arrangement reduces the harmonic pollution from power electronic equipment.

The *dc-bus* configuration eliminates the need for requirement of frequency and voltage synchronisation among various generating sources. This configuration is advantageous for situation when majority of the loads in the system are dc-loads. However, this configuration encounters a demerit that, if the inverter which is interfaced between the dc-bus and grid is out of service, then the system fails to deliver its power to grid. Moreover, if majority of the loads are ac-loads then power conversion stages increase, which leads to poor conversion efficiency in the system.

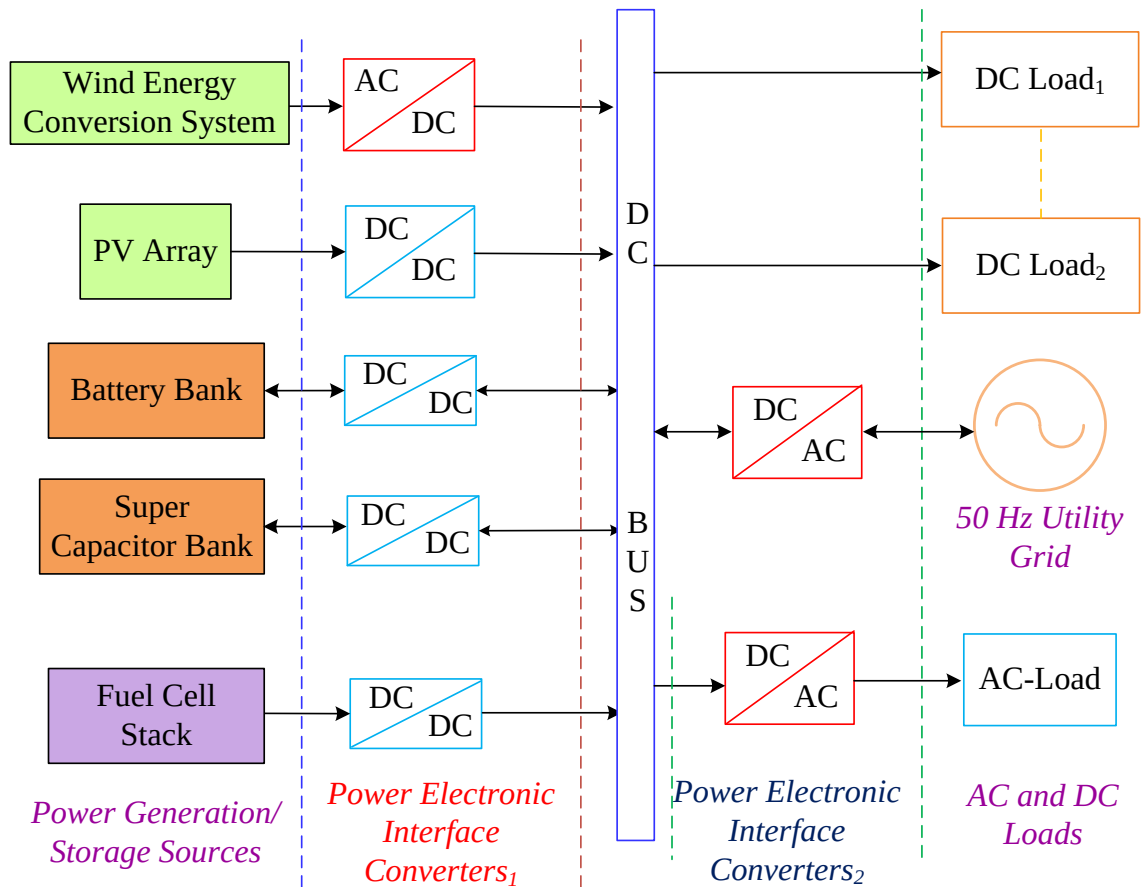


Fig. 1.2. Centralized dc bus configuration.

The hybrid bus arrangement uses both the common ac bus and dc bus as depicted in Fig. 1.3. This type of arrangement offers flexibility for cases whenever the HSES is having a combined arrangement of ac-dc sources and ac-dc loads [9]. The dc sources and loads are connected directly to the dc bus while the ac sources and loads can be connected directly to ac bus. Thus, this presented topology offers a convenient feature of lower conversion losses at various stages due to non-requirement of any additional power electronic circuits.

In *hybrid dc-ac bus configuration*, both the buses are connected through a bidirectional converter that permits power exchange between the two buses. This arrangement enhances the system's power reliability due to uninterrupted power supply. In all the above configurations, the role of controllers in the power electronic converters is significant as it governs the important system parameters. The provision of grid synchronization, fault ride through (FRT) capability, voltage control, frequency control and power control are some of the critical functions handled by these converters in a hybrid energy system.

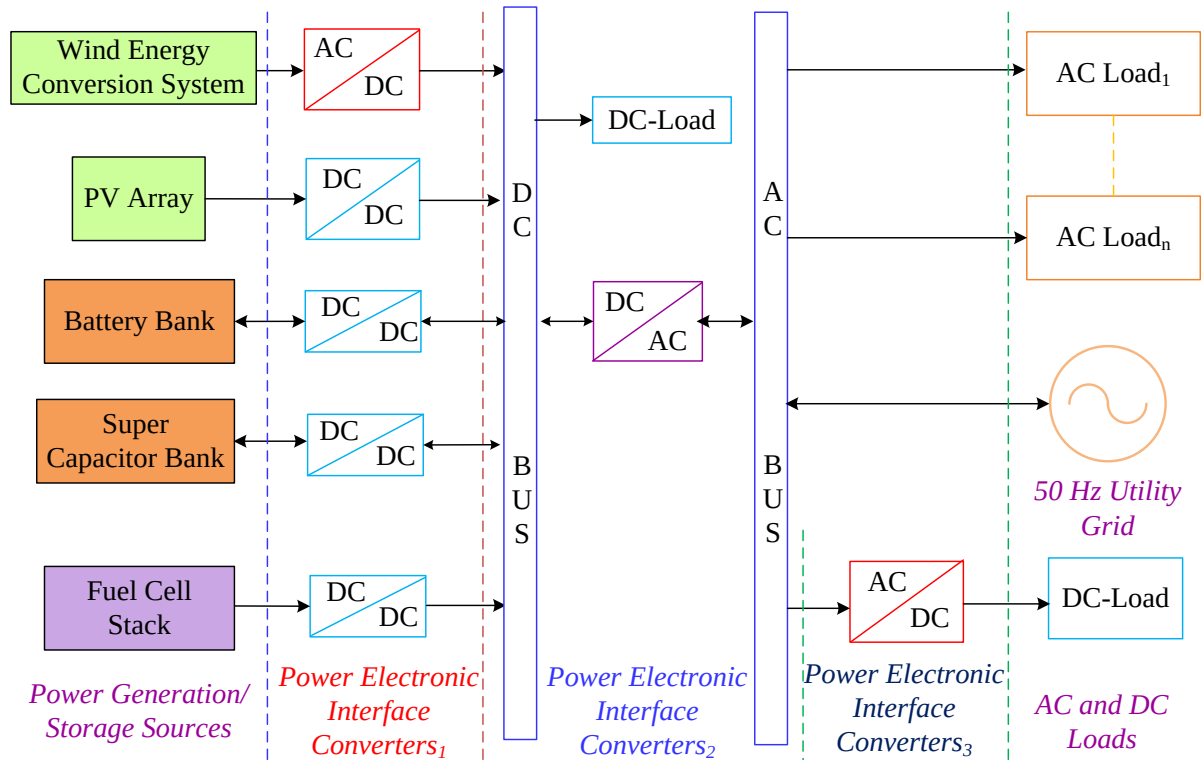


Fig. 1.3. Hybrid dc-ac bus configuration.

In situations where the power generated from renewable energy generators are in bulk, grid integration of such systems is a preferred choice. However, a grid-connected renewable generator must meet the standard specified as per IEEE-1547 [10]. The grid codes demand that a grid connected renewable energy generator must stay connected with the grid even during a grid fault event for specific duration defined by the LVRT curves. This feature is essential in order to prevent instability of grid, instability at the consumer end, and also, to prevent power system black out. This aspect is termed as low voltage ride through (LVRT) capability or FRT capability [11].

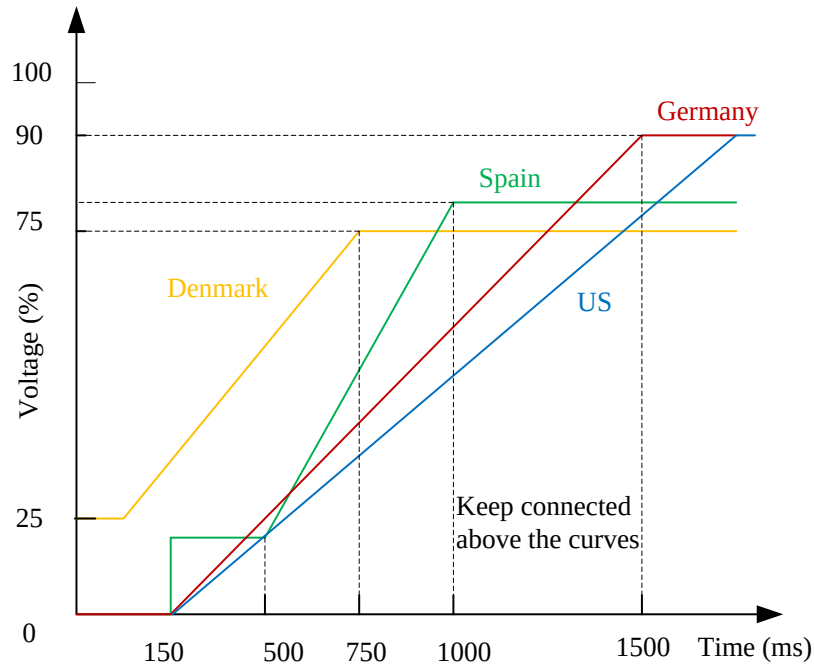


Fig. 1.4. LVRT capability curve as per the grid code of various countries [13].

A typical LVRT capability curves shown as per Fig. 1.4 varies from country to country as per the standards set by the nation's electricity grid codes [12]. For instance, the grid-code of India formulated by an organization named Central Electricity Authority (CEA) specifies that a grid-connected wind or solar generating unit must remain connected to the grid for 300 mS even if the voltage at the interconnection point dips up-to 0.15 P.U [13]. When sustainable energy systems are integrated at the distribution end, it brings the concept of micro-grid which is being referred as emerging power system concept [14]. The design of a micro-grid is done either by considering standalone or grid connected mode of operation. Various aspects of control, protection and stability are to be considered while proposing a micro-grid model.

1.2 Literature Review

The literature survey to demonstrate the allied technicalities involved with a hybrid renewable energy system is diverse. The associated literature is categorized into following subsections; firstly, various hybrid system topologies are reviewed where emphasis towards the design, modeling and control of such systems are deliberated. Simultaneously, the role of storage devices like battery, SC and H₂ based storage specifically FC & electrolyzer combination as a potential supporting backup source in hybrid system is realized. Secondly, the literature related to various grid integrated distributed energy resources (DER) are reviewed where specific attention towards its control is highlighted. Special emphasis is given to various methodologies to render the LVRT control and power management control. Finally, few

advanced control techniques for achieving the LVRT enhancement and power management control in a sustainable energy system are reviewed. An emphasis is given towards the merits of applying the artificial intelligence (AI) based control techniques in hybrid energy systems.

1.2.1 Design and Modeling of the Hybrid System

The aspect of design and modeling is essential and a fundamental task in order to propose a distributed generation (DG) model. The aspect of design involves the following modalities;

- i.* Selection of the ratings of individual DGs and storage present in the hybrid system.
- ii.* Selection of voltage ratings at the dc-bus or ac-bus.
- iii.* Various design calculations of active and passive components present in the system.

On the other hand, the aspect of modeling in hybrid system is necessary due to following reasons;

- i.* The performance of the hybrid system will depend on the performance of individual components. Thus, the method of modeling will help to analyse the behaviour of overall system.
- ii.* Modeling enables towards the understanding of interrelation among various input and output parameters of individual subsystems in a hybrid system.
- iii.* Lastly, modeling helps towards establishing the transfer function of various power electronic converters and controllers present the hybrid system. This further guides towards the proposal of new control schemes and also guide towards stability analysis.

Overall, it is apt to say that relevant mathematical modeling equations of various associated components are imperative. Various literature where the design and modeling of renewable energy generators, storage devices and the associated power electronic converters are reviewed in this section.

(a) Hybrid System Involving Wind Energy Conversion Systems

Wind energy conversion systems (WECS) share its highest installed capacity in India among various renewable generators [15]. A variable speed WECS are advantageous because of its proven efficiency and increased energy capture. Among several available wind generators, permanent magnet synchronous generator (PMSG) is a convincing technology to harness electrical power in wind energy systems due to high power factor operation and requirement of low-speed operation [16]. Since, the power generation from a WECS or PV

system is dependent on the climatic condition, it is essential to capture the maximum power generated from these systems. This feature is provided by the maximum power tracking (MPPT) controller. MPPT techniques depend on various control strategies or on the number of control variables. These techniques are well established in solar PV systems [17]. Similarly, in WECS, the use of MPPT in WECS is covered in numerous literatures, where the basic idea lies towards the control of rotor speed in order to capture the maximum power coefficient [18]. A hybrid system topology consisting of PMSG and battery operating in stand-alone mode is showcased in [19]. It is significant to consider that the regulation of voltage and frequency while satisfying the MPPT operation are the important control objectives in stand-alone hybrid systems.

Doubly fed induction generator (DFIG) based WECS are also the preferred candidates to harness wind power due to its amicable attributes of viable speed operation, high energy conversion efficiency, flexible controllability and requirement of lower ratings of the power converters [20]. A back-to-back converter arrangement namely rotor side converter (RSC) and grid side converter (GSC) configuration are used to enable the power controllability in a DFIG system [21]. Approach to hybridize the DFIG system with PV, battery and other storage devices is presented in the work [22]-[23]. However, the discussion on the design criteria of the storage components is lacking in these literatures.

(b) Role of Storage in Hybrid Energy System

As a standard practice, the intermittency in renewable generator is removed by the use of storage system. The use of more than one storage system is referred as hybrid storage. Hybrid storage are classified into high power density and high energy density-based storage systems which offers an enhanced system and economic efficiency [24]. An illustration of various storage technologies is shown in Fig. 1.5. Each storage devices differ from each other in terms of their response characteristics. For instance, batteries, super capacitors are effective in meeting the power demand for short term while hydrogen-based storage are good candidates for satisfying the long-term power demand. In order to fetch the benefit of complimentary characteristics of the individual storage devices, hybrid storage for a DFIG based wind energy system is proposed in [25].

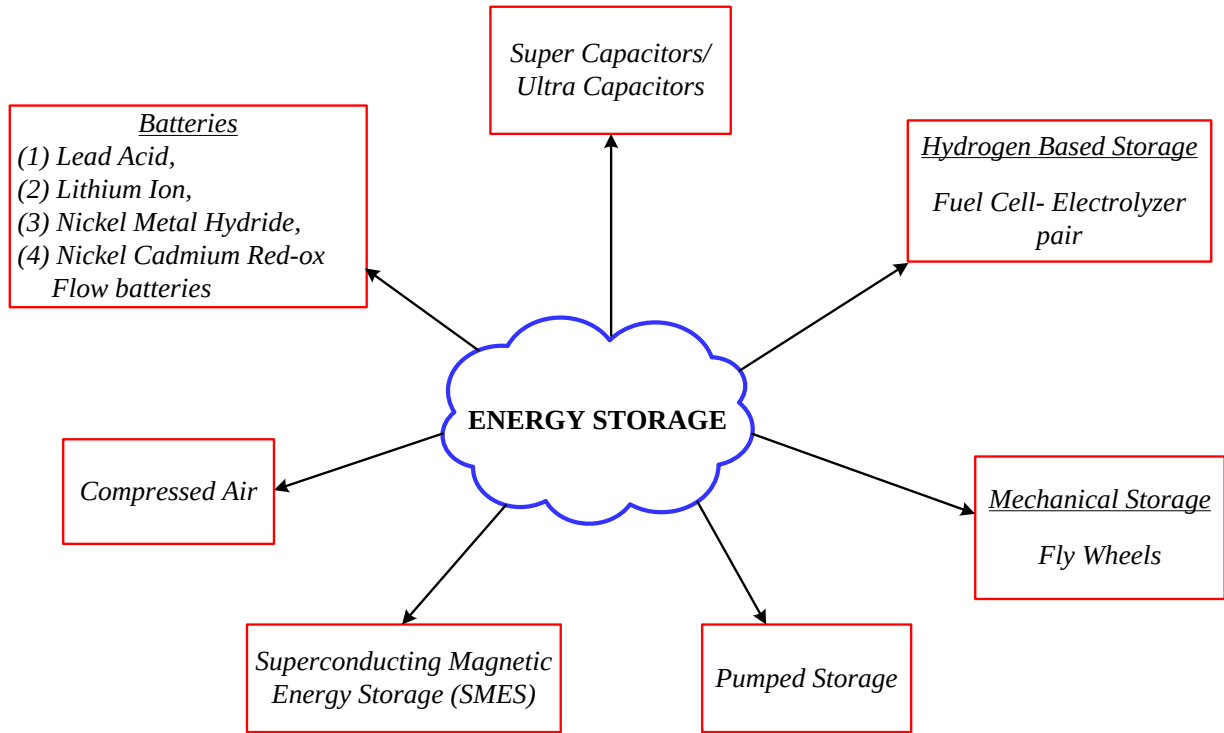


Fig. 1.5. Illustration of various storage technologies.

- **Hydrogen Based Storage**

Energy backup in form of H_2 storage is a convincing way for creating long term energy backup as it neither causes disposal issues nor causes pollution [26]. An added flexibility imposed by H_2 energy is that the excess energy generated from the renewable generators can be used to run an electrolyzer to generate H_2 . The role of FC is significant in this aspect, as it is a promising device to harness the energy from H_2 . FC's are among the promising backup source due to its high efficiency, low emissions, simple construction and salient operation. The basic energy conversion process lies in conversion of chemical energy to electrical energy. Based on operating temperature, FC's are majorly classified as proton exchange membrane fuel cell (PEMFC), solid oxide fuel cell (SOFC) and molten carbonate fuel cell [27]. PEMFC is among the most preferred technology for domestic use because of its low operating temperature and quick starting capability. While the utility of SOFC is in combined heat and power application, since it is characterized with high operating temperature ranging from 500 to 1000°C.

The accurate modeling of FC systems is an important aspect as it brings out the exact analysis about its operating characteristics. Some significant contributions towards the modeling of FCs are performed in [28]-[29], here the dynamic model of PEMFC systems and

SOFC systems are proposed. The effect of gas diffusion at PEMFC electrodes is considered to determine the expression of effective partial pressure of H_2 and oxygen (O_2). The effect of partial pressure of reactants, activation drop, ohmic drop, concentration drop and double layer charge effect inside the SOFC & PEMFC stack helps to derive the exact stack output voltage. Overall, FC is used in various works to enhance the reliability of power generation from the renewable generators. However, an essential criterion for H_2 based systems is that the stored H_2 must be available in a controlled manner which is done by the help of process automation as discussed in [30].

Electrolyzer's are the electrical device which works on dc power to generate H_2 . The modeling of electrolyzer depicts that the generated H_2 in the electrolyzer is related with faradays efficiency, number of electrolyzer cells and also with the electrolyzer's current. Electrolyzer's along with FC device have been used in conjunction with renewable energy generators in various works [31]-[32]. In all these works, the electrolyzer serves two-fold purposes. Firstly, it helps in maintaining the power balance of the system by acting as a dump load where the excess power of the system is absorbed by it. Secondly, it generates H_2 which in-turn serves as a fuel for the FC device.

- **Battery and Supercapacitor-Based Storage**

FC exhibits sluggish response towards power delivery; hence, it becomes unsuitable if it is required to support the transient power demand in a hybrid system. Thus, battery and SC are good candidates in meeting the transient power demand. The capability of battery to perform the function of voltage regulation, power quality improvement and for load levelling in a hybrid energy system is illustrated in [33]. Batteries are also hybridized with FC in order to compensate the slow dynamic response of FC in various works [34]-[35]. SC are also known as ultracapacitors (UC) and they have high power density compared to battery. These devices provide the support to meet the short-term power deficiency in a hybrid system which ranges from few seconds to minute [36]. The combination of FC, battery and SC is hybrid energy storage is attempted in an ac/dc microgrid environment in [37] where the objective of the hybrid storage is to meet the respective steady, dynamic and transient load profiles.

(c) Role of Power Electronics in Hybrid Energy System

Power electronic converters are the core component of a renewable energy-based hybrid energy system. Converters play a significant role to append the control capability in renewable energy generators which are inherently non-dispatchable [38]. A dynamic model of a

standalone wind and FC based hybrid energy system is proposed in [39]. However, in this study the details regarding the design calculations for various power electronic components are not included. The dynamic modeling of electrolyzer and H₂ storage vessel, compressor and piping valves are also not considered. Typically, dc-dc converters are added as an interface element in order to facilitate the objectives like MPPT control, power management control, frequency and voltage control. Boost converters, buck converter and buck boost converters are the typically used dc-dc converters in a hybrid energy system. It is necessary to put in place the correct components in these power converters by performing design calculations. A summarized design calculations of these converters are detailed in [40]. Apart from dc-dc converter, design and selection of components like dc-link capacitor, filter at the output of the inverter, selection of controller gains is significant from the domain of power converters.

1.2.2 Control of Hybrid Energy System

In order to harness power from hybrid system, the aspect of control is imperative. It is due to the fact that, when renewable generators are included in hybrid system, the entire system becomes stochastic in nature. Inclusion of electrical loads and participation of grid in case of a smart grid environment further increases the degree of uncertainty in a grid-connected hybrid sustainable system. In order to unify the aspect of control in HSES, power electronics and its control plays major role. These power electronic converters perform the following control task;

- i. MPPT control: dc-dc converters are connected directly across the output of DG sources.
- ii. Power dispatch control: to ensure the power balance with in the hybrid system.
- iii. Voltage control: it involves the regulation of voltage at various nodes of the hybrid system. For example, regulation of dc-link voltage or regulation of voltage at the PCC.
- iv. For providing ancillary services like LVRT control, harmonic control, active filtering, frequency regulation etc.

Depending on the configuration of a hybrid system the control approach changes for stand-alone mode and grid connected mode.

(a) Control in Standalone System

The control in hybrid energy system is facilitated by the use of power electronic converters. The approach towards the control capability differs depending on the stand-alone mode or for grid connected mode. In standalone systems, voltage control of inverter is a

preferred choice [41]. The use of vector control scheme in synchronously rotating reference frame is selected for regulating the voltage and frequency of the ac output at the point of common coupling (PCC). Along with voltage control, the regulation of dc-link voltage and the issues related to power quality in standalone wind-solar hybrid energy system is demonstrated in [42]. The control of active and reactive power is essential in standalone DG systems. The control for the same is achieved by mimicking the control mechanism found in synchronous generator in [43]. The real power is governed by controlling voltage phase angle and the reactive power is regulated by controlling the modulation index of the inverter. It is probable that transients and load unbalancing are encountered in stand-alone systems. In this aspect, the stand-alone inverter is controlled in positive, negative, and homopolar sequence components of three-phase supply voltages and currents to ensure balanced voltage in [44].

(b) Control in Grid-Connected System

With the promotion and utilization of sustainable energy sources worldwide, grid integration of such system is an encouraging aspect. Moreover, the concept of smart grid brings the mutual participation of sustainable generators and utility grid towards power exchange [45]. Aspects like hardware topologies, control strategies, power quality issues, control under grid fault and grid synchronization of DER is reviewed in [46]. Current control is the preferred strategy towards the control of grid-interfaced voltage source converter. Current control is performed in synchronous reference frame (SRF), stationary reference frame, natural frame using PI, PR, hysteresis and dead-beat controller. Dead beat controller possesses larger band width hence it exhibits good response under fault conditions [47]. Multiple control objectives are necessary in a grid-integrated DER, thus the concept of generic current controller capable of performing multiple functionalities such as reactive power support, active filtering capabilities along with the basic function of dc to ac power conversion is proposed in [48].

Hybrid grid integrated DG architectures involving FC proves to be a motivating choice towards the power harnessing. A SOFC and gas turbine operating together in grid connected mode is proposed in [49] where due to the inclusion of SOFC in the system, the dynamic stability of the entire system gets enhanced. The integration of FC with gas turbine in grid connected mode is proposed in [50]. In the studies shown as per [49]-[50], it is interesting to state that the selection of generation mix is an important aspect towards the transient stability behaviour of the entire hybrid system. In fact, as the fuel cell's rating increases in these system, firm transient stability is observed.

1.2.3 Low-Voltage Ride Through Capability

With the changing power system paradigm, large scale penetration of renewable energy-based DG is encountered in the electrical network. In recent scenario, the integration of DG with the utility grid enables to suffice the power demand of certain area of a power system network. Such integration eliminates the areas of power system network, which is power starved. If renewable generator-based DGs participate toward bulk power exchange with the grid, then its frequent tripping is not desirable. An uncontrolled outage of such DG unit will lead to power system instability and network black out. Looking into this aspect the grid-codes demand that a grid-connected DG must remain unified with the grid even under the event of low voltage or grid fault. This aspect is referred as FRT or LVRT capability. The literature highlighting various techniques to facilitate the LVRT capability in grid integrated DG system is reviewed in this section.

The aspect of LVRT is first introduced for a large-scale grid integrated wind generator [51]. The approach towards FRT capability is attributed in DG systems by adopting either active or passive LVRT strategies. An illustration towards the classification of various LVRT techniques is given in Fig. 1.6, and specific discussion of various active and passive LVRT schemes are detailed categorically.

(a) Active LVRT Control Schemes

Active LVRT approach involves towards the modification in the power electronic converter control or by the modification of the phase locked loop (PLL) control schemes. It is necessary that fault must be detected prior to the activation of LVRT control in DG. Schemes like use of notch filter, band stop filter, and delayed cancellation technique are used for the same [52]. LVRT enhancement by the advanced control of PLL is proposed in various literatures [53]-[58]. Enhanced PLL enabled the synchronization of power electronics converter even in high harmonic environment [53]. Advanced PLL structure such as dq -PLL [54], $\alpha\beta$ -PLL [55], double decoupled PLL [56] and $d\alpha\beta$ -PLL [57] enables the LVRT enhancement via synchronization of inverter under faults and under high harmonic conditions.

The LVRT capability is attained by the generation of flexible current references for the grid interfaced inverter. Control objectives like elimination of active/ reactive power oscillations and negative sequence current minimization are the necessary objectives of a LVRT algorithm [58]. Symmetric sequence instantaneous active power control is proposed in [59] to achieve ride through characteristics like controlled dc-link voltage and smooth active power profile. Strategies like active power curtailment philosophy [60] enables to limit the

surge in dc-link voltage. However, this technique is complex and the control algorithm adds computation burden on the inverter control algorithm.

(b) Passive LVRT Control Schemes

Another popular choice to assimilate the LVRT feature in case of DFIG based wind energy systems is by using an additional hardware like a braking resistor and crowbar device. When a fast crowbar is used in a DFIG based generator, the uncontrolled generation by the reverse diodes and subsequent overvoltage of the dc bus is prevented [61]. Whereas, a braking resistor can take energy out of the system to prevent over acceleration of the rotor system. Passive LVRT schemes are also applied to capture the additional energy in the rotor circuit in the form of inertia by using a flywheel or super conducting magnetic energy storage (SMES) device [62]-[64]. Nevertheless, the cost of additional hardware, system modification with the addition of new auxiliary devices adds to the system complexity.

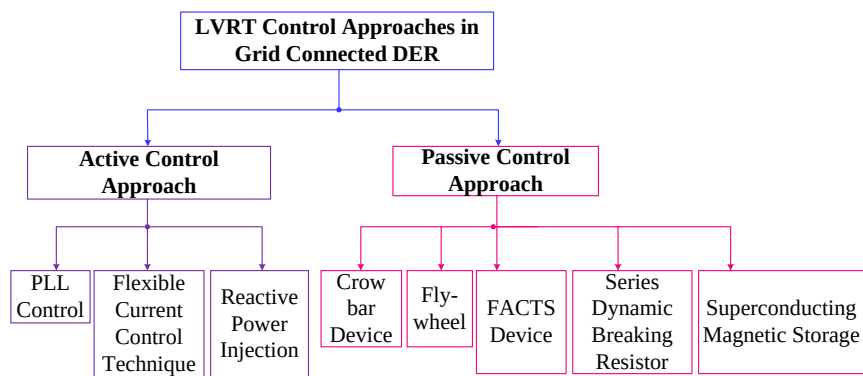


Fig. 1.6. Brief classification of various LVRT techniques.

(c) LVRT Schemes in PV

The FRT capability in single phase PV system is proposed in [65]. The control strategies consist of inner current loop for power quality regulation and outer voltage loop for voltage control. The LVRT capability demands for reactive power injection control strategies, fast voltage sag detection, accurate synchronization [66]. It is demonstrated that, under the grid faults the reactive power injection is done by; constant peak current, constant active current and by constant average active power control strategy. A general approach is to inject the required reactive power or reactive current via the grid-connected inverter control algorithm as per the magnitude of voltage dip [67]-[68]. In case of a two-stage configuration PV system, LVRT feature is unified to the system by shifting the MPPT point of the PV panel. It is done by creating a momentarily short circuit across the PV panels during voltage sag condition [69]-[70].

(d) LVRT Schemes in hybrid energy systems

LVRT control in considering multiple DG sources are attempted in selected literature. In [71]-[72], positive and negative sequence control for the grid interfaced inverter is performed for LVRT enhancement in a FC/battery-based hybrid generation system. The combination of wind and PV generation for LVRT enhancement is selected in one of the recent works [73]. It is significant to consider that voltage profile at various buses of the micro-grid must exhibit least deviation [74]. The same technical criteria are necessary for a successful ride through operation along with the control of surge in dc-link voltage, minimization of voltage ripples in dc-link and reduced grid current harmonics. A hybrid energy system has to satisfy the power demand of variety of loads connected to PCC along with LVRT control. In this aspect, a simple simulation approach to observe the effect on hybrid solar and wind power based standalone system for R, RL and RLC load respectively is showcased in [75].

1.2.4 Power Management Control

The management of power within the hybrid system is an essential aspect for maintaining constant voltage profile at the ac-bus or dc-bus. Power management control necessitates proposal of power management controller for the hybrid system. A power management controller enables the determination of appropriate split of power from the individual sources connected with in the hybrid system. The approach towards power management differs depending upon the configuration of the microgrid which could be either in standalone or in grid-connected configuration. Eventually, literature involving the proposal of various power management algorithms and controllers considering stand-alone and grid connected topology are discussed.

(a) Power management in standalone configuration

Different approaches towards power management are highlighted in a standalone PV, wind and PEMFC based hybrid energy system in [76]. An extensive power management control between two dc-microgrids using bus signalling technique is demonstrated in [77]. The control demonstration of a hardware-based power management controller for standalone HSES is presented in [78]. Frequency deviation is a major challenge in an islanded microgrid [79], this is due to the improper power balance with in the microgrid system. The above challenge is overcome by the adaptation of droop-based power controllers for standalone hybrid DG systems [80]. As per [81], the concept on droop control and reverse droop control is applied to regulate the voltage and frequency in a residential microgrid.

(b) Power management in grid connected configuration

Grid integration of hybrid microgrids is imperative due to the restructuring of power system and the evolution of smart grid philosophy. Therefore, power management schemes are essential for both islanded and grid-connected microgrids [82]. The objective of power management, considering the participation of utility grid is undertaken in various literature [83]-[88]. Approach towards power management involves the use of supervisory central controller [83]-[84], control of individual interfacing dc-dc converters on the basis of current or power reference generation [85]-[86]. The control of grid interface inverter requires a modified control for enabling power exchange with the grid. Approach like grid following strategy and source following strategy is proposed in [87] where, the regulation of dc-bus voltage plays the key role for an apt power management. Multiple control objectives are also suggested in [88] where along with fixed power exchange with the grid, power quality standards are also maintained.

1.2.5 Application of Artificial Intelligence Techniques in Hybrid Energy System

The evolution of artificial intelligence (AI) based control techniques is a promising solution to facilitate the control action in nonlinear systems where the exact mathematical modeling is difficult. AI techniques which are reviewed in this section are fuzzy logic control (FLC), artificial neural network (ANN) and adaptive neuro-fuzzy inference systems (ANFIS).

Intelligent controllers are motivating to perform the power management control in hybrid DG systems [89]-[92]. For instance, an ANN controller to regulate the real and reactive power in a hybrid solar and FC based system is proposed in [89]. Regulation of power flow by the use of a radial basis function ANN in a grid integrated wind and PV hybrid system is done in [90]. A neuro-fuzzy controller is applied to perform power management in a hybrid FC and battery-based DER in [91]-[92] where, the fuzzy controller is used to generate the weight for ANN. The ANN controllers show good dynamic response in a non-linear system whenever there is a necessary to generate dynamic control references [93]-[94].

The intelligent controllers are also applied in LVRT enhancement studies for a grid integrated DG system. An enhancement in the LVRT control is proposed for a wind/fuel hybrid system by the proposal of a type-1 fuzzy controller in [95] while type-2 fuzzy control is applied for ride through control in a PMSG based WCS in [96]. Apart from the objective of LVRT control, the objective of power quality improvement in grid connected renewable generator by using FLC is performed in [97]-[98]. Besides intelligent controllers, model predictive controllers are explored successfully for solving the LVRT aspect in converter and in grid tied

PV system in [99]-[100]. Inclusion of nonlinearities and constraints enables a better response of predictive controller via the illustration of better steady state and transient state response in the grid-connected DG system.

1.3 Identified Research Gaps

According to the literature survey in the domain of HSES, the gaps in research and further technological enhancement are identified. The gaps are segregated into following sub areas in brief;

1. In the area of *design and modeling* of a hybrid system.
2. In the area of control coordination of a grid integrated hybrid energy system specifically the aspect of *low-voltage ride through capability*, where the control aspect during grid disturbances also shows a promising road map for exploring further research and scientific development.
3. In the area of *power management control* inside a hybrid energy system operating in grid connected environment shows immense opportunities in the enhancement of existing power sharing modalities.

A hybrid generation system comprises of numerous individual systems and subsystems. Therefore, the determination of specifications of each subsystem and its associated components requires a knowledge base of individual subsystem's dynamics. Looking into this aspect, the thesis outlines a detailed discussion on the aspect of design and modeling in a hybrid energy system. This aspect assists to lay fundamental foundations towards the proposal of new control architectures essential to meet the certain technical criteria in a hybrid energy system.

A great inclination of this dissertation is focused on the LVRT studies in renewable energy generators with specific consideration to wind generators. As per the existing literature, the LVRT studies are more specific by considering only a single entity based renewable energy generators. The related literatures considering LVRT techniques in hybrid sustainable energy generators are lesser in number. Moreover, the LVRT techniques includes the utilization of passive and active methods where the passive methods add to system cost and affects its reliability. Whereas, the active ride through technique associates good amount of complex mathematical modeling, use of a greater number of PI controllers and additional computational effort. Accordingly, new LVRT approaches have been proposed in this dissertation to encounter the discussed hindrances with them.

In the domain of power management control within the hybrid generation system, it is inferred that the power management control aspect is very well established in stand-alone hybrid system mostly via the process of droop control [80], rule-based control [77], state-flow based control [91], intelligence or optimization-based controls [92]. But the research works showing the power sharing in grid integrated environment are seldom as compared to the power management schemes in standalone environment. Moreover, the literatures discussing hybrid systems with integrated control towards power management and LVRT control are few in numbers. Consequently, another effort of this thesis work aims in proposing new power management control algorithms fit for grid connected hybrid system architecture. At the same time, the sequential work presented in this dissertation solves the integrated power management and LVRT control in hybrid system architectures specifically considering PMSG or DFIG based wind generators as the primary generation sources.

1.4 Thesis Objectives

The research gaps in the area of HSES (hybrid sustainable energy systems) bring to following objectives for a new set of research work;

1. Design of HSES
2. Modeling of HSES
3. Control of HSES
4. Investigation on HSES under Fault Condition

1.5 Organization of the Thesis

With the proposal of the laid objectives, this thesis dedicates the following set of methodologies to meet the objectives. A chronological order is followed in form of specific chapters where detailed methodology, relevant model, design and control solutions are presented in details in order establish the study on modeling and control of HSES.

In **Chapter-2**, the methodology to establish the design of hybrid system is discussed in detail. Various set of modalities associated with component specifications, control specifications in stand-alone and grid connected hybrid energy generation system are discussed. Also, this chapter details out some preliminary investigation-based studies done in MATLAB/ Simulink environment when the system is subjected to electrical dynamics such as unbalance faults or load transients.

In **Chapter-3**, the modeling of various subsystems in a HSES is presented. Modeling of wind generators specially a PMSG and DFIG is showcased. Modeling of short-term energy storage devices such as battery and SC is detailed. A brief discussion towards the modeling of H₂ based back up device consisting of FC and electrolyzer is also presented. Finally, the modeling of associated power electronic converters specifically the dc-dc converter and dc-ac converter is presented in detail.

The major contributions of the thesis are dedicated in **Chapter-4, 5 and 6** respectively. In **Chapter-4**, a grid-connected hybrid system based on PMSG based WECS and FC is investigated for FRT control. This chapter proposes a new feed-forward based FRT control scheme for the grid connected inverter. The chapter also discusses on the idea of applying the fuzzy logic based current controllers to enhance the FRT capability of the hybrid system. The proposed feed-forward-fuzzy FRT control scheme is compared with the conventional dq current control and feed-forward FRT control for various grid voltage sag tests. The enhanced LVRT control is justified by the simulation results obtained from MATLAB/Simulink.

In **Chapter-5**, a grid integrated hybrid system consisting of *PMSG based WECS* backed up by a battery energy storage system, PEMFC and electrolyzer is considered for validating a new control algorithm for achieving the objective of power management. The objective of LVRT control is also unified in this system by proposing a new dynamic current feed-forward based LVRT control scheme for the grid-interfaced inverter. The inverter control is coupled with an inherent mode selection capability between the grid feeding mode and LVRT mode in order to realize the multiple control objectives. Various practical case scenarios are considered to validate the integrated power management strategy and LVRT control scheme for the considered hybrid energy system.

In **Chapter-6**, another grid-integrated hybrid system configuration consisting of *DFIG based WECS* as primary power generator along with hybrid storage units consisting of SC, FC-electrolyzer pair is considered. A new central power management controller which takes into account the power demand request of the grid operator is proposed. The LVRT capability in this system is also unified via the proposal of various multi-dimensional LVRT control approaches. A feed-forward-ANFIS based control for the GSC of DFIG is proposed. The unified operation of proposed power management controller and LVRT control schemes are validated in MATLAB/Simulink based testbed for varied generation, loading and voltage sag conditions. Finally, the conclusions and future scope related from the presented research work are drawn in **Chapter-7**.

Design of Stand-alone & Grid Connected Hybrid Sustainable Energy Systems

2.1 Introduction

In order to propose a model of a hybrid sustainable energy system (HSES), the specifications of individual units in the hybrid energy system needs to be planned. It involves decision towards the selection of generation capacity for various distributed generation (DG) units and selection of various components specifications/ ratings. Looking into this aspect, the ratings of various generation units, storage units, power electronics devices, selection of various passive elements and choice of voltage levels is essential. This chapter details the major design considerations for few selected configurations of a stand-alone and a grid-connected hybrid energy system. The integration of wind energy conversion system (WECS) and fuel cell (FC) is one of the motivating choices of this thesis work as this very combination forms a reliable DG system where FC forms a sustainable backup source during low power generation from WECS. This combination is also claimed to be cost effective and a clean generation choice in various works [31], [39]. In this chapter, two different stand-alone DG configurations are selected which is shown as per Fig. 2.1 and Fig. 2.2. Apart from these stand-alone system configurations, the chapter also investigates on a grid connected WECS-FC based hybrid DG model in order to validate the design and control aspects of a typical grid integrated hybrid system. A special emphasis is given towards the effect of unbalance fault or a voltage sag in a grid connected hybrid system as such investigation studies assists towards the proposal of new fault ride through (FRT) control schemes. It is significant to state that the design of hybrid energy system (HES) is also dependent of the control philosophy adopted. Thus, the typical control philosophy for interfacing inverter which is operating either in stand-alone or in grid-connected mode is also discussed in this chapter.

Further, this chapter is organized as follows; in Section 2.2 the design considerations for a hybrid energy system is presented. The design equations necessary for selecting the voltage levels and various passive components in the hybrid system are deliberated in this section. In Section 2.3, the inverter control technique in a hybrid system when it is operating in standalone mode is discussed. The Section 2.4 presents an investigation study on a standalone FC system and on a standalone hybrid WECS-FC system. Preliminary investigation studies and relevant

results are presented when the considered standalone DG systems operate under ideal condition and during the occurrence of unbalance fault. In Section 2.5, the inverter control using direct power control (DPC) scheme for a grid integrated DG system is discussed. Subsequently in Section 2.6, investigation studies on a grid connected hybrid WECS-FC system is performed to validate the presented system design and control scheme. Finally, the significant conclusions of this chapter are summarized in Section 2.7.

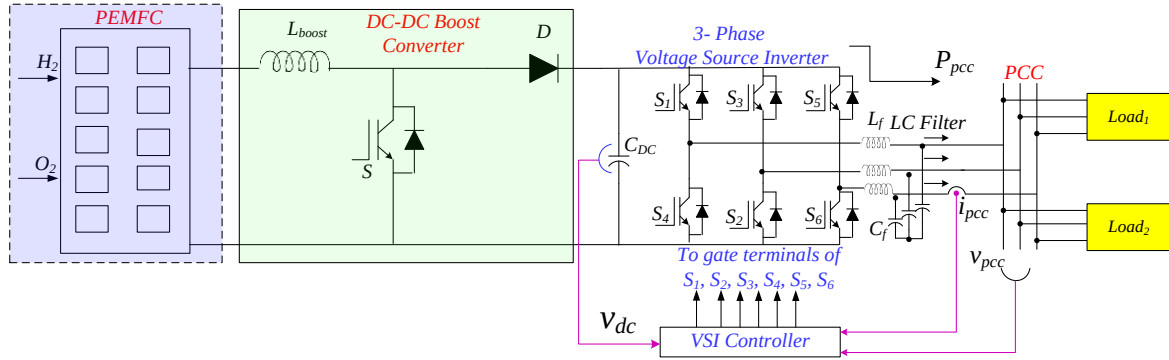


Fig. 2.1. Stand-alone PEMFC based system architecture.

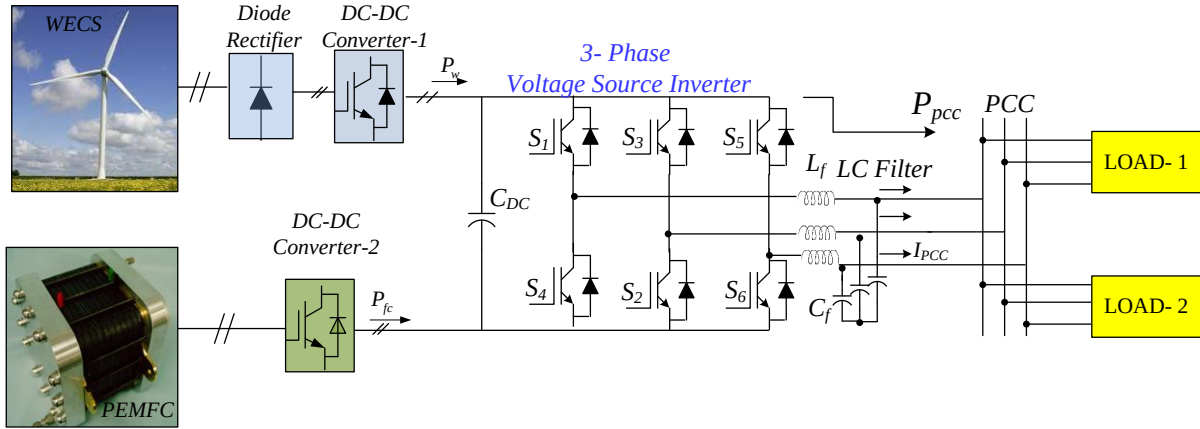


Fig. 2.2. Stand-alone WECS-PEMFC based hybrid energy system architecture.

2.2 Design Philosophy of Hybrid Energy Systems

Power electronic converters are the heart of hybrid energy systems as these converters furnishes the control capability to the energy system as a whole. Thus, the selection of various component parameters and electrical ratings attributes to the system design. Majorly, the dc-dc converters and dc-ac converters are the back bone of a hybrid energy system, which is evident by visualizing Fig. 2.2. As a classification of dc-dc converters, boost converter, buck

converter and buck-boost converter are typically used in this research work. The relevant design equations pertaining to dc-dc and dc-ac converters are discussed in this section.

2.2.1 Selection of dc-Link Voltage

The hybrid system architecture uses a common dc-bus architecture. The selection of rated voltage of the dc-link denoted as v_{dc} is derived by fixing the rated line to line ac output voltage of the inverter terminals (v_{rms}^{LL}). Considering, the inverter is operated by maintaining a modulation index (m_f), the dc-link voltage of dc-bus is calculated based on (2.1) [101].

$$v_{dc} \geq (2/m_f) \sqrt{2/3} \times v_{rms}^{LL} \quad (2.1)$$

As a typical design example, if $v_{rms}^{LL} = 415$ V and $m_f = 1$ is selected, then the calculated value of v_{dc} is 677 V which is approximated to 680 V. The calculation of rated value of dc-link voltage helps in the selection of further components like dc-link capacitor and inductances for various dc-dc converter used in the hybrid system.

2.2.2 Design and Selection of dc-link Capacitor

The purpose of adding the dc-link capacitor C_{DC} is to maintain the dc-link voltage at a constant level for voltage source inverter (VSI), and also to minimize the ripple content at the dc bus. The design of C_{DC} is generally done by considering a 3% to 5% allowable voltage ripple of rated dc-link voltage, and is formulated as per (2.2) [102].

$$C_{DC} = \frac{P_{dc}/v_{dc}}{2 \times \omega \times \Delta v_{dc}} \quad (2.2)$$

Here, P_{dc} is the rated power available at the dc-link, v_{dc} is the rated dc-bus voltage, ω is the angular frequency, and Δv_{dc} is the percentage voltage ripple with respect to the rated dc-link voltage. As a typical example, considering a FC plant rated at 30 kW, v_{dc} as 680 V, ω as 314 rad/s and percentage voltage ripple as 3%, the value of dc-link capacitance is given as,

$$C_{DC} = \frac{(30 \times 10^3 / 680)}{(2 \times 314 \times 0.03 \times 680)} \approx 3443.08 \mu F \quad (2.3)$$

Considering the commercial availability of standard capacitors, the value of C_{DC} is selected as 3700 μF .

2.2.3 Design dc-dc of Buck Converter

A buck converter is required in a hybrid generation system if there is a requirement of stepping down the dc voltage. This converter is used for interfacing an electrolyzer with the common dc bus [103]. Considering the dc bus has been fixed at higher dc voltage level while; the terminal of the electrolyzer is maintained at a lower dc voltage level. The selection of inductor L_{buck} is done such that the continuous conduction mode is maintained within the converter as per the design equation depicted in (2.4).

$$L_{buck} \geq \frac{(1-D) \times v_o}{2 \times f_s \times i_o} \quad (2.4)$$

Where, D is the duty cycle of the buck converter, v_o is the output voltage, f_s is the switching frequency and i_o is the rated output current of the converter. The output capacitor of the converter denoted by C_o is determined as per (2.5) [104].

$$C_o \geq \frac{i_o}{2 \times \omega \times \Delta v_{co}} \quad (2.5)$$

In (2.5), ω is the angular frequency of the ac mains and Δv_{co} is the % ripple voltage of the output of the capacitor.

2.2.4 Design of dc-dc Boost Converter

The dc-dc boost converter is one of the widely applicable converters in HSES. In this research work, dc-dc boost converter is used at the terminal of WECS and at the terminal of FC. The design of inductor L_{boost} is performed as per (2.6) [105].

$$L_{boost} \geq \frac{D \times (1-D) \times v_o}{f_s \times \Delta i_1} \quad (2.6)$$

Where, D is the duty cycle, v_o is the output voltage, f_s is the switching frequency, and Δi_1 is the input current ripple in the inductor which can be considered between 6% to 10% range of the rated inductor current i_1 . The value of i_1 is expressed as $i_1 = p_{in} / v_{in}$ where, p_{in} and v_{in} is the input power rating and voltage rating of the converter. The design procedure for the capacitor is the same as mentioned in equation (2.2).

2.2.5 Design of dc-dc Buck-Boost Converter

The buck-boost converter has been used in the hybrid system for interfacing the battery bank and SC bank. Since, these storage devices require to perform the charging and discharging process depending on the power management control logic. Whenever the process of discharging happens then boost operation is activate while; buck operation is used for charging process. The inductance is considered by referring the buck mode and boost mode design operations [106]. For buck mode, the inductor is selected as per the design equation depicted in (2.7);

$$L_{buck} = \frac{(v_{dc} - v_b) \times D}{f_s \times \Delta i_l} \quad (2.7)$$

where, v_b is the terminal voltage of the battery and v_{dc} is the dc-bus voltage, f_s is the switching frequency and Δi_l is the % ripple of the charging current and D is the duty ratio expressed as $D = v_b / v_{dc}$. For the operation in boost mode, the power needs to be transferred from the battery terminal to the dc-bus. The design of inductor is done as per (2.8) where the duty ratio D is expressed as per (2.9).

$$L_{boost} = \frac{v_b \times D}{f_s \times \Delta i_l} \quad (2.8)$$

$$D = \frac{v_{dc} - v_b}{v_b} \quad (2.9)$$

The minimum value inductance obtained among equations (2.7) and (2.8) is selected as the final inductance value for the buck-boost converter.

2.2.6 Design of LC Filter

The LC filter is connected at the output of voltage source converter (VSC). As the output voltage and current profile from the VSC terminal is inherently non sinusoidal and contains harmonics due to the high switching frequency of VSC. Therefore, a LC filter helps towards the removal of voltage and current harmonics. Further, the minimization of harmonics at the inverter terminals helps towards the reduction of conduction losses in the power electronic switches of VSC. The design of LC filter is done as per [107] where the value of inductance (L_f) for the filter is chosen based on the maximum current ripple (Δi_{pp}) at the inverter output. The value of L_f is given by (2.10) – (2.11), where Δi_{pp} is considered as 10% of the inverters

rated current denoted by i_{rated} , v_{dc} is the dc bus voltage and f_{sw} denotes the inverter switching frequency.

$$\Delta i_{pp} = 10\% \times i_{rated} \quad (2.10)$$

$$L_f = \frac{v_{dc}}{4 \times f_{sw} \times \Delta i_{pp}} \quad (2.11)$$

The filter capacitor C_f is connected in shunt at the terminal of VSC, as capacitor offers low reactance for the high frequency ripple currents. As per the harmonic standard [108], the harmonic order greater than 33 must not exceed 0.3% of the rated current. On this basis, the capacitance is calculated as

$$C_f = \frac{1}{4\pi^2 f_{sw}^2 L_f} \quad (2.12)$$

2.3 Inverter Control Philosophy in Standalone Hybrid Energy System

In stand-alone mode, voltage control of the inverter is done in synchronously rotating dq -frame [109] depicted as per Fig. 2.3. The dq -control favours the advantage of having only two control variables instead of three. Due to reduction in number of control variables, an ease and convenience towards better regulation of various control variables is experienced. Technically, the aspect of voltage control and frequency regulation are the prime objectives of this inverter control structure. The indirect voltage control is achieved by the regulation of d -axis and q -axis current variables i_d and i_q respectively. In this control structure, the voltage reference v_d^{ref} is generated by the PI controller PI_1 which ensures the regulation of dc-link voltage v_{dc} at its reference value v_{dc}^{ref} . The term v_q^{ref} , denotes the q -axis reference voltage, it is fixed to zero for achieving unity power factor operation of the inverter. A virtual PLL is used to fix the angular frequency ω of the synchronously rotating frame. The transformation angle θ is calculated from ω and it is used for the 3-phase voltages (v_a, v_b, v_c) and 3-phase currents (i_a, i_b, i_c) transformation to their corresponding dq - reference frame variables v_d, v_q, i_d and i_q respectively.

2.4 Investigation Studies on Standalone Hybrid Energy System

This section intends to utilise the aspects of design and control of a standalone DG system. Looking into this aspect, two different standalone systems presented as per Fig. 2.1 and Fig. 2.2 are considered. The standalone system shown as per Fig. 2.1 uses only a 50 kW PEMFC system. This system is designed by following the design equations discussed as per Section 2.2 and the corresponding selected component values are summarised as per Table 2.1. Apart from this system, another standalone system as per Fig. 2.2 is considered. This system is a hybrid system, which is designed by considering a 40 kW PMSG based wind energy system and a 15 kW fuel cell system. Both the standalone systems are evaluated under steady state and unbalance fault conditions in order to understand the control aspects and its associated challenges. Two case studies namely Case study-1 and Case study-2 are undertaken in this section to validate the standalone system's design and control. In all the case studies, the behaviour of the standalone system under ideal system condition and under unbalance faults are presented. Parameters like, dc-link voltage v_{dc} , PCC terminal voltage v_{pcc} , PCC current i_{pcc} , frequency of the inverter's output terminal voltage denoted by F , active power delivered by the inverter denoted by P_{pcc} and the anode channel pressure of PEMFC- P_{H_2} are recorded in each simulation case studies.

2.4.1 Case Study-1: Investigation on a Standalone Fuel Cell System

For this case study, the stand-alone FC system presented as per Fig. 2.1 is considered. The control of inverter is performed as per the voltage control schematic of Fig. 2.3. The system performance without the presence of unbalance fault is presented as per Fig. 2.4(a) while the effect of a single line to ground (SLG) fault on the system is portrayed as per Fig. 2.4(b). In order to observe the effect of load transient in this system, two 3-phase resistive loads, namely, load-1 and load-2 are connected to the PCC at 0.2 s and at 0.3 s respectively. The profile of dc-link voltage and PCC voltage are well regulated even during load transients as per Fig. 2.4(a). It is interesting to observe the effect of loading on the system where a corresponding increase of PCC current is registered at 0.2 s and 0.3 s respectively. The frequency of PCC voltage is well regulated at 50 Hz due to the effective voltage control offered by the inverter control structure.

The impact of unbalance fault on the stand-alone system of Fig. 2.1 is simulated in MATLAB/ Simulink platform using a "Fault Block" from the Sim-Power-Systems library [111]. The considered fault duration is from 0.5 s to 0.6 s and the corresponding results are

presented as per Fig. 2.4(b). It is inferred that under fault condition, the unbalancing in PCC voltage and current waveforms are prominent. This leads to distortion of dc-link voltage, frequency and active power profile as per Fig. 2.4(b). Such, oscillatory response is undesirable as it will lead to poor power quality and mal-operation of the ac loads. It is further inferred that, the control of VSC cannot sustain the unbalancing in form of faults, as it leads to change in phase of terminal voltage of VSC. Further, as per the inverter control schematic of Fig. 2.3, the effective generation of voltage reference (v_d^{ref}) is affected due to the presence of unbalance faults. Also, from Fig. 2.4(b), it is inferred that oscillatory response in channel pressure of the PEMFC system is encountered. This can adversely affect the life time of PEMFC membrane. As a conventional voltage controlled VSC control system does not have the rejection capability to the negative sequence voltage and current components, such adverse behaviour is encountered during unbalance fault. Thus, an enhanced control of VSC for a stand-alone system is desirable.

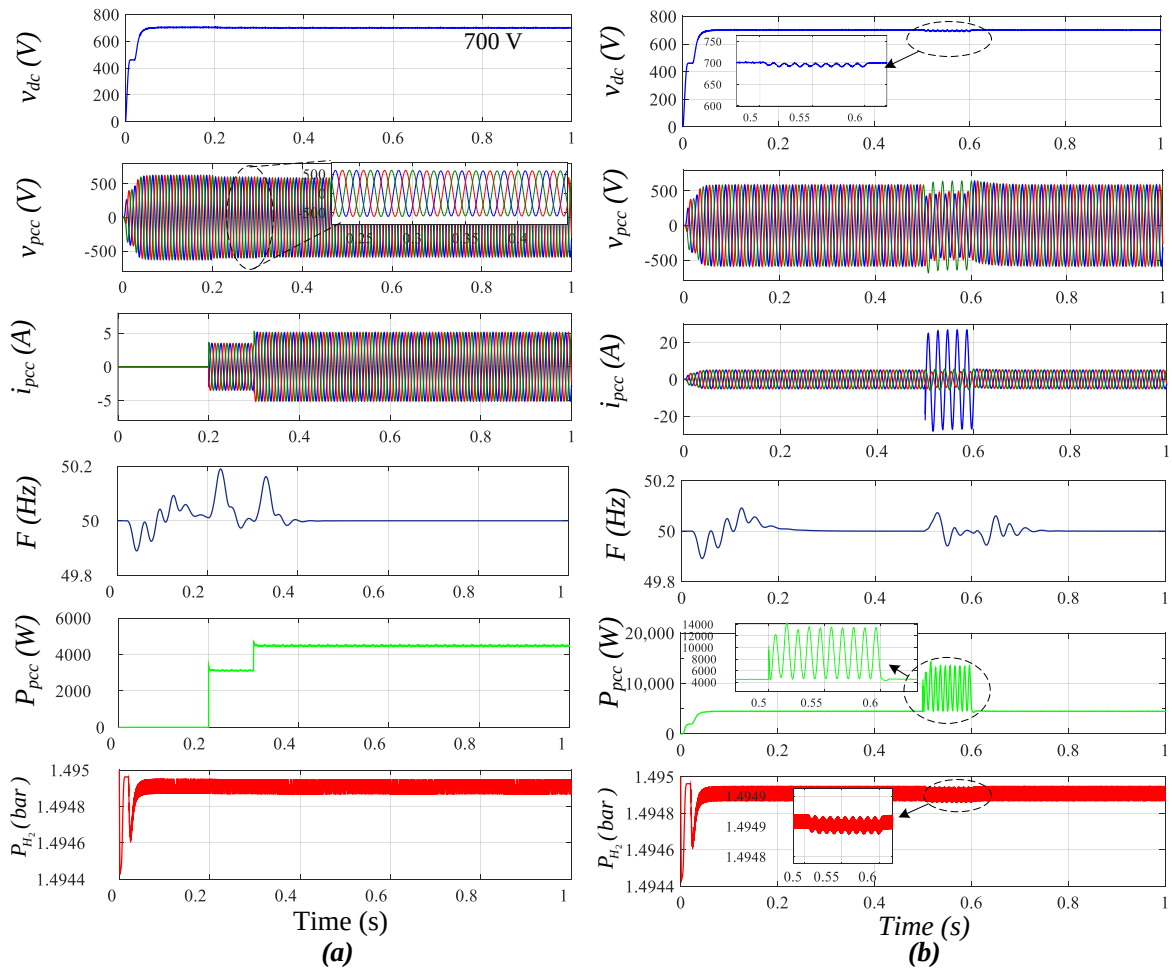


Fig. 2.4. Simulation results of PEMFC based stand-alone system. (a) Under normal condition. (b) Under SLG fault condition.

2.4.2 Case Study-2: Investigation on a Standalone WECS/ Fuel Cell Hybrid Energy System

A similar investigation is carried out as when the considered stand-alone system consists of hybrid power generation sources. The PMSG and PEMFC based hybrid system is depicted as per the configuration of Fig. 2.2. The investigation results of this stand-alone hybrid system under steady state and under fault condition are presented as per Fig. 2.5(a) and Fig. 2.5(b) respectively. A constant loading of 16 kW at the PCC is considered for the validation of inverter control scheme. The dc-link voltage, PCC voltage and the inverter's terminal frequency are well regulated as per Fig. 2.5(a). Steady power at the PCC and constant anode channel pressure is maintained in this case.

The same stand-alone hybrid system is now analysed when it is subjected to SLG fault for the duration of 0.5 s to 0.6 s. The response of the system is shown as per Fig. 2.5(b) where, the result depicts that the system encounters over current in the phase where the fault has occurred. The profile of active power at the PCC registers oscillations due to the flow of negative sequence currents in PCC. It is interesting to note that the profile of anode channel pressure is quite smooth as per Fig. 2.5(b) as compared to the profile of FC channel pressure oscillations as shown in Fig. 2.4(b). This difference is due to the voltage support gained in the system due to hybridization of WECS and PEMFC at the common dc-link. However, this aspect has minimum significance since, the magnitude of channel pressure oscillation is also dependent on the severity of SLG fault and the fault impedance.

2.5 Inverter Control Philosophy in Grid-Connected Hybrid Energy System

The grid integration of a HES consisting of WECS and FC is performed in this section. The schematic of this system is as per Fig. 2.6, where a 40 kW wind turbine driving a PMSG based wind generator is integrated with a 15 kW FC system at a common dc-bus. The detailed design and selection of various components and system parameters of this hybrid system is performed as per the design procedure detailed in Section 2.3. Further, these selected values are presented in Table 2.2. The control of inverter for such grid integrated hybrid energy system is done in dq - reference frame with the adoption of direct power control (DPC) strategy [109]. The detailed control philosophy towards DPC is explained in the consequent subsections.

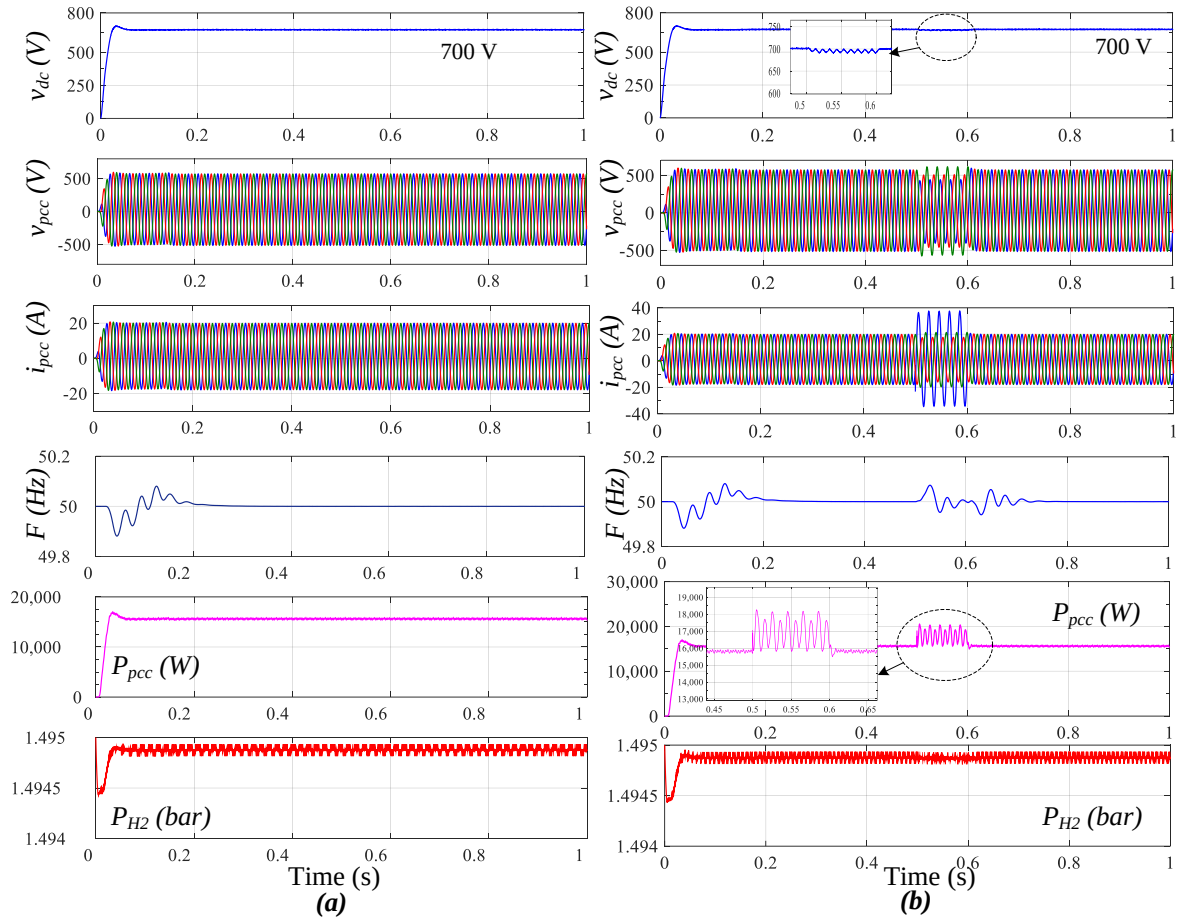


Fig. 2.5. Simulation results of standalone hybrid WECS/ PEMFC system. (a) Under normal condition. (b) Under SLG fault condition.

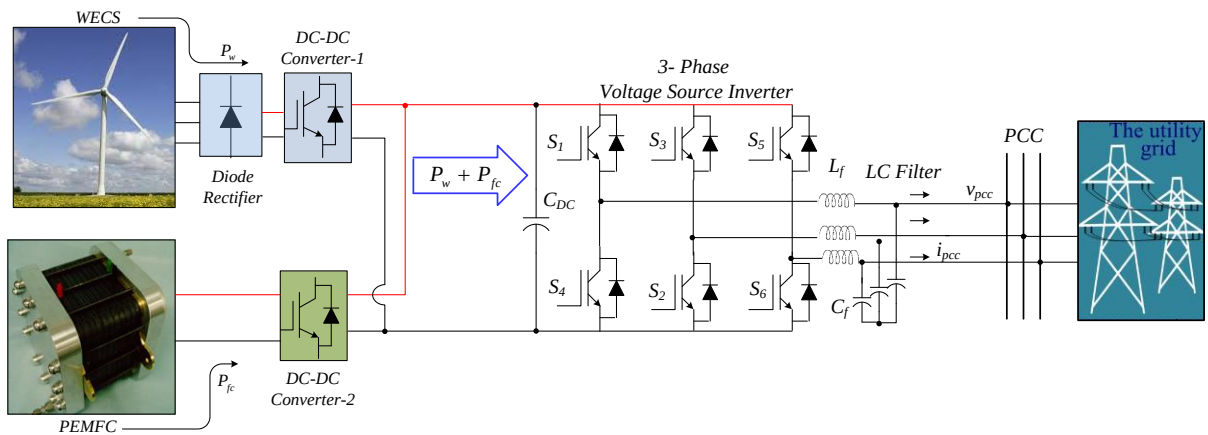


Fig. 2.6. Grid-connected WECS /FC hybrid system architecture.

Table. 2.2**Design parameters of the grid-connected WECS-FC hybrid energy system**

Device /Components	Ratings from design calculations
Parameters of WECS	Rated power of the wind turbine = 40 kW
	Wind Generator type: PMSG
	Rated speed of the PMSG = 314 rad/s
	Base wind speed of the turbine = 12 m/s
	Pitch angle (β) = 0°
dc-dc boost converter-1	Input voltage = 630 V, Output voltage = 680 V
	Duty cycle (D) = 0.0735
	Switching frequency = 10 kHz
	$L_{boost} = 1.2$ mH
PEMFC Stack Parameters	Power rating of individual stack= 1.2 kW
	Rated voltage of a single stack= 26 V, Rated stack current= 46 A
	Operating temperature= 55°C
	Nominal supply pressure of H ₂ = 1.5 Bar
	Number of series connected stacks = 12, Number of strings of parallel connected stacks = 1
	Overall rating of the PEMFC array = 15 kW
dc-dc boost converter-2	Input voltage = 312 V Output voltage = 680 V
	Duty cycle (D) = 0.5412
	Switching frequency = 10 kHz
	$L_{boost} = 6$ mH
dc link capacitor (C_{DC})	4700 μ F
dc link voltage (V_{dc})	680 V
Inverter	Rated kVA = 55 kVA
	Terminal voltage (L - L) = 415 V
	Switching frequency = 20 kHz
LC filter	$L_f = 1.42$ mH, $C_f = 0.1$ μ F
Utility Grid	Rated voltage (L - L) = 415 V, Rated frequency = 50 Hz

2.5.1 Direct Power Control Scheme

The DPC inverter control scheme offers the flexibility to extract the desired active power or reactive power from the hybrid generators. This aspect is realised by referring to its control structure as depicted in Fig. 2.7. In this structure, P^{ref} and Q^{ref} refers to the fixed active and reactive power desired from the inverter. The process of tracking this desired power from the inverter system is performed by the indirect current control. The information regarding the actual power generated by the hybrid sources is fetched by sensing the dc-link voltage. The outer voltage loop generates a current reference i_{dc}^{ref} when the error between the desired dc-link

voltage v_{dc}^{ref} and actual dc-link voltage v_{dc} is being processed by the PI controller PI_1 as per (2.13). The proportional and the integral gain of this controller is denoted by k_p^1 and k_i^1 respectively. The actual power generated by the hybrid sources denoted by P is estimated by the product of v_{dc} and i_{dc}^{ref} as per (2.14).

$$i_{dc}^{ref} = k_p^1 (v_{dc}^{ref} - v_{dc}) + k_i^1 \int (v_{dc}^{ref} - v_{dc}) \quad (2.13)$$

$$P = v_{dc} i_{dc}^{ref} \quad (2.14)$$

The error between the actual generated power and the desired power is denoted by ΔP^{ref} . The parameters ΔP^{ref} and Q^{ref} are used to generate the current references in dq - frame for the inner current control loop by applying (2.15) and (2.16) respectively.

$$i_d^{ref} = \frac{1}{v_d^2 + v_q^2} (v_d \Delta P^{ref} - v_q Q^{ref}) \quad (2.15)$$

$$i_q^{ref} = \frac{1}{v_d^2 + v_q^2} (v_q \Delta P^{ref} + v_d Q^{ref}) \quad (2.16)$$

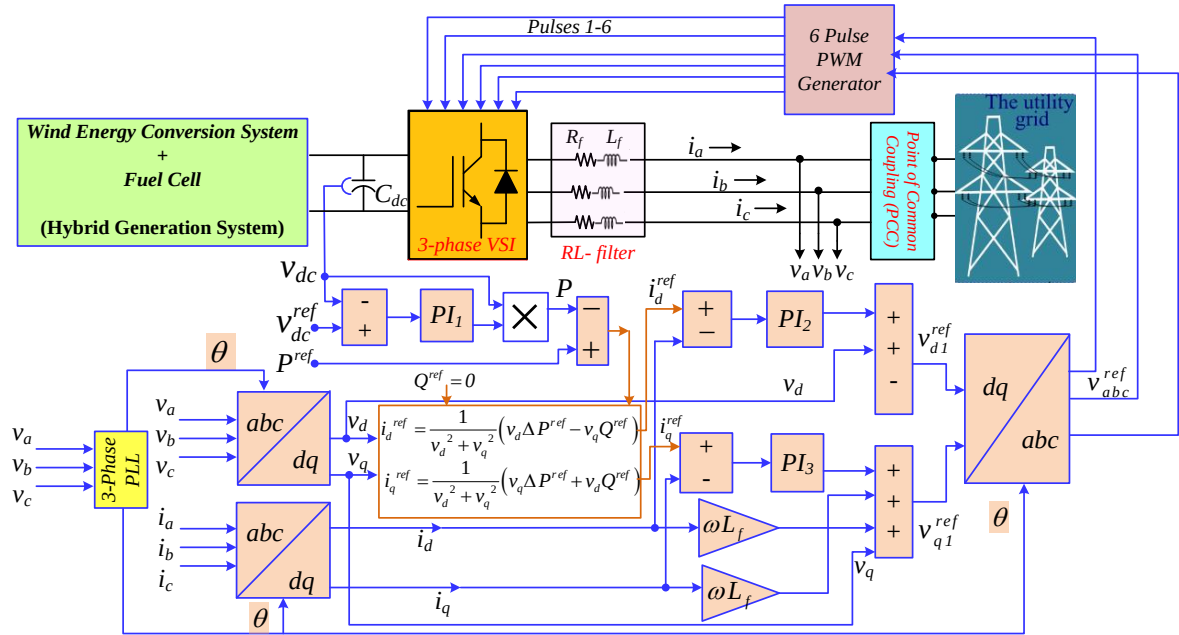


Fig. 2.7. VSI control based Direct power control scheme for grid connected mode.

In general, the desired reactive power Q^{ref} is fixed to zero for maintaining the unity power factor operation at the inverter terminals. The regulation of reference currents i_d^{ref} and

i_q^{ref} by the PI controller PI_2 and PI_3 ensures the desired dispatch of active power or reactive power from the 3-phase VSI system. However, the controller gains of PI_2 and PI_3 is a significant aspect towards the regulation of active and reactive power from the grid connected inverter system. Therefore, a design methodology towards its tuning is deliberated in the next subsection.

2.5.2 PI Controller Tuning in DPC

As inferred from Fig. 2.7, the DPC mechanism uses three PI controllers, each attributed with specific functions. The PI controller PI_1 enables the regulation of dc bus voltage hence is referred as voltage controller. The PI controllers, PI_2 and PI_3 are meant for regulating the dq -axis current, thus it is referred as current controller.

The tuning of proportionality constant (k_p) and the integral gain (k_i) constant of the current controllers are done using equation (2.17) [110] where, R_f and L_f denotes the resistance of the RL filter connected at the output of inverter, τ_i represents the time constant of the inverter current control loop. The value of τ_i is derived with the knowledge of inverter time constant τ_c , which is the reciprocal of inverter's switching frequency. Generally, for feasible current regulation, the time constant of current loop is 10 times of the inverter time constant, thus $\tau_i = 10 * \tau_c$.

$$k_i = \frac{R_f}{\tau_i}; k_p = \frac{L_f}{\tau_i} \quad (2.17)$$

2.6 Investigation Studies on Grid-connected Hybrid Energy System

The designed grid integrated hybrid energy system is as per Fig. 2.6 whose parameters are detailed in Table 2.2. This system is validated in MATLAB/ Simulink environment where it is investigated under ideal condition and for low voltage sag conditions. The respective investigation studies are referred as Case Study-1 and Case Study-2.

2.6.1 Case Study-1: Investigation Under Ideal Condition

Under an ideal condition a constant wind speed is considered for the WECS, while constant pressure of the H_2 fuel at the anode is considered. The investigation results for a simulation time span of 1 s are presented as per Fig. 2.8. A firm dc-link voltage v_{dc} around 680 V is maintained in the system which is as per Fig. 2.8(a). The line voltage at the PCC denoted by v_{pcc} is maintained constant at its rated value of 415 V as per Fig. 2.8(a). This is due to the

effective control offered by the inverter control scheme. The desired power reference P^{ref} is fixed to 40 kW which is based on the assumption that the hybrid DG system must meet a power obligation of 40 kW towards utility grid. As per the profile of active power delivered at the PCC terminal denoted by P_{pcc} , it is inferred that the inverter control is able to regulate its power near as that of the desired power reference P^{ref} . Accordingly, the profile of current at the PCC is registered as per Fig. 2.8(a). An interest lies to observe a physical parameter in this system which is the channel pressure at the anode of PEMFC denoted by P_{H2} . The profile of P_{H2} is shown as per Fig. 2.8(a) which indicates that the anode channel of the PEMFC is within the nominal operating pressure.

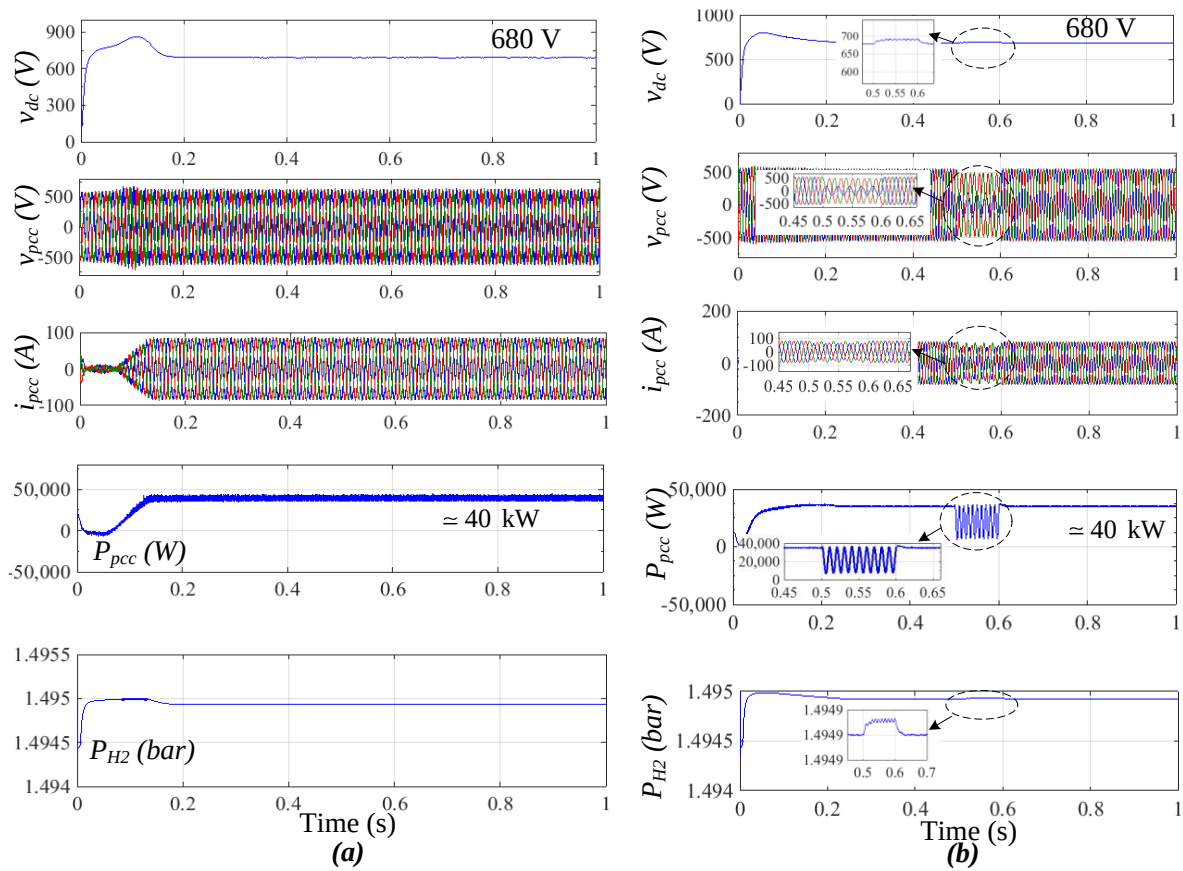


Fig. 2.8. Simulation results of grid connected hybrid WECS/ PEMFC system. (a) Under normal condition. (b) Under 1-phase voltage sag condition.

2.6.2 Case Study-2: Investigation Under Unbalanced Voltage Sag

A 1-phase voltage sag is simulated in the considered grid-connected HES for the span of 0.5 s to 0.6 s. A surge in the profile of dc-link voltage is observed as per Fig. 2.8(b) due to an imbalance between generated power and dispatched power during fault condition. The profile of PCC current is as per Fig. 2.8(b) where it is significant to observe that due to presence of

negative sequence currents in the system during voltage sag, oscillations in the profile of active power are observed. On critical observation of the profile of active power it is apt to infer that, there is a dip in the average value of active power of the PCC during the span of voltage sag. As per the profile of anode channel pressure as per Fig. 2.8(b), pressure oscillations are originated inside the channel during voltage sag duration.

The results of Fig. 2.8(b) signify that a hybrid system must have control mechanism to overcome the effects of unbalance faults or voltage sag. Such study, motivates towards deeper investigations on fault ride through mechanisms in hybrid sustainable energy system and encourages to offer new FRT control mechanisms.

2.7 Chapter Summary

From the aforementioned discussions, it is concluded that design and modeling of the hybrid system is essential in order to establish a practically realizable model of the system. This exercise will be helpful for further investigations for validating various control performance. Design calculations of different components involved in the model such as the rated dc-link voltage, dc-link capacitance, *LC*-filter parameters are showcased. This chapter has considered two stand-alone system topologies, consisting of only FC in the first topology and a WECS- FC in the second topology. The related control scheme for the inverter operation under stand-alone mode is discussed. The performance of these standalone system is investigated for ideal and under unbalance fault condition. Further, the chapter also presents the design of hybrid grid integrated WECS and FC system. The inverter control in grid-connected environment is performed by DPC and this control scheme could successfully regulate the active power. The same system is also investigated for unbalance fault condition at PCC. The investigation results suggest that, surge and oscillation in dc-link voltage, over current at the inverter terminal, dip and oscillation of active power at PCC are some of the major challenges in the operation of a hybrid system under faulted condition.

Modeling of Different Sub-Systems in HSES Architecture

3.1 Introduction

The thesis considers various architectures of HES which comprises of several sub-systems. In this chapter, a detailed deliberation towards the modeling of individual renewable/sustainable energy generators, storage devices and power electronic converters are presented. In all the HSES (hybrid sustainable energy system) architectures, wind energy system is considered as the primary source of power generation. The specific reason of selecting WECS is the abundance potential of wind energy in India. As per the technical report published by the CEA India [15], wind energy is the largest contributor for the renewable power in the country. This chapter emphasis on the modeling of two most widely used wind generators, namely, DFIG and PMSG.

In subsequent chapters of this dissertation work, three different HSES architectures have been proposed; firstly, the combination of PMSG and FC is selected for investigating the LVRT capability in the system as per Chapter-4. Secondly, the combination of PMSG, FC, battery and electrolyzer are used to validate the concept of integrated power management and LVRT control in the grid-integrated environment in Chapter-5. Lastly, in Chapter-6, the merits of DFIG are utilized to hybridize a SC bank, FC and electrolyzer towards the validation unified power management and LVRT control in HSES. As the proposed HSES configurations uses storage devices, the dynamics and modeling of these devices namely; FC, electrolyzer, battery and SC are also presented in this chapter. Apart from the modeling of primary and backup power sources, the modeling of dc-dc and dc-ac power electronic converters are also discussed.

3.2 Modeling of Wind Energy Conversion System

The prime components of a WECS are wind turbine, wind generator, gear-box, power electronics converters and its corresponding control circuitry. In this thesis work, PMSG and DFIG based WECS are selected as the prime renewable energy generator because of their relative merits. A PMSG is characterized with advantageous technical feature of low driving speed requirement, and thus, the prerequisite of a gear box interface between the wind turbine and generator is eliminated depending on the on-site wind potential generation. A PMSG is singly excited machine as the magnetic field in the rotor circuit is created by the permanent magnets which brings a robust construction and leads to low maintenance cost. On the other

hand, a DFIG based wind energy system attributes to a marginally higher cost due to the simultaneous magnetic field excitation requirement for both the stator and rotor winding. However, the provision of wider flexibility in the control of the active and reactive power from the stator's terminals via the use of back-to-back power electronic converters proves to be an added advantage. Moreover, in the DFIG system the converters namely RSC and GSC are rated around 30% of the DFIG machine's rating. Therefore, both the PMSG and DFIG based wind generators are comparable looking into their aspects of technical benefits and control flexibilities.

3.2.1 Modeling of Wind Turbine

A turbine generator model has been considered in this work without the presence of gear box arrangement. Here, the conventional two mass drive train model is ignored. The mechanical power generated by wind turbine is given by (3.1) [112],

$$P_m = \frac{1}{2} C_p(\lambda, \beta) \rho A v^3 \quad (3.1)$$

where, P_m is the mechanical power developed by the wind turbine, ρ is the air density in kilograms per cubic meter, A denotes blades swept area in meter square, v represents wind speed in meter per second, and C_p represents power coefficient which is function of tip speed ratio (λ) and pitch angle (β) and is expressed as per (3.2) and (3.3).

$$C_p(\lambda, \beta) = c_1 \left(\frac{c_2}{\lambda} - c_2 \beta - c_4 \right) e^{\frac{c_5}{\lambda_i}} + c_6 \lambda \quad (3.2)$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \quad (3.3)$$

where, $c_1 = 0.5176$, $c_2 = 116$, $c_3 = 0.4$, $c_4 = 5$, $c_5 = 21$ and $c_6 = 0.0068$, the knowledge of characteristics between C_p vs. λ for different values of pitch angle helps in calculating the maximum possible wind power for a particular wind speed. This forms the basis of MPPT control in WECS. The mechanical torque T_m generated by the wind turbine is used for generation of electromagnetic torque T_e in the generator. A general relation between T_m and T_e is expressed as per (3.4) [96] where, J denotes the inertia constant of the rotor and ω_r is the rotor speed of PMSG.

$$T_m = T_e + J \frac{d\omega_r}{dt} \quad (3.4)$$

3.2.2 Modeling of Permanent Magnet Synchronous Generator

In this work, a salient pole PMSG is considered, the modeling of stator voltage equations is based on parks transformation which considers synchronously rotating reference frame in the rotor axis expressed as per (3.5)-(3.6) [113].

$$v_{sd} = L_s \frac{di_{sd}}{dt} + i_{sd} R_s - \omega_e L_s i_{sq} \quad (3.5)$$

$$v_{sq} = L_s \frac{di_{sq}}{dt} + i_{sq} R_s + \omega_e L_s i_{sd} + \omega_e \lambda_f \quad (3.6)$$

In above expressions, R_s and L_s are resistance and inductance of PMSG stator winding respectively, v_{sd} , v_{sq} , i_{sd} and i_{sq} are the stator voltage and current transformed to dq -reference frame, λ_f is the magnetic flux and ω_e is the electrical angular speed. The equivalent circuit model of PMSG is fetched from equations (3.5) and (3.6) which is replicated as per Fig. 3.1. The generated electromagnetic torque T_e generated inside the rotor of PMSG is given as per (3.7);

$$T_e = \frac{3}{2} \frac{P}{2} \left\{ \lambda_f i_{sq} + (L_{sd} - L_{sq}) i_{sd} i_{sq} \right\} \quad (3.7)$$

where, L_{sd} and L_{sq} are the stator winding inductances in d - q reference frame respectively and P is the total number of magnetic poles in the machine. If a surface mounted non salient pole PMSG machine is considered then $L_{sd} \approx L_{sq}$ thus (3.7) gets simplified as per (3.8).

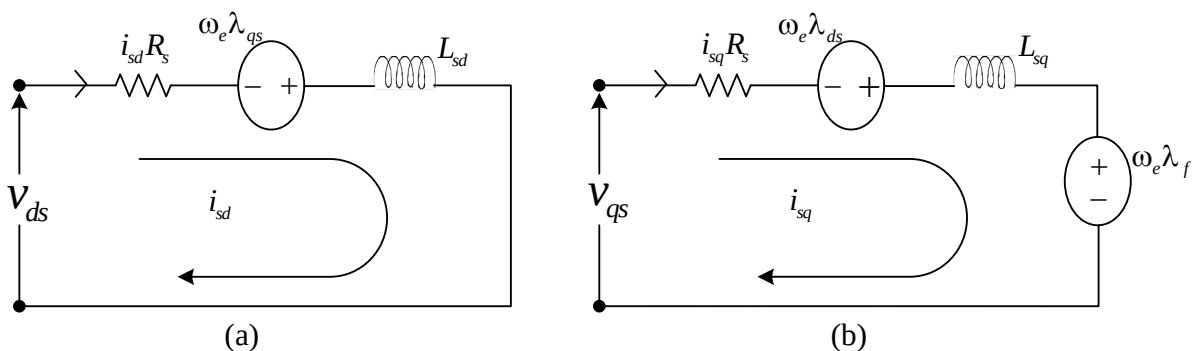


Fig. 3.1. Equivalent circuit of PMSG. (a) d-axis equivalent. (b) q-axis equivalent.

$$T_e = \frac{3}{2} \frac{P}{2} \left\{ \lambda_f i_{sq} \right\} \quad (3.8)$$

The above equation relates the direct dependency of the rotor's electromagnetic on i_{sq} , λ_f and P respectively.

3.2.3 Modeling of Doubly Fed Induction Generator

The modeling of DFIG is done in synchronously rotating reference frame in which the synchronous reference frame (SRF) quantities rotate synchronously with the stator flux. The stator and rotor voltages in dq -axis frame are given as per (3.9)-(3.12) respectively [114].

$$v_{ds} = r_s i_{ds} + \frac{d\lambda_{ds}}{dt} - \omega_e \lambda_{qs} \quad (3.9)$$

$$v_{qs} = r_s i_{qs} + \frac{d\lambda_{qs}}{dt} + \omega_e \lambda_{ds} \quad (3.10)$$

$$v_{dr} = r_r i_{dr} + \frac{d\lambda_{dr}}{dt} - (\omega_e - \omega_r) \lambda_{qr} \quad (3.11)$$

$$v_{qr} = r_r i_{qr} + \frac{d\lambda_{qr}}{dt} + (\omega_e - \omega_r) \lambda_{dr} \quad (3.12)$$

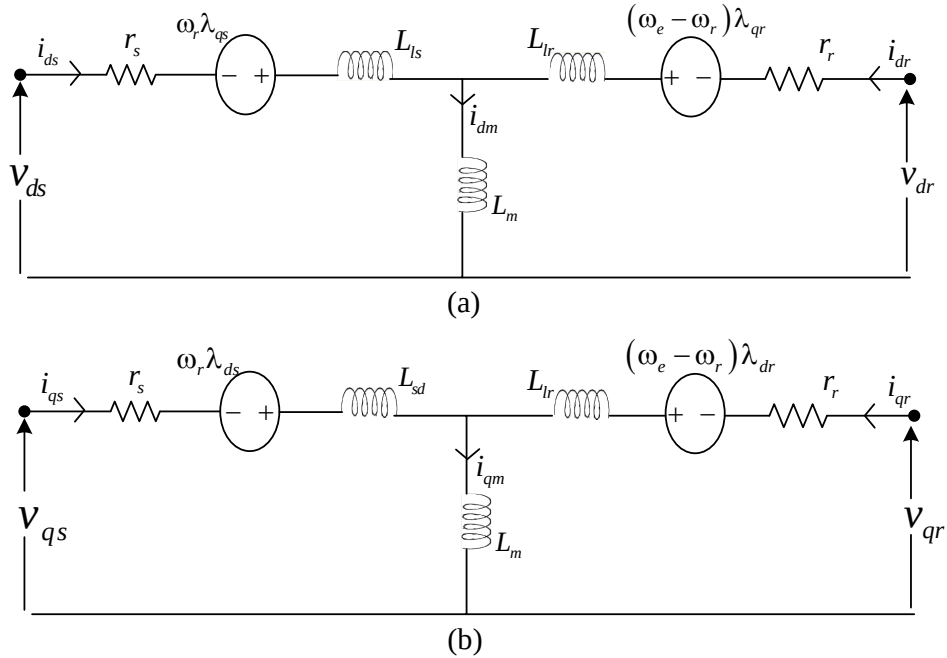


Fig. 3.2. Equivalent circuit of DFIG. (a) d-axis equivalent. (b) q-axis equivalent.

where, v_{ds} , v_{qs} are the stator voltage in synchronous rotating frame, i_{ds} , i_{qs} are the stator currents in dq -frame. The supply and rotor angular frequencies are represented by ω_e and ω_r

respectively. λ_{ds} and λ_{qs} represents the stator flux linkage in dq - axis respectively. While; v_{dr} , v_{qr} are the rotor voltages in SRF, i_{dr} , i_{qr} are the rotor currents in dq frame. λ_{dr} and λ_{qr} represents rotor flux linkage in dq - axis respectively and the stator and rotor resistances are denoted by r_s and r_r respectively.

The equivalent circuit of the DFIG machine in dq coordinate is derived as per (3.9)-(3.12). This circuit is presented as per Fig. 3.2 where, L_{ls} and L_{lr} represents the leakage inductance of the stator and winding respectively. L_m represents the magnetizing inductance between stator and rotor winding of the DFIG machine. The expression of stator's active (P_s) and reactive power (Q_s) is given by (3.13) and (3.14) respectively.

$$P_s = \frac{3}{2} (v_{ds} i_{ds} + v_{qs} i_{qs}) \quad (3.13)$$

$$Q_s = \frac{3}{2} (v_{qs} i_{ds} - v_{ds} i_{qs}) \quad (3.14)$$

The expression of stator currents is also related with the rotor currents i_{dr} , i_{qr} as per (3.15)-(3.16) where, L_s , L_r and L_m denotes the stator inductance, rotor self-inductances and mutual inductance respectively.

$$i_{ds} = \frac{1}{L_s} [\lambda_{ds} - L_m i_{dr}] \quad (3.15)$$

$$i_{qs} = \frac{1}{L_s} [\lambda_{qs} - L_m i_{qr}] \quad (3.16)$$

If this expression is substituted in (3.13) -(3.14), then the dependency of P_s and Q_s with i_{dr} , i_{qr} is related as per (3.17) and (3.18) respectively.

$$P_s = \frac{3}{2} \left[\frac{1}{L_s} (v_{ds} \lambda_{ds} + v_{qs} \lambda_{qs}) - \frac{L_m}{L_s} (v_{ds} i_{dr} + v_{qs} i_{qr}) \right] \quad (3.17)$$

$$Q_s = \frac{3}{2} \left[\frac{1}{L_s} (v_{qs} \lambda_{ds} - v_{ds} \lambda_{qs}) - \frac{L_m}{L_s} (v_{qs} i_{dr} - v_{ds} i_{qr}) \right] \quad (3.18)$$

The expression of generator's electromagnetic torque T_e is formulated in various ways where, its dependence with various stator and the rotor side electrical parameters is expressed as per (3.19) [115]-[116],

$$\begin{aligned}
T_e &= \frac{3}{2} \frac{P}{2} \{ \lambda_{ds} i_{qs} - \lambda_{qs} i_{ds} \} \\
&= \frac{3}{2} L_m \{ i_{qs} i_{qr} - i_{ds} i_{dr} \} \\
&= \frac{3}{2} \frac{P}{2} \{ \lambda_{dr} i_{qr} - \lambda_{qr} i_{dr} \}
\end{aligned} \tag{3.19}$$

3.3 Modeling of Proton Exchange Membrane Fuel Cell

The PEMFC is modelled as per (3.20) -(3.21). The internal potential e_{cell} generated across the two electrodes is as per the Nernst equation denoted by (3.20),

$$e_{cell} = \left[e_o + \frac{RT}{2F} \log \left(\frac{p_{H_2} \times p_{O_2}^{1/2}}{p_{H_2O}} \right) \right] \tag{3.20}$$

where, the standard reference potential under standard condition of 1 atm and 25°C is denoted by e_o . The magnitude of e_{cell} depends on the stack temperature represented by T , universal gas constant R , faradays constant F and the partial pressures of H_2 , O_2 and H_2O are denoted by p_{H_2} , p_{O_2} and p_{H_2O} respectively. The magnitude of terminal voltage is always less than e_{cell} due to the presence of activation loss, ohmic loss and concentration losses inside the PEMFC. The partial pressure of the reactants at anode and cathode of the FC preliminarily depends on the molar flow of reactants at anode-cathode, stack current of the FC and with various modeling constants. The same is expressed as per (3.21),

$$\begin{aligned}
p_{H_2} &= z_{H_2} (q_{H_2}^{in} - 2K_r i_{stack}) \\
p_{O_2} &= z_{O_2} (q_{O_2}^{in} - 2K_r i_{stack})
\end{aligned} \tag{3.21}$$

where, p_{H_2} and p_{O_2} are the partial pressure (in bar) of H_2 and O_2 at anode and cathode respectively, $q_{H_2}^{in}$ and $q_{O_2}^{in}$ denotes the molar flow (kmol/s) of the reactants at anode and cathode of the FC, while z_{H_2} , z_{O_2} , K_r are the modeling constants and i_{stack} is the stack current of FC. Considering a constant temperature and pressure in the fuel cell's stack chamber, the quantity of reacted H_2 in the FC denoted by $q_{H_2}^r$ (mol/s) is given as per (3.22) [117],

$$q_{H_2}^r = N_0 I_{stack} / 2F = 2K_r I_{stack} \tag{3.22}$$

where, N_0 is the number of series connected cells, F is the faradays constant (C/mol) and K_r is the modeling constant [mol/(sA)].

3.4 Modeling of Battery System

The terminal voltage v_{term} and battery state of charge (SOC) are the important parameters for a battery model. A battery storage system is modeled as per (3.23) and (3.24) respectively [85];

$$v_{term} = v_{oc} + i_b R_b - k \frac{Ahr}{Ahr + \int i_b dt} + v_a e^{B \int i_b dt} \quad (3.23)$$

$$SOC = \left(1 - \frac{\int i_b dt}{Ahr} \right) \times 100 \quad (3.24)$$

where, v_{term} denotes the battery terminal voltage, v_{oc} is the open circuit voltage, i_b is battery current, R_b is the battery internal resistance, k is the polarization voltage, v_a is the exponential voltage and B is the exponential capacity.

3.5 Modeling of Super Capacitor System

SCs are characterized by rapid transient response, low start up time, large power density, rapid discharging and charging cycles and does not require of extra cryogenic cooling systems as in case of a super-conducting energy storage device [118]. The modeling of SC is done via the utilization of the equivalent circuit shown as per Fig. 3.3 [119], where C_{sc} denotes the capacitance of SC, R_{sc}^p and R_{sc}^{se} is the series and parallel resistance, v_{csc} is voltage across the SC, v_{sc} is the entire voltage across the SC and parallel branch, i_{sc} is the current delivered by the SC. The dynamic KCL and KVL equations which explicates the working mechanism of the SC are presented as per (3.25) and (3.26) respectively.

$$\frac{v_{csc}}{R_{sc}^p} + C_{sc} \frac{dv_{csc}}{dt} = i_{sc} \quad (3.25)$$

$$v_{csc} - i_{sc} R_{sc}^{se} - v_{sc} = 0 \quad (3.26)$$

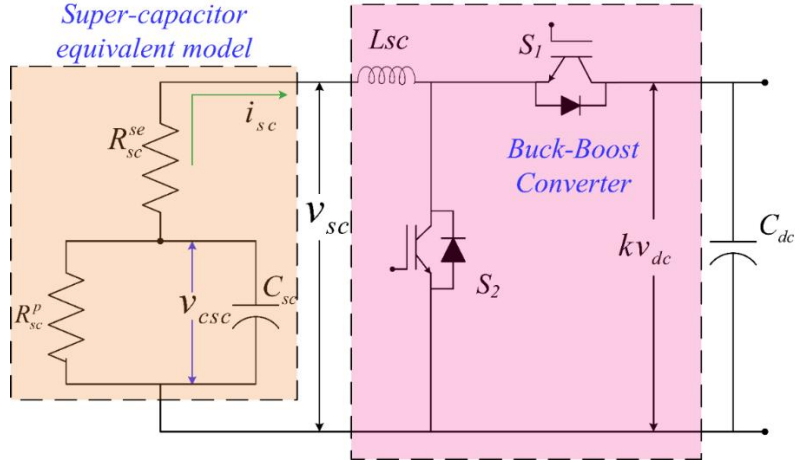


Fig. 3.3. Supercapacitor equivalent model and its integration with Buck-Boost converter.

3.6 Modeling of Electrolyzer

The electrolyzer system forms the supporting system for PEMFC where H_2 gets generated with the help of excess power from the WECS. The cell voltage and current relation in an electrolyzer is related as per (3.27) [120]. Where, v_{cell} is the electrolyzer cell voltage, v_{therm} is the thermodynamic cell voltage, T is electrolyzer temperature in $^{\circ}C$, r_1 and r_2 are the ohmic resistance parameters, t_1 , t_2 , t_3 and u_1 are the over-voltage parameters, while; i_{elz} is the current through the electrolyzer, A is the cell electrode area in m^2 and i_{elz}/A is the electrolyzer current density in A/m^2 . The number of electrolyzer cells connected in series denoted by n_s , is decided as per the required electrolyzer power rating as per (3.28).

$$v_{cell} = v_{thrm} + \frac{r_1 + r_2 T}{A} i_{elz} + u_1 \log \left(1 + \left(t_1 + \frac{t_2}{T} + \frac{t_3}{T^2} \right) \left(\frac{i_{elz}}{A} \right) \right) \quad (3.27)$$

$$v_{elz} = n_s v_{cell} \quad (3.28)$$

The electrolyzer generates H_2 as a function of electrolyzer current and Faraday's efficiency and is expressed as per (3.29).

$$n_{H_2} = \frac{\eta_F n_s i_{elz}}{2F} \quad (3.29)$$

In the above Eqn., n_{H_2} is the generated H_2 from the electrolyzer in (mol/s), η_F denotes the Faraday's efficiency, while n_s represents the number of series connected cells in the electrolyzer, F and i_{elz} are the faradays constant (C/mol) and electrolyzer current (A)

respectively. The significance of faradays efficiency is that it conveys the ratio of practical and theoretical maximum quantity of H_2 generated in the electrolyzer. The value of η_F is a function of electrolyzer current which is denoted as per (3.30);

$$\eta_F = 96.5 \exp(96.6 / i_{elz} - 75.5 / i_{elz}^2) \quad (3.30)$$

3.7 Modeling of dc-dc Converters

As the thesis work uses WECS, FC, battery, SC and electrolyzers, their controlling capability is possible with the use of power electronic interface- based converters. Typically, dc-dc converters are used for the interface purpose. Different control approach is possible for these converters in order to achieve sharp and desired system's control performance. A brief description regarding all the possible dc-dc converters namely; dc-dc boost converter, dc-dc buck converter and dc-dc buck boost converters are described in the Subsections 3.7.1- 3.7.3 respectively.

3.7.1 DC-DC Boost Converter

A dc-dc boost converter is being typically used to raise the dc-voltage level at a particular node in an electrical network. A boost converter is also referred as a step-up dc transformer since it elevates the dc voltage level in the system to a higher voltage level. In general, these converters find applications in PV systems, WECS etc. In this thesis, boost converters are used at the output terminals of the PEMFC in order to match the low voltage output from the PEMFC array with the common dc-link voltage of the system. Whereas, in WECS, the dc-dc boost converter has been used to perform the function of MPPT.

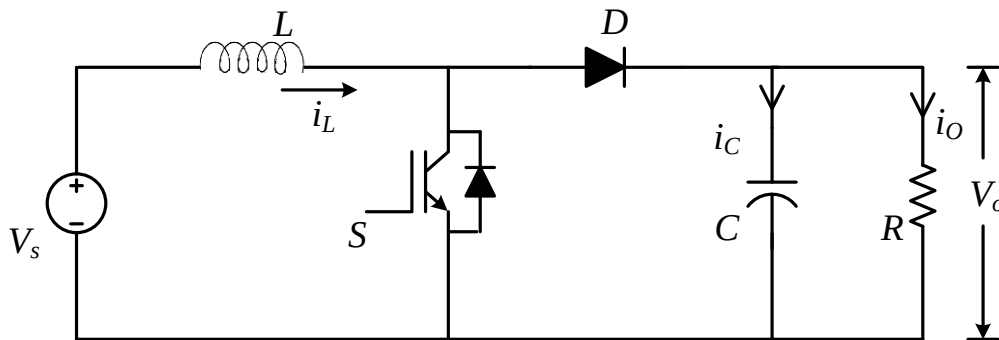


Fig. 3.4. Boost converter model.

A typical circuit model of such a converter assuming an IGBT based power electronic switch 'S' is shown in Fig. 3.4 where V_s and V_o are the input and output dc voltage for the converter, L and C are the inductance and capacitance of the converter, R is the output

resistance and D is the diode. The current through the inductor i_L and voltage across the capacitor V_o are taken as the state variables while V_s is considered as the input variable in order to express the behaviour of the converter in state-space form. The state equations of the converter are expressed as per (3.31) where, ‘ d ’ denotes the duty ratio of the converter which is expressed as per (3.32) [122].

$$\begin{bmatrix} \frac{di_L}{dt} \\ \frac{dV_c}{dt} \end{bmatrix} = \begin{bmatrix} 0 & -\frac{(1-d)}{L} \\ \frac{(1-d)}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_L \\ V_c \end{bmatrix} + \begin{bmatrix} 1/L \\ 0 \end{bmatrix} [V_s] \quad (3.31)$$

$$d = 1 - \left(\frac{V_s}{V_o} \right) \quad (3.32)$$

These equations help in selections of converter controller parameters, and also towards conducting its stability analysis.

3.7.2 DC-DC Buck converter

A buck converter is typically used to reduce the dc-voltage level in the system. This converter has been used in the work to interface an electrolyzer with the dc-bus of HES. As common dc-bus architecture is considered in all the HES architectures, the voltage level of this dc-bus is at a higher level. On the other hand, the electrolyzer input terminal voltage is rated at a lower dc-voltage level. The interface and control of the buck converter facilitates the desired operation of the electrolyzer as per specific system requirement. Fig. 3.5 represents the typical model of a buck converter where; the duty ratio of the switch ‘ S ’ and the ratings of passive components determines the output voltage of the converter.

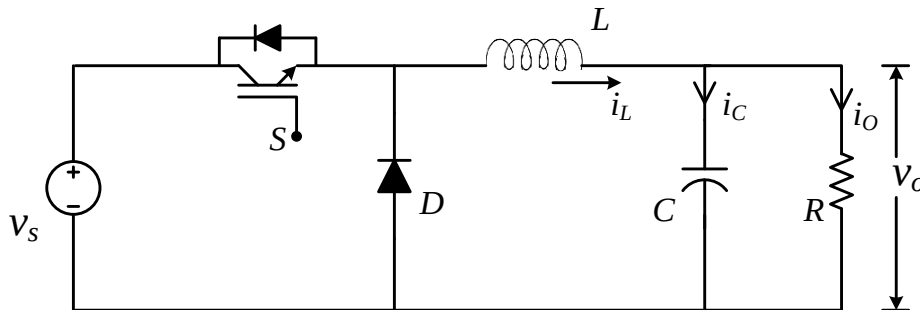


Fig. 3.5. Buck converter model.

The state equations representing the entire dynamics of the buck converter are represented as per (3.33) [122] where; v_s and v_o are the input voltage and output voltages of the converter. The state variables are current through the inductor i_L and voltage across the capacitor v_c . The duty ratio of the converter ‘ d ’ is given as $d = \frac{v_o}{v_s}$.

$$\begin{bmatrix} \frac{di_L}{dt} \\ \frac{dv_c}{dt} \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_L \\ v_c \end{bmatrix} + \begin{bmatrix} d/L \\ 0 \end{bmatrix} [v_s] \quad (3.33)$$

3.7.3 DC-DC Buck-Boost Converter

This converter has the capability to either step up or step down the dc-voltage level depending on the converter’s duty ratio. This converter typically finds its application as an interfacing media for a battery bank or a SC bank where repeated charging and discharging cycles are experienced. This dissertation has considered two types of hybrid system configuration one with the PMSG-WECS and battery banks and other with DFIG-WECS and SC bank deliberated in Chapters-5 and Chapter-6 respectively. In these chapters, buck boost converter is utilized as an interface for battery and SC with the dc-bus. The typical model of a buck boost converter is shown as per Fig. 3.6.

The averaged state-space model of the buck-boost converter is expressed as per equations (3.34) and (3.35) respectively where ‘ d ’ represents the duty ratio of this converter which is expressed as per (3.36) [104].

$$\frac{di_L}{dt} = (1-d) \frac{1}{L} v_c + (d) \frac{v_s}{L} \quad (3.34)$$

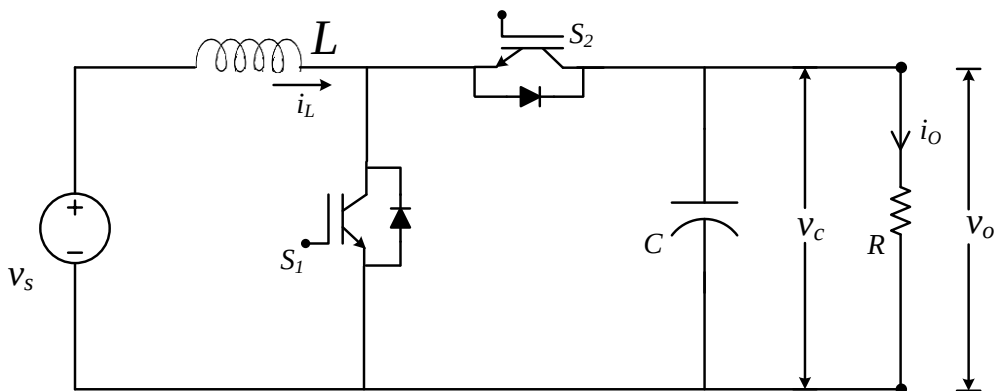


Fig. 3.6. Buck-Boost converter model.

$$\frac{dv_c}{dt} = -(1-d)\frac{1}{C}i_L - \left(\frac{1}{RC}\right)v_c \quad (3.35)$$

$$\left. \begin{aligned} v_o &= \left(\frac{d}{1-d}\right)v_s \\ d &= \frac{v_o}{v_o + v_s} \end{aligned} \right\} \quad (3.36)$$

3.8 Modeling of Grid Interfaced Voltage Source Inverter

In this thesis, the configurations of HSES uses a common dc-bus architecture. In this architecture, the conversion of dc voltage to ac voltage is performed by a voltage source inverter (VSI). This converter performs the function of synchronization and various control functionalities like unity power factor control, LVRT control, grid power levelling, reactive power dispatch control etc. Typically, in an ac microgrid, depending upon the microgrid's configuration, a VSI is controlled as a grid feeding, grid forming or as a grid supporting converter [123]. As per the objectives of this thesis work, the hybrid systems are operated in grid-integrated mode where it is desired to inject the power generated by HES to the utility grid. In this aspect, the grid feeding converter schematic has been considered in this work. The corresponding modeling of a VSI is being discussed in this section. A typical VSI converter used in a hybrid generation system as shown in Fig. 3.7. Different sustainable generators have been considered and the dc-dc interfacing converters are not shown for convenience. The inverter needs to be controlled such that it meets all the grid synchronization requirements.

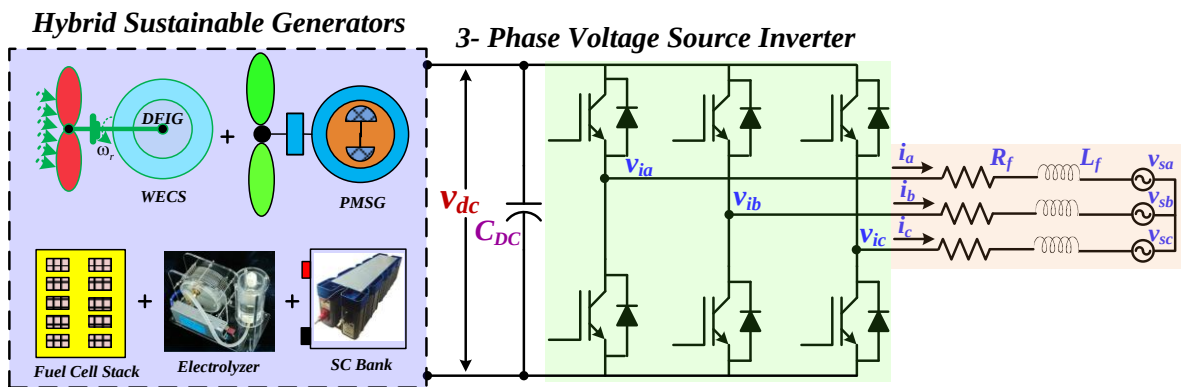


Fig. 3.7. Voltage source inverter model.

The inverter modeling is performed in the dq - reference frame shown as per Fig. 3.8. The frame is rotating synchronously at an angular velocity ω and subtends an angle θ with the a -axis.

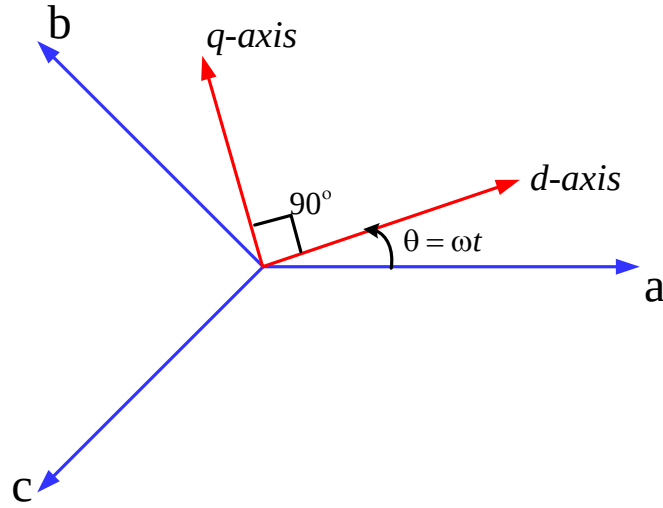


Fig. 3.8. Synchronous reference frame.

In current control of VSI, the angle θ is the same as that of the phase angle of the grid voltages. A PLL device is typically used to extract the information of the phase angle. As per Fig. 3.7, the KVL equations in the inverter and grid circuit enables the modeling of inverter control in dq -frame. The control of VSI in dq -frame enables an easy control of active and reactive power dispatch by the grid connected VSI. According to Fig. 3.7, the utility grid's phase voltages is denoted as v_{sa} , v_{sb} and v_{sc} respectively while the terminal voltages across the inverter are denoted as v_{ia} , v_{ib} and v_{ic} respectively.

The inverter is connected via an RL filter bearing the resistance and inductance as R_f and L_f respectively. The inverter terminal voltage equations are expressed as per (3.37).

$$\left. \begin{aligned} v_{ia} &= R_f i_a + L_f \frac{di_a}{dt} + v_{sa} \\ v_{ib} &= R_f i_b + L_f \frac{di_b}{dt} + v_{sb} \\ v_{ic} &= R_f i_c + L_f \frac{di_c}{dt} + v_{sc} \end{aligned} \right\} \quad (3.37)$$

Using the general expression for the abc to dq -transformation as per (3.38), the inverter output voltage in the dq -axis frame is modeled as per (3.39). From (3.38), it is inferred that the number of variables gets reduced when dq -transformation is undertaken. Moreover, these dq -variables are time invariant which eases the controllability aspect in the inverter when PI controllers are used.

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos \theta & \cos(\theta - 120^\circ) & \cos(\theta + 120^\circ) \\ -\sin \theta & -\sin(\theta - 120^\circ) & -\sin(\theta + 120^\circ) \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (3.38)$$

$$\left. \begin{aligned} v_{id} &= R_f i_d + L_f \frac{di_d}{dt} - \omega L_f i_q + v_{sd} \\ v_{iq} &= R_f i_q + L_f \frac{di_q}{dt} + \omega L_f i_d + v_{sq} \end{aligned} \right\} \quad (3.39)$$

In general, the current control technique is widely applied for the grid-connected mode inverter control as it renders an easy control of active P_i and reactive power Q_i delivered by the inverter via the control of i_d and i_q respectively. The expression for P_i and Q_i in SRF is depicted as per (3.40).

$$\begin{aligned} P_i &= \frac{3}{2} (v_{id} i_d + v_{iq} i_q) \\ Q_i &= \frac{3}{2} (v_{id} i_q - v_{iq} i_d) \end{aligned} \quad (3.40)$$

Now, if the d -axis of the rotating frame is aligned to the ac voltage vector of the abc -frame then $v_{iq}=0$. Thus, as per (3.40) the control of P_i and Q_i are commanded by the regulation of the currents i_d and i_q respectively.

3.9 Chapter Summary

This chapter presented a brief idea regarding the modeling equations of various subsystems present in the considered model of hybrid energy systems. The $dq0$ axis-based modeling remains a preferred choice for the modeling of PMSG and DFIG due to its control flexibility. Further, the modeling of inverter system is also performed in the SRF frame. The chapter also highlighted the basic modeling characteristics of storage devices viz. FC, electrolyzer, battery and SC. Lastly, the modeling of various dc-dc converters in their respective state space domain are showcased.

LVRT Enhancement in a Grid-Connected Wind/Fuel Cell Hybrid System by Combined Feed-Forward and Fuzzy Logic Control

4.1 Introduction

As per the present grid code demands, fault ride through (FRT) capability is an essential practice for grid-connected renewable energy based distributed energy resources (DERs). As inferred from the discussions of Section 1.2.3, studies on FRT capability for grid-connected hybrid systems are limited. The chapter considers a wind energy conversion system (WECS) and a fuel cell system interconnected at a common dc bus. This chapter presents a new feed-forward based FRT control scheme for the inverter control where, new current references in dq -axis frame are derived by tracking the positive sequence power. The newly derived references are fed forward to the input of the current regulator of the voltage source inverter (VSI). Secondly, a fuzzy logic based current controllers are suggested to improve the tracking capability of the current references in the inverter control scheme so as to enhance the FRT capability of the hybrid system as a whole. The proposed feed-forward-fuzzy control scheme for achieving an enhanced FRT capability is compared with the conventional dq current control and feed-forward FRT control for various grid voltage sag tests, where the performance of the combined feed-forward-fuzzy control is found better. The validation of the proposed FRT control scheme is performed in MATLAB-Simulink environment.

4.2 Motivation and Contribution towards LVRT Enhancement

Low voltage ride-through (LVRT) capability emphasizes that a grid-connected DER is expected to stay connected to the grid until the PU voltage levels are above the LVRT curve [124]. An approach to operate multiple DERs in parallel offers the benefit of enhanced system reliability and uninterrupted power at the load end. These DERs may contain sustainable energy sources such as PV or wind. Among various wind generators, a direct driven PMSG offers the advantage of single excitation and non-requirement of the gear box arrangement. As a backup device, FC offers appreciable features like modular configuration, eco-friendly and salient operation. The LVRT control in PMSG is embedded in [96] and [125] by swapping the MPPT function of the machine side converter with GSC. Under grid-voltage dip, GSC is made

to achieve the ride through control by reactive power injection strategies instead of dc-link voltage control.

The discussions deliberated in Section 1.2.3 of Chapter-1 emphasised that the LVRT enhancement is achieved by reactive power injection schemes, active and passive LVRT control schemes. The issue of additional cost and control requirements is associated with the passive LVRT schemes [63]-[64]. While; the active control schemes encounter the use of numerous PI controllers [59] and exhibits computation burden on the inverter control algorithm [60]. In a current controlled grid connected inverter control algorithm, the inclusion of feed forward term improvises the dynamic response of the inverter against ambience changes. Such control enhancement is demonstrated in case of a two stage, 3-phase solar PV system [126]. Whereas, in a PMSG based WECS, the ride through and frequency support is provided in via feed-forward based control approach along with the conventional PI controller [127]. Looking into the control flexibility and enhancement offered by the inclusion of feed-forward terms, the use of feed-forward control is motivating choice for this work.

Fuzzy logic controller (FLC) proves to be effective for the control of microgrid system as the amount of nonlinearity in such systems is large [128]-[130]. In [96], interval Type-2 fuzzy control is utilized to achieve LVRT enhancement in PMSG wind turbine, however, the monitoring of electromagnetic torque in PMSG is not executed under fault conditions. The use of shrinking span membership functions base fuzzy control is used in [131] for achieving FRT capability in multiple wind farm while; the discussion on the instantaneous active power profile was not performed. From the reviewed literature, it is perceived that the FRT control largely uses a complex control algorithm or uses an additional hardware. Fuzzy control is a preferable choice for systems with non-linearities like microgrids. Hence, this chapter attempts to contribute towards the enhancement of LVRT capability for a hybrid grid-connected wind/fuel cell system by the following ways;

1. The presented FRT control utilizes sequence components to compute the feed-forward current references, which are used in conjunction with the conventional dq - current control of the VSI system.
2. The proposed FRT control does not use any additional or external devices like series dynamic breaking resistor (SDBR), crowbar circuits, dc-link chopper controlled braking resistor etc. Hence, the use of extra hardware in the system is eliminated.

3. This chapter also presents the use of fuzzy logic controllers (FLC_1 and FLC_2) embedded in the control scheme in order to track the newly generated feed-forward current references.

The presented FRT controller is incorporated for a grid-connected hybrid system consisting of PMSG based wind generation and a proton exchange membrane fuel cell (PEMFC) system concatenated at a common dc bus whose schematic diagram is depicted as shown in Fig. 4.1. This system inherits technical benefits of rendering continuous power as the PEMFC system acts as back up when power generation from the wind is deficient. In the entire analysis, the power sharing algorithm between PMSG, PEMFC, loads at the PCC and the utility grid is not taken into account. Simultaneously, the MPPT functionality of WECS under the FRT control mode is also not taken into account, as the motivation of this chapter is to evaluate the FRT studies with the proposed control schemes such that the objective of control detailed as one of the thesis objectives as per Section 1.4 is met. The rest of the chapter is organized as follows: the entire hybrid generation system model is briefly discussed in Section 4.3, the grid-connected hybrid system's behaviour under grid fault and the limitations of the existing FRT control schemes are explicated in Section 4.4. While in Section 4.5, a thorough discussion on the proposed feed-forward and feed-forward-fuzzy control for rendering the FRT capability is presented. The performance of the proposed FRT controllers is highlighted by considering relevant case studies along with a comparative analysis with the conventional dq -current control and feed-forward control schemes in Section 4.6. Finally, the conclusions regarding the merits and limitations of the proposed LVRT controller are drawn in Section 4.7.

4.3 Hybrid Generation System Model

A grid-integrated renewable energy-based hybrid generation system considered for the study is depicted as per Fig. 4.1 and the corresponding ratings of various components in this system are tabulated in Table. 4.1. The PMSG based WECS is considered as the primary source of power generation whereas a PEMFC is added in parallel to the system in order to improve the system redundancy. The system intends to support its local ac loads connected at the PCC and export its excess power during high wind speed to the utility grid.

The ac output of the PMSG-WECS is conditioned to dc via an uncontrolled bridge rectifier having diodes D_1 - D_6 . The dc-dc boost converter-1 with inductor L_1 , diode D_7 and controlled insulated gate bipolar transistor (IGBT) switch S_1 performs the function of MPPT. Boost converter- 2 with inductor L_2 , diode D_8 and controlled IGBT switch S_2 is used to control

the FC power as per the desired power reference, such that the power deficit between the WECS and load demand is met. The controlled power conversion from dc to ac is performed by a 3-phase voltage source inverter having controlled IGBT switches S_3 - S_8 .

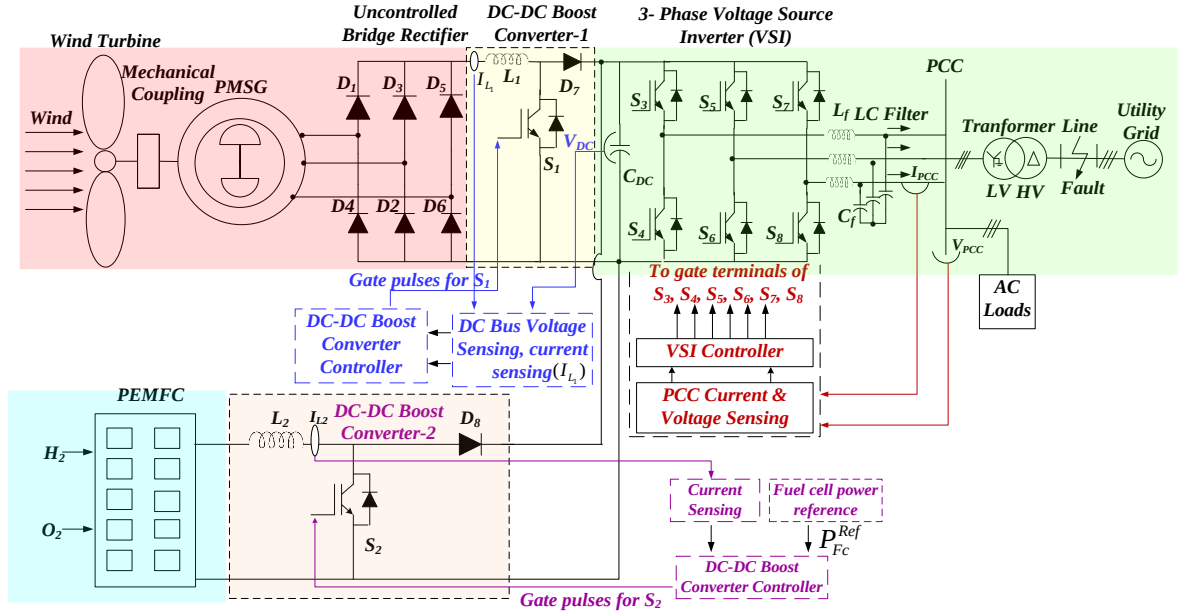


Fig. 4.1. Schematic of the grid-connected hybrid sustainable generation system.

Table 4.1
System parameters of PMSG-PEMFC hybrid energy system

PMSG Wind Energy system	
Rated Power	40 kW
Rated Speed	314 rad/s
Rated Torque	126 Nm
Base wind speed	12 m/s
PEMFC Stack [28]	
Power rating	1200 W
DC voltage range	22 V- 50 V
Rated voltage	26 V
Rated current	46A
Number of cells	48
Nominal stack efficiency	46 %
Operating temperature	55°C
Nominal supply pressure of H ₂	1.5 Bar
Nominal supply pressure of O ₂	1 Bar
System Electrical Parameters	
Base Voltage (Line to Line)	415 V
VSI switching frequency	20 kHz

4.3.1 Modeling of Wind Turbine and PMSG

The wind energy system consists of a wind turbine and a wind generator. The selected wind generator is a salient pole PMSG. The modeling of the wind turbine and PMSG is

discussed in Chapter-3. Equations (3.1) – (3.4) are used for the modeling of wind turbine, while; (3.5) -(3.6) are considered for the modeling of PMSG in synchronously rotating reference frame in the rotor axis.

4.3.2 Modeling of FC

In this thesis work, PEMFC is selected as a primary backup source owing to its low operating temperature and high efficiency [132]. The mathematical modeling of FC is deliberated in Section 3.3 of Chapter-3. The modeling expressions relevant to stack voltage, reactants partial pressure and H₂ consumption are detailed as per (3.20) -(3.22) respectively.

4.4 Grid Connected-VSI Behavior Under Grid Faults

The prime objective of this chapter is to investigate the FRT capability of a grid connected (GC) hybrid generation system modeled as per Fig. 4.1. The main contribution is towards the control of GC- VSI during the faults occurring at high voltage (HV) side of the transformer. When fault gets impinged in the system, there is rapid fall of power at the PCC side. This fall of power may slant to null depending on the severity of the fault, magnitude of the network impedance, location of the fault etc. While; the power generated by the WECS and the PEMFC remains unchanged, the power imbalance between the power generated by DERs and the power at the PCC leads to rapid surge of power across the dc-link capacitor. This power surge appears instantly in the form of dc-link voltage surge.

4.4.1 DC-link Voltage Surge and dc-Link Voltage Ripple

The surge in dc-link voltage appears as an addition of energy stored by the dc-link capacitor and is accompanied by the presence of voltage ripples. Voltage ripples occur due the presence of voltage and current unbalance happening because of the injection of negative sequence voltage and current components in the power system. The energy absorbed by the dc-link capacitor due to voltage surge is expressed as per (4.1) [63],

$$\Delta P_{dc} \cdot \Delta t = \frac{1}{2} C_{dc} (\bar{v}_{dc} + \Delta v_{dc})^2 - \frac{1}{2} C_{dc} (\bar{v}_{dc})^2 \quad (4.1)$$

where, ΔP_{dc} is the change in dc-link power, Δt is the transient time, C_{dc} is the dc-link capacitance, $\bar{v}_{dc}$ represents the mean value of dc-link voltage and Δv_{dc} is the surge magnitude of dc-link voltage. The approximate analysis results in magnitude of dc-link voltage fluctuation as per (4.2).

$$\Delta v_{dc} = \frac{\Delta P_{dc} \cdot \Delta t}{C_{dc} \cdot v_{dc}} \quad (4.2)$$

The dc-link voltage fluctuation is undesirable from the view point of the system's stability. A straight forward approach to remove the fluctuations in dc-link voltage can be by increasing the value of dc-link capacitance. But this approach is non-feasible as it increases system cost and bulkiness.

4.4.2 Active and Reactive Power Ripple

The grid codes demand for the injection of reactive currents by the inverter during the detection of voltage dip at the utility side for FRT accomplishment. The basic mathematical foundation is based on expressing the instantaneous powers in terms of the positive- negative sequence current and voltage components in a suitable reference frame and to perform appropriate current control functionality. During ideal condition, that is, in the absence of grid fault, the apparent power delivered by the grid connected VSI contains only the positive sequence voltage and current components. The same may be expressed in synchronous reference frame (SRF) quantities as per (4.3),

$$s = v_{dq}^p (i_{dq}^p)^* \quad (4.3)$$

where, the subscript 'dq' denotes the quantities in dq- axis frame, prefix 'p' denotes positive sequence quantities, '*' represents the complex conjugate term, v_{dq}^p denotes the PCC voltage in dq frame, i_{dq}^p is the PCC current in dq frame. During the presence of grid unbalance, the instantaneous apparent power is expressed in positive and negative sequence quantities in the SRF frame as per (4.4),

$$s = (v_{dq}^p e^{j\theta} + v_{dq}^n e^{-j\theta})(i_{dq}^p e^{j\theta} + i_{dq}^n e^{-j\theta})^* \quad (4.4)$$

where, the prefix 'n' denotes negative sequence quantities, operator 'j' means the 90° phase shift in the electrical quantities and θ is the electrical phase angle. The instantaneous active power $P(t)$ and reactive power $Q(t)$ is represented as per (4.5) and (4.6) [12].

$$P(t) = P_o + P_{c2} \cos(2\omega t) + P_{s2} \sin(2\omega t) \quad (4.5)$$

$$Q(t) = Q_o + Q_{c2} \cos(2\omega t) + Q_{s2} \sin(2\omega t) \quad (4.6)$$

The terms P_o , Q_o in (4.5) and (4.6) represents the average active and reactive power, P_{c2} , P_{s2} , Q_{c2} and Q_{s2} represents the second order ripple components in the active and reactive powers

respectively. The conventional approach involves to convert quantities of (4.5) and (4.6) in the SRF quantities as per (4.7) -(4.12) in order to achieve flexible control strategies.

$$P_o = 1.5(v_d^p i_d^p + v_q^p i_q^p + v_d^n i_d^n + v_q^n i_q^n) \quad (4.7)$$

$$P_{c2} = 1.5(v_d^p i_d^n + v_q^p i_q^n + v_d^n i_d^p + v_q^n i_q^p) \quad (4.8)$$

$$P_{s2} = 1.5(v_q^n i_d^p - v_d^p i_q^p - v_q^p i_d^n + v_d^n i_q^n) \quad (4.9)$$

$$Q_o = 1.5(v_q^p i_d^p - v_d^p i_q^p + v_q^n i_d^n - v_d^n i_q^n) \quad (4.10)$$

$$Q_{c2} = 1.5(v_q^p i_d^n - v_d^p i_q^n + v_q^n i_d^p - v_d^n i_q^p) \quad (4.11)$$

$$Q_{s2} = 1.5(v_d^p i_d^n + v_q^p i_q^n - v_d^n i_d^p - v_q^n i_q^p) \quad (4.12)$$

The terms of (4.7) -(4.12) are represented as per the matrix equation given in (4.13) while the current references are generated as per (4.14) according to the desired FRT requirement. It is significant to note that the calculation of inverse matrix of (4.14) increases the quantum of computational effort of the digital processor used for the inverter control algorithm.

$$\begin{bmatrix} P_o \\ Q_o \\ P_{s2} \\ P_{c2} \\ Q_{s2} \\ Q_{c2} \end{bmatrix} = \frac{3}{2} \begin{bmatrix} v_d^p & v_q^p & v_d^n & v_q^n \\ v_q^p & -v_d^p & v_q^n & -v_d^n \\ v_q^n & -v_d^n & -v_q^p & v_d^p \\ v_d^n & v_q^n & v_d^p & v_q^p \\ -v_d^n & -v_q^n & v_d^p & v_q^p \\ v_q^n & -v_d^n & v_q^p & -v_d^p \end{bmatrix} \begin{bmatrix} i_d^p \\ i_q^p \\ i_d^n \\ i_q^n \end{bmatrix} \quad (4.13)$$

$$\begin{bmatrix} i_d^p \\ i_q^p \\ i_d^n \\ i_q^n \end{bmatrix}^{ref} = \frac{2}{3} \begin{bmatrix} v_d^p & v_q^p & v_d^n & v_q^n \\ v_q^p & -v_d^p & v_q^n & -v_d^n \\ v_q^n & -v_d^n & -v_q^p & v_d^p \\ v_d^n & v_q^n & v_d^p & v_q^p \\ -v_d^n & -v_q^n & v_d^p & v_q^p \\ v_q^n & -v_d^n & v_q^p & -v_d^p \end{bmatrix}^{-1} \begin{bmatrix} P_o \\ Q_o \\ P_{s2} \\ P_{c2} \\ Q_{s2} \\ Q_{c2} \end{bmatrix} \quad (4.14)$$

The above equations are used to extract the current references for achieving various desired flexible control objectives such as (a) smoothening of active power ripples (b) elimination of reactive power ripples (c) elimination of simultaneous active and reactive power ripples and (d) injection of balanced grid currents etc. The approach of obtaining the flexible control objectives in FRT involves a good amount of computations such as referring the three

phase quantities to SRF quantities, extraction of sequence components of corresponding voltages and currents etc. Moreover, the computation of inverse matrix as per (4.14) even further complicates the reference current computation process. Another challenge involves around the tracking of the current references. In general, the PI controllers are the widely acceptable controller variant. The reference tracking functionality is performed by four sets of PI controllers as reported in the literature [12]. However, faults are dynamic in nature and occurrences happen for a range of short span. Thus, the smooth tracking of current references in such cases possess a considerable amount of challenge. Looking specifically to the challenge of computational burden and effective current reference tracking, this chapter attempts to eliminate the above limitations by proposing set of modalities via introducing feed-forward and fuzzy control. The proposed control approach is named as feed-forward-fuzzy control which is elucidated in the next section.

4.5 Proposed Feed-Forward-Fuzzy Control

The idea proposed in the chapter to improve the FRT capability especially for a grid connected hybrid sustainable grid connected energy systems is based on the concept of elimination of negative sequence current components and tracking the positive sequence active power. The details of feed-forward current reference generation are elaborated in the sub-section.

4.5.1 Feed-Forward Current Reference Generation

The generation of the feed-forward current reference is based on the fundamentals of power balance between the generated power by the hybrid sustainable sources and power absorbed by the grid. As depicted in Fig. 4.2, the quantum of power flow is from hybrid generation system to grid, where the sum of power generated by WECS (P_W) and power generated by fuel cell (P_{FC}) is taken as P_{SUS} . This total power is supplied to the dc-link referred as (P_{DC}), meets various losses in the dc-dc converters, goes to the inverter referred as (P_{INV}), LC filter bearing the filter inductance L_f and filter capacitance C_f and eventually transmitted to the utility grid. The power balance between the dc-link capacitor, and power injected to grid (P_{GRID}) neglecting the converter losses is depicted by (4.15).

$$P_{SUS} = P_{DC} + P_{INV} + P_{GRID} \quad (4.15)$$

Assuming a loss less condition where the inverter power losses are neglected, the equation (4.15) can be expressed as per (4.16).

$$P_{SUS} = P_{DC} + P_{GRID} \quad (4.16)$$

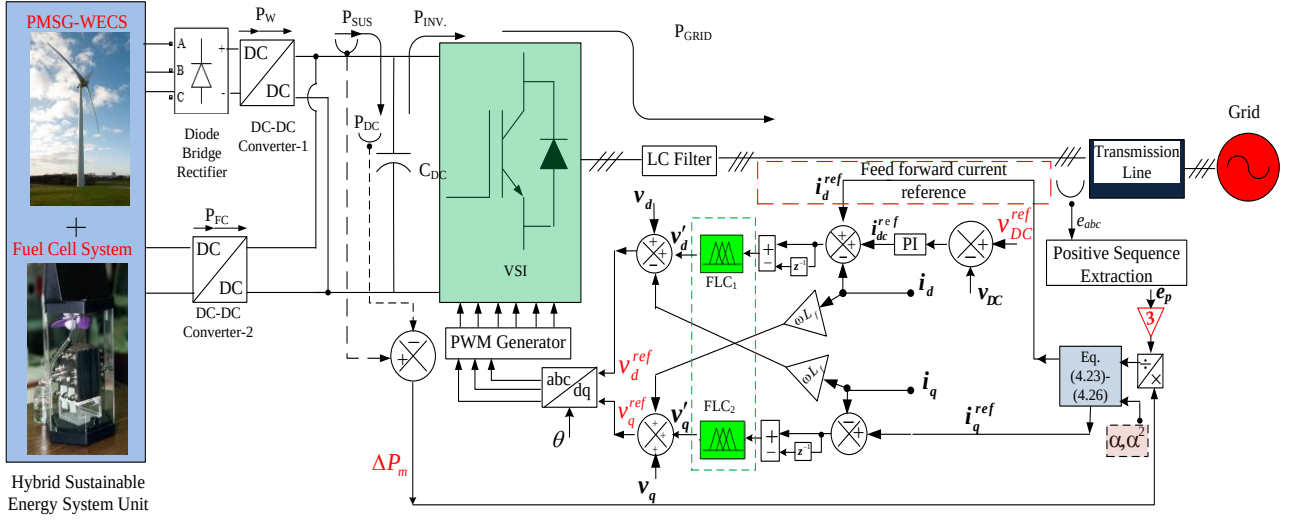


Fig. 4.2. Schematic of the proposed controller.

The grid active power can be expressed as the instantaneous summation of sequence powers in positive sequence (P_p), which is further composed of positive sequence voltage (e_p) and positive sequence current (i_p). The negative sequence power (P_n) is composed of negative sequence voltage (e_n) and negative sequence current (i_n) and zero sequence power (P_o) is composed of zero sequence voltage (e_o) and zero sequence current (i_o). This is expressed as per (4.17)-(4.18).

$$P_{SUS} = P_{DC} + 3(P_p + P_n + P_o) \quad (4.17)$$

$$P_{SUS} = P_{DC} + 3(e_p i_p + e_n i_n + e_o i_o) \quad (4.18)$$

In the meantime, a 3-phase, 3-wire system is considered, zero sequence quantities are inherently absent. Due to the absence of neutral terminal, the zero-sequence power term is not included in (4.18). During unbalance fault, the presence of negative sequence current and voltage component gives rise to double frequency oscillation in the power delivered to grid. Thus, in order to incorporate an inverter mechanism, which suppresses the oscillating negative sequence power, appropriate current reference needs to be generated. In Eq. (4.18), the negative and zero sequence currents are made null which brings the new expression for P_{SUS} as per (4.19) and (4.20). This equation aims to obtain the current references for the grid side inverter such that the negative sequence currents do not appear. The prediction of new current reference (i_p^{ref}) depends on the extraction of positive sequence voltage, and its calculation is performed as per (4.21)-(4.22). The extraction of e_p is as per the multivariable structure sequence detection scheme algorithm of [59].

$$P_{SUS} = P_{DC} + 3(e_p i_p) \quad (4.19)$$

$$\text{Let,} \quad P_{SUS} - P_{DC} = \Delta Pm \quad (4.20)$$

substituting (4.20) in (4.19) leads to a new expression as (4.21).

$$3(e_p i_p^{ref}) = \Delta Pm \quad (4.21)$$

$$i_p^{ref} = \frac{\Delta Pm}{3e_p} \quad (4.22)$$

The desired positive sequence reference current is obtained as per (4.22). This current is translated to the instantaneous current phasors 'abc'. The positive sequence reference currents need the input of sequence factors (α and α^2) which gives phase shift of 120° and 240° to generate the current references as per (4.23)-(4.25). The terms of (4.23)-(4.25) are complex quantities which cannot be processed by a PI controller. Therefore, the modulus operator is applied and the magnitude terms $|i_b^{ref}|$ and $|i_c^{ref}|$ are being used for processing. The reference currents are translated to current reference in the dq frame as per (4.26).

$$i_a^{ref} = \frac{\Delta Pm}{3e_p} \quad (4.23)$$

$$\begin{aligned} i_b^{ref} &= \alpha^2 \left(\frac{\Delta Pm}{3e_p} \right) = (-0.5 - j0.866) \left(\frac{\Delta Pm}{3e_p} \right) \\ &= \left\{ -0.5 \left(\frac{\Delta Pm}{3e_p} \right) - j0.866 \left(\frac{\Delta Pm}{3e_p} \right) \right\} \end{aligned} \quad (4.24)$$

$$\begin{aligned} i_c^{ref} &= \alpha \left(\frac{\Delta Pm}{3e_p} \right) = (-0.5 + j0.866) \left(\frac{\Delta Pm}{3e_p} \right) \\ &= \left\{ -0.5 \left(\frac{\Delta Pm}{3e_p} \right) + j0.866 \left(\frac{\Delta Pm}{3e_p} \right) \right\} \end{aligned} \quad (4.25)$$

$$\begin{bmatrix} i_d^{ref} \\ i_q^{ref} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos \theta & \cos(\theta - 120^\circ) & \cos(\theta + 120^\circ) \\ -\sin \theta & -\sin(\theta - 120^\circ) & -\sin(\theta + 120^\circ) \end{bmatrix} \begin{bmatrix} |i_a^{ref}| \\ |i_b^{ref}| \\ |i_c^{ref}| \end{bmatrix} \quad (4.26)$$

$$i_d^{ref} = \sqrt{\frac{2}{3}} \left[\cos \theta |i_a^{ref}| + \cos(\theta - 120^\circ) |i_b^{ref}| + \cos(\theta + 120^\circ) |i_c^{ref}| \right] \quad (4.27)$$

$$i_q^{ref} = \sqrt{\frac{2}{3}} \left[-\sin\theta \cdot |i_a^{ref}| - \sin(\theta - 120^\circ) \cdot |i_b^{ref}| - \sin(\theta + 120^\circ) \cdot |i_c^{ref}| \right] \quad (4.28)$$

The current reference term obtained in (4.27) is added to the output of the dc-link PI controller i_{dc}^{ref} obtained after processing the error of reference dc-link voltage v_{DC}^{ref} and actual dc-link voltage v_{DC} to generate the intermediate d -axis current as per (4.29). The proportional and integral gains of the dc-link PI controller are denoted as K_p^V and K_I^V respectively.

$$i_{dc}^{ref} = K_p^V (v_{DC}^{ref} - v_{DC}) + K_I^V \int (v_{DC}^{ref} - v_{DC}) dt \quad (4.29)$$

The current reference obtained from (4.27) and (4.29) is fed forward in the summer block, after which it is subtracted to the actual d -axis current (i_d), and is processed further to the inputs of the fuzzy logic controller (FLC₁) to generate the intermediate d -axis voltage (v_d'). Similarly, the error between q -axis current reference i_q^{ref} obtained from (4.28) and the actual q -axis current i_q is pushed to the FLC₂ for obtaining the intermediate q -axis voltage term (v_q').

4.5.2 Fuzzy Logic Controller Design

Since the hybrid generation system has many non-linearities, the reference tracking capability of the PI controller is a challenging aspect. For transient events like faults, the challenge increases manifolds. The chapter presents the use of two FLC controllers FLC₁ and FLC₂ in the VSI control algorithm for tracking the new d -axis current reference (i_d^{ref}) and q -axis current reference (i_q^{ref}) generated as per (4.27) and (4.28). FLC possess the advantages of easy variable gain generation, it can work on uncertain system models where, the exact mathematical model is unknown. FLC is parameter insensitive and is accompanied with fast convergence [130]. The steps involved in the implementation of FLC consists of fuzzification, design of the fuzzy inference engine and defuzzification respectively.

4.5.3 Fuzzification

In fuzzification process, the input signals to the FLC are mapped within the close interval of $[-1 \text{ to } 1]$, and are subsequently assigned membership function (MF) variables. As the inverter control is based on the sensing of per-unit quantities of voltages and currents, the input variables of FLC are inherently in the range of $[-1 \text{ to } 1]$. Triangular membership functions are selected due to the ease of assigning crisp range for different membership variables and these membership functions are more sensitive to small signal variations [129]. The input variables

for the FLC₁ and FLC₂ are error and change in error respectively which are shown in Fig. 4.3 and Fig. 4.4. The error function for the FLC₁ at the k^{th} sample instant is given by $e_1(k) = [i_d^{\text{ref}}(k) + i_{dc}^{\text{ref}}(k)] - [i_d(k)]$ and the change of error denoted by $\Delta e_1(k) = e_1(k) - e_1(k-1)$ is obtained by processing the error through a unit delay block and subtracting the error $e_1(k)$.

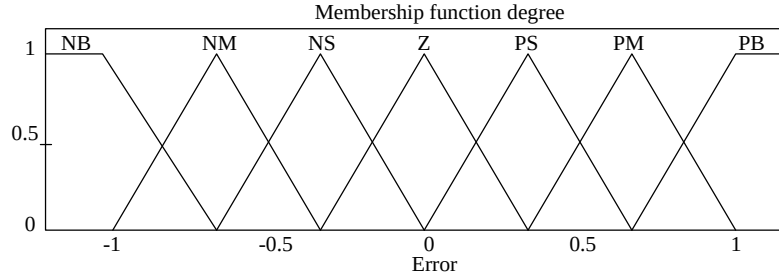


Fig. 4.3. Membership function for input variable 'error $e_1(k)$ and $e_2(k)$ '.

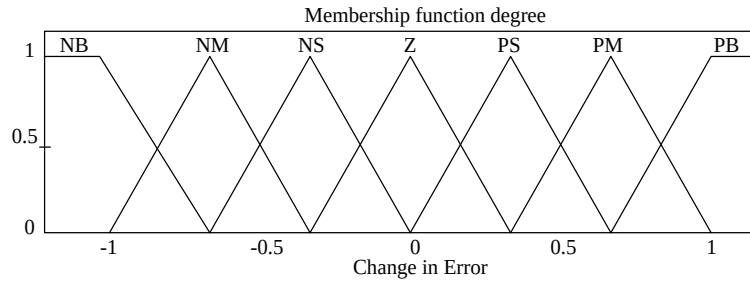


Fig. 4.4. Membership function for input variable 'change in error $\Delta e_1(k)$ and $\Delta e_2(k)$ '.

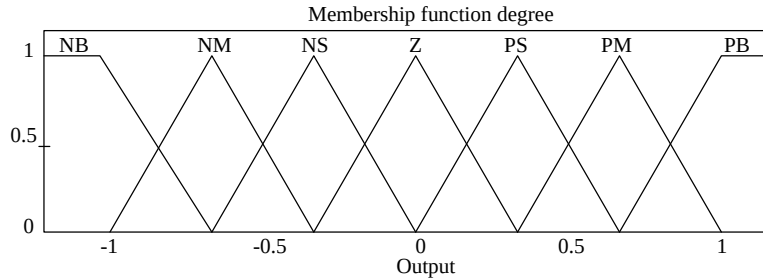


Fig. 4.5. Membership function for output variable v'_d and v'_q .

Similarly, the error function of the FLC₂ at the k^{th} instant is the difference between the reference q -axis current and the actual q -axis current given by $e_2(k) = i_q^{\text{ref}}(k) - i_q(k)$ and the second input of FLC₂ is the change of error denoted by $\Delta e_2(k) = e_2(k) - e_2(k-1)$. The output variable of each fuzzy controllers is being represented with the membership function as per Fig. 4.5.

4.5.4 Fuzzy Inference Engine

The fuzzy inference engine primarily consists of knowledge base or the rule base which is based on the “if- then” prepositions. The Mamdani fuzzy inference is used for the design of the proposed FLC₁ and FLC₂ which is based on rules and its related consequents. Crisp output can be fetched after processing the rules, provided overlapping of the neighbouring MFs are ensured [128]. A total of 49-rules is considered for making the correlation between the linguistic variable inputs and outputs of the two fuzzy controllers as presented in Table. 4.2. The linguistic variables are abbreviated as negative big (NB), negative medium (NM), negative small (NS), zero error (ZE), positive small (PS), positive medium (PM) and positive big (PB) respectively. The rules of FLC are selected such that the rise time, over shoot and settling time of the desired system parameters are minimised as per the required FRT conditions. The surface plot representing the behaviour of the fuzzy rules with the inputs and output variable is shown in Fig. 4.6.

Table 4.2
Fuzzy Rule Base for FLC₁ and FLC₂

Output variables v'_d and v'_q		Input variable-2 $\Delta e(k)$						
		NB	NM	NS	ZE	PS	PM	PB
Input variable-1 $e(k)$	NB	NB	NB	NM	NM	NS	ZE	ZE
	NM	NB	NM	NM	NS	NS	ZE	PS
	NS	NM	NM	NS	NS	ZE	PS	PS
	ZE	NM	NS	NS	ZE	PS	PS	PM
	PS	NS	NS	ZE	PS	PS	PM	PM
	PM	NS	ZE	PS	PS	PM	PM	PB
	PB	ZE	PS	PS	PM	PM	PB	PB

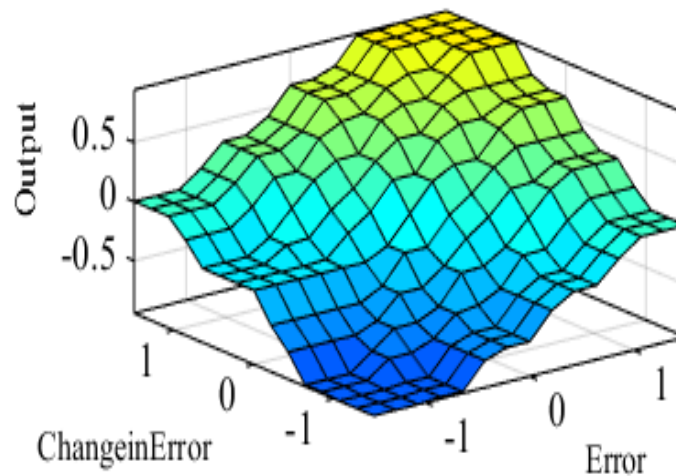


Fig. 4.6. Fuzzy rule base surface view.

4.5.5 Defuzzification

The fuzzy controllers have only one output variable which are fetched from the input variable sets. The widely used method for defuzzification is the centre of gravity method. This specific method is selected as it is simple and accurate which calculates the output by calculating the weighted average of the fuzzy functions after the process of the fuzzy rules as per the formula of (4.30), where, x^* denotes the fuzzy controller's output, x_i is the value of input variable and $\mu(x_i)$ is the value of the grade of membership function [129].

$$x^* = \frac{\sum_{i=1}^n x_i \mu(x_i)}{\sum_{i=1}^n \mu(x_i)} \quad (4.30)$$

The output voltage terms of FLC₁ and FLC₂ are v_d' and v_q' respectively. These are summed up along with the cross-coupling voltage terms, d -axis voltage v_d and q -axis voltage v_q to give the final dq -axis voltage references v_d^{ref} and v_q^{ref} as per (4.31) and (4.32). The phase angle of the PCC voltage θ and the corresponding angular frequency ω provided by the PLL is also used in the voltage reference generation. The new dq voltage references are translated to abc -references, which are then compared with a PWM bearing a 20 kHz frequency of the carrier signal in order to generate the gate pulses for the VSI. A brief comparison between the feed-forward FRT control and feed-forward-fuzzy FRT control is detailed in Table 4.3.

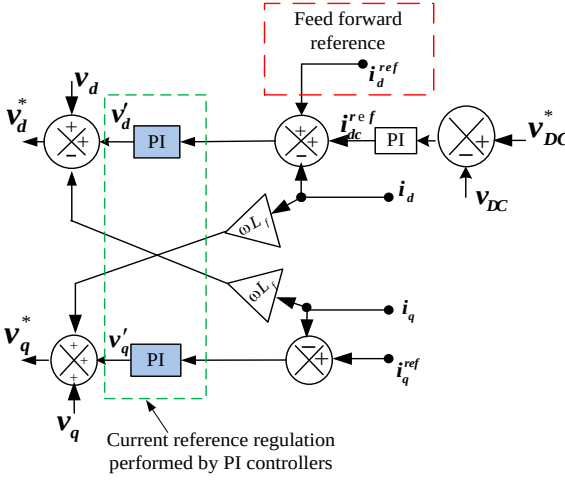
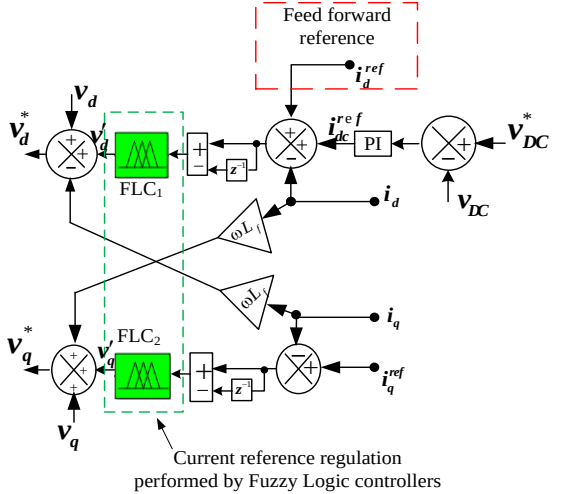
$$v_d^{ref} = v_d' + v_d - \omega i_q L_f \quad (4.31)$$

$$v_q^{ref} = v_q' + v_q + \omega i_d L_f \quad (4.32)$$

Table 4.3

Comparison between feed-forward FRT control and feed-forward-fuzzy FRT control

Feed-forward based FRT control	Feed-forward-fuzzy FRT control
It refers to the inverter current control in order to achieve FRT requirement which is done using the philosophy deliberated in Section 4.5.1. Here, the fuzzy controllers are not used to regulate the current references, instead they are regulated by the conventional PI controllers.	It refers to inverter control done to achieve the FRT requirement by using the philosophy deliberated in Section 4.5.1 and 4.5.2 where the new current references for the d -axis and q -axis are controlled by the fuzzy logic controllers namely FLC ₁ and FLC ₂ .

In the feed-forward based FRT control, the derived current references of Eq. (4.27) and (4.28) are controlled in a manner where, the current reference i_d^{ref} is fed-forward at the output of the PI controller regulating the dc-link voltage. Further the controller in the inner-loop are PI controllers which regulate the d-axis and q-axis current references.	In the feed-forward-fuzzy based FRT control, the derived current references of Eq. (4.27) and (4.28) are controlled in a manner where the current reference i_d^{ref} is fed-forward at the output of the PI controller regulating the dc-link voltage. Further the controller in the inner-loop are Fuzzy Logic Controllers (FLC₁ and FLC₂) which regulate the d-axis and q-axis current reference.
 Current reference regulation performed by PI controllers	 Current reference regulation performed by Fuzzy Logic controllers
The feed-forward control will render the FRT feature, but will lag performance in terms of effective reference tracking, settling time, overshoot of the dc-link voltage etc. This is due to the inability of the PI controllers to perform effectively on a non-linear system like a grid-connected hybrid generation system as considered in this paper.	The proposed feed-forward-fuzzy-based FRT control performs better since fuzzy logic controller has a better performance while controlling a non-linear system. Hence, to handle the voltage sag problem on a system with high non-linearities such as microgrids, the proposed feed-forward-fuzzy based FRT control performs better.

4.6 Case Studies and FRT Controller Validation

The validation of the proposed feed-forward-fuzzy logic fault ride through control is performed by attempting series of test cases in the MATLAB-Simulink simulation environment. The entire schematic is modeled as per Fig. 4.1 with the system parameters presented in Table. 4.1. The snippet of the controller part implementation is illustrated in Fig. 4.7. The case studies involving unbalanced and balanced voltage sag cases viz. (a) single phase sag (b) two phase sag and (c) three phase sag are undertaken. Each case is tested for the FRT capability of the hybrid generation using the conventional dq - current controller, using only feed-forward FRT control where the current references are completely regulated by the PI controllers and lastly by the proposed combined feed-forward-fuzzy control.

In the subsequent subsections, the various system parameters for each test cases are portrayed simultaneously on a common axis in order to understand the differences in the individual controller performance with ease.

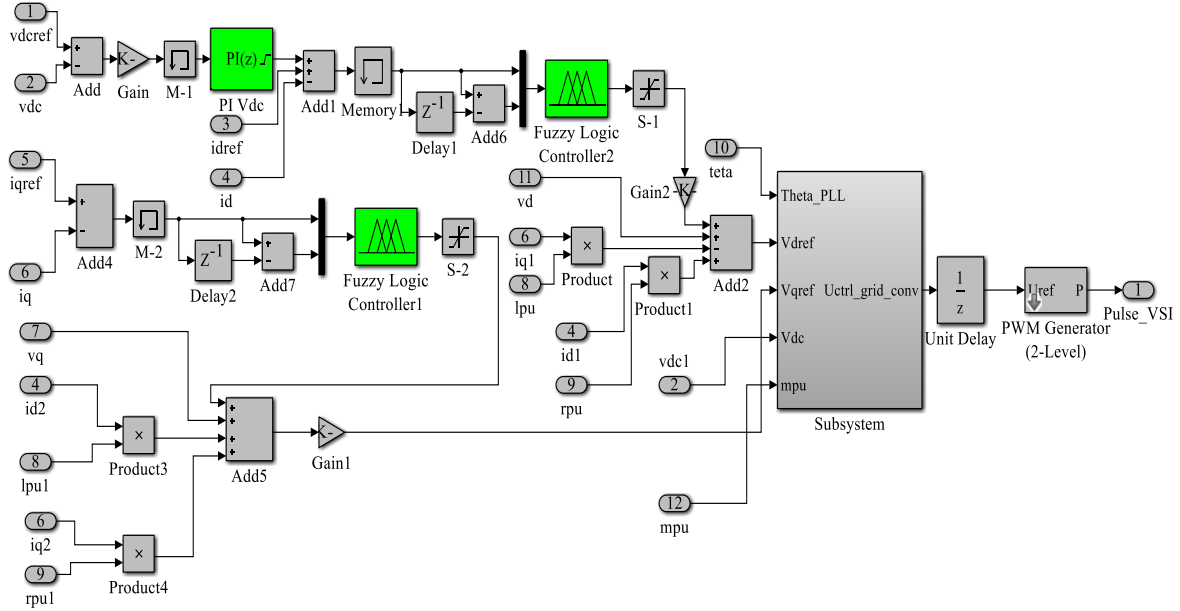


Fig. 4.7. MATLAB-Simulink implementation of the feed forward fuzzy controller.

4.6.1 System Performance Under Unbalanced Sag: 1-Phase Sag

The performance of the HSES when a 50% voltage sag at *Phase-a* occurs due to an unbalance fault event at the transmission line is discussed. The PCC voltage of *Phase-a* drops as per Fig. 4.8 (a) during the sag event from 1 s to 1.2 s. The PCC current is shown in Fig. 4.8 (b) for the case when the proposed feed-forward-fuzzy control is used. It is inferred that the currents are balanced and are limited during the voltage sag span. This action is due to the effective tracking of current references by the FLC₁ and FLC₂ which restricts the negative sequence current components at the PCC. The dc-link voltage profile for three different controllers is presented simultaneously on a common axis as per Fig. 4.8 (c) where, the rise and ripples in dc-link voltage profile is prominent for the conventional *dq*-control and feed-forward FRT control, whereas the proposed feed-forward-fuzzy controller outperforms the rest two controllers. The profile of active power delivered to the PCC is as per Fig. 4.8 (d).

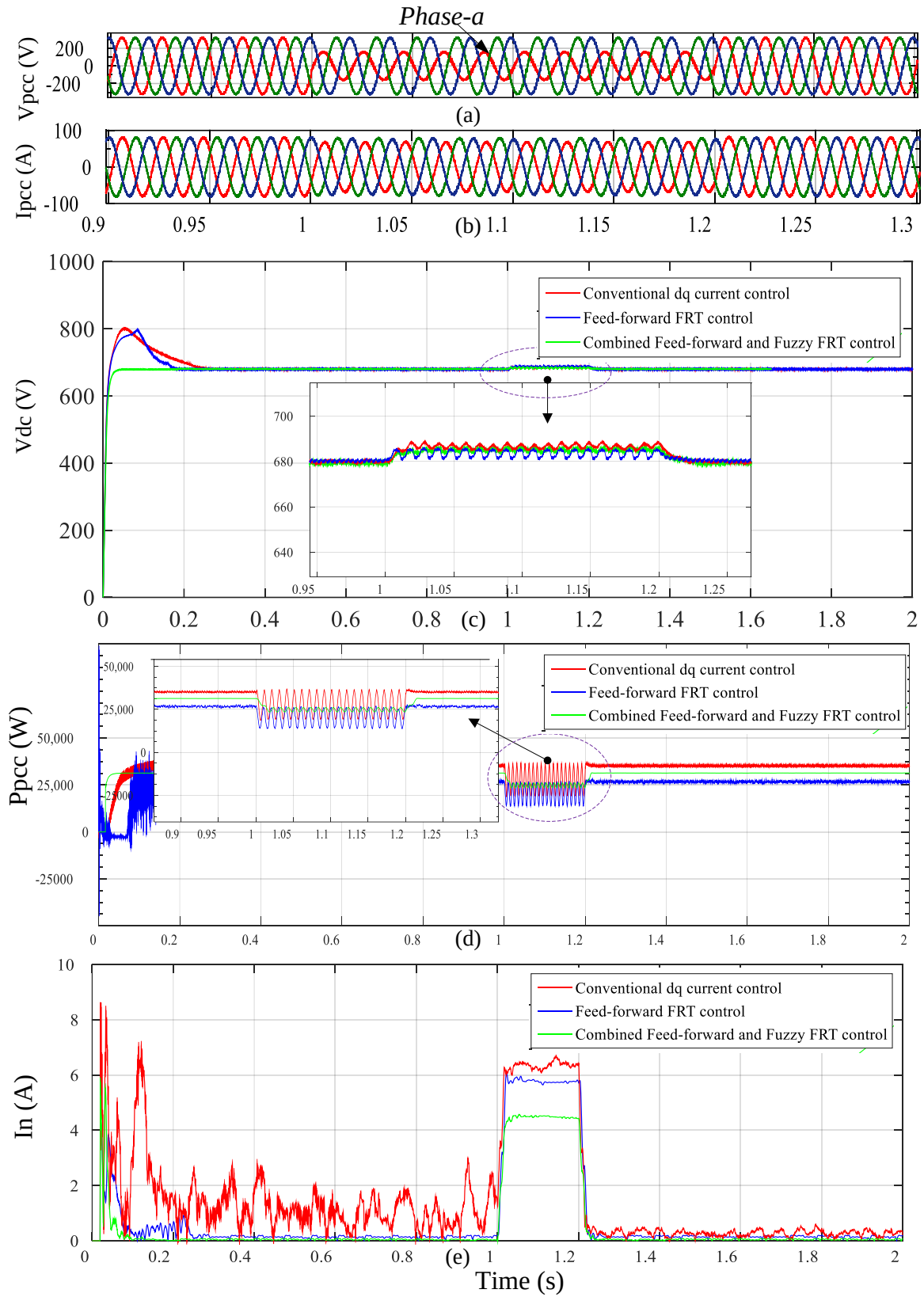


Fig. 4.8. Parameters at PCC during 1-phase sag, (a) PCC voltage, (b) PCC current, (c) DC-link voltage, (d) Active power delivered, (e) negative sequence current.

In the presented system the rated electrical angular velocity of the instantaneous positive sequence current is 314 rad/s while the negative sequence currents possess the angular velocity of 314 rad/s, which comes to the system during unbalance fault condition. Thus, the resultant velocity of the current becomes $314 \text{ rad/s} - (-314 \text{ rad/s}) = 628 \text{ rad/s}$, that is, twice the rated angular velocity. This appears as a form of ripples in the instantaneous active power profile where the magnitude of ripples is oscillated at a rate of twice the rated angular frequency. Thus, the power ripples possess a frequency of 100 Hz as the utility grid's power frequency is 50 Hz. From Fig. 4.8 (d), it is established that the proposed feed-forward-fuzzy control achieves a much smoother profile with less power oscillation and power surge. The effectiveness of the proposed feed-forward-fuzzy control over other FRT control method is because of the minimization of the magnitude of the negative sequence currents as evident as per Fig. 4.8 (e). The Table. 4.4 shows the comparative analysis of various controllers used for the FRT provisions where, it is evident that the combined effect of the proposed feed-forward-fuzzy control gives a better FRT behaviour compared to the conventional dq - control and with only feed-forward FRT control.

4.6.2 System Performance Under Unbalanced Sag: 2-Phase Sag

In this case, a more stringent condition is applied to test the LVRT efficacy of the proposed feed-forward-fuzzy FRT controller. During a two-phase voltage sag, the magnitude of the voltage dip is much more as compared to a single-phase voltage sag. As observed from Fig. 4.9 (a), dip in Phase-a and Phase-b voltages are present during the span of 1 s to 1.2 s. The PCC currents are balanced during the faulted span as per Fig. 4.9 (b) due to the proposed feed-forward-fuzzy control. A larger inrush of active power from the DER during two-phase voltage sag leads to a larger surge in the dc-link voltage when no FRT control is applied.

Table 4.4

Comparative analysis of the FRT control performance for various controllers under 50% voltage sag at Phase-a

Parameters	Conventional dq-control [109]	Feed-forward FRT control	Proposed Feed forward-fuzzy FRT control
dc-link voltage (peak value)	690 V with oscillations.	685 V with oscillations.	684 V with less oscillations.
Active power (peak value)	34 kW with oscillations.	26 kW with oscillations.	25 kW with minimised oscillations.
Negative sequence current magnitude	7 A	5.9 A	4.2 A

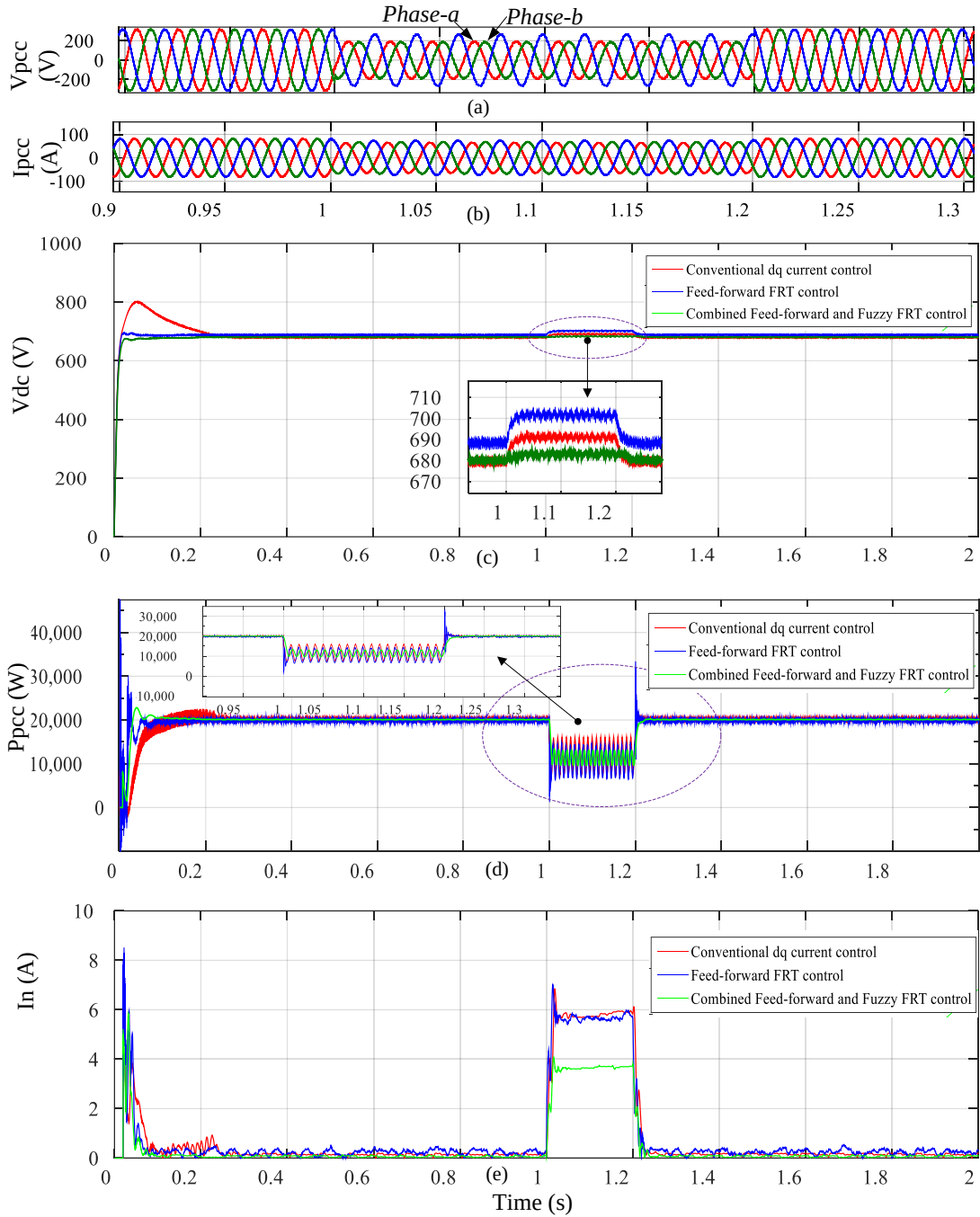


Fig. 4.9. Parameters at PCC during 2-phase sag, (a) PCC voltage, (b) PCC current, (c) DC-link voltage, (d) Active power delivered, (e) negative sequence current.

While; the feed-forward FRT control is unable to mitigate the surge in the dc-link voltage due the poor regulation of its PI controllers, the proposed feed- forward-fuzzy control FRT control enables a better dc-link voltage profile free from oscillations which is evident as per Fig. 4.9 (c). A similar behaviour is found for the profile of generated active power as per Fig. 4.9 (d). Here, the magnitude of power oscillation is much lesser for the proposed feed-forward-fuzzy controller during the faulted span. It is to be noted that, the tuned values of K_P and K_I of

the PI controllers used in the inner current control loop of the feed-forward FRT control during 1-phase sag could successfully regulate the current reference. Thus, the magnitude of negative sequence currents as per Fig. 4.8 (e) is limited to 5.9 A. However, when the same values of controller gains are used for the FRT control during 2-phase sag, these gains could not achieve the sufficient amount of current reference regulation so as to reduce the negative sequence currents. In order to achieve an improved FRT control during 2-phase voltage sag using the feed-forward FRT control, fresh tuning of PI controllers is required. This limitation is overcome by the incorporation of feed-forward fuzzy logic FRT control, which is capable of handling the system non-linearities and provide the dynamic current regulation once the rule base is properly established. The magnitude of negative sequence current in the system is less when for the feed-forward-fuzzy LVRT control is applied to the inverter current control scheme which is visible as per Fig. 4.9 (e). A parametric comparison between the existing dq -control [109], feed-forward FRT control and the proposed feed-forward-fuzzy FRT control for rendering the LVRT capability in the system under 2-phase voltage sag condition is tabulated in Table. 4.5.

Table 4.5
Comparative analysis of the FRT control performance for various controllers under 50% voltage sag at Phase-a and Phase-b

Parameters	Conventional dq -control [109]	Feed-forward FRT control	Proposed feed- forward-fuzzy FRT control
dc-link voltage (peak value)	690 V with ripples.	700 V with ripples.	680 V without any ripples.
Active power (peak value)	15 kW with ripples.	15 kW with ripples.	14 kW with less ripples.
Negative sequence current magnitude	6 A	5.8 A	3.7 A

4.6.3 System Performance Under Balanced Sag: 3-Phase Sag

A balanced 3-phase sag do not contain any negative sequence current. Thus, the profile of dc-link voltage and active power do not contain any oscillations, but the dc-link voltage surge is present. For validation, equal voltage dip at *Phase-a*, *Phase-b* and *Phase-c* are created as per Fig. 4.10 (a). The peak value of dc-link voltage with the proposed feed- forward-fuzzy control is 685 V, while the peak value of 700 V and 698 V are obtained for the feed-forward and conventional dq -control. Another distinct feature of the proposed control is that the peak overshoot and the settling time is less for the profile of active power as per Fig. 4.10 (d).

The voltage sag impacts the electromagnetic torque of the PMSG, as the presence of unbalance leads to generation of torsional oscillations in the PMSG rotor structure. Fig. 4.11

shows the electromagnetic torque profile of the PMSG. The torque profile of the generator is shown when the PMSG machine is loaded with an electrical load of 3.6 kW. Since the machine runs as a generator, the torque is negative, and the developed torque is 11.6 Nm corresponding to the electrical power output of 3.6 kW. Thus, the torque profile of the machine is registered as -11.6 Nm as per Fig. 11. It is inferred from the result that the electromagnetic torque profile is also improved with the use of presented feed-forward-fuzzy control under voltage sag conditions. Hence, it is summarized that proposed control has not only improved the dc-link voltage and active power profile, but also the electromagnetic torque profile of the PMSG in the WECS is improved to a great extent.

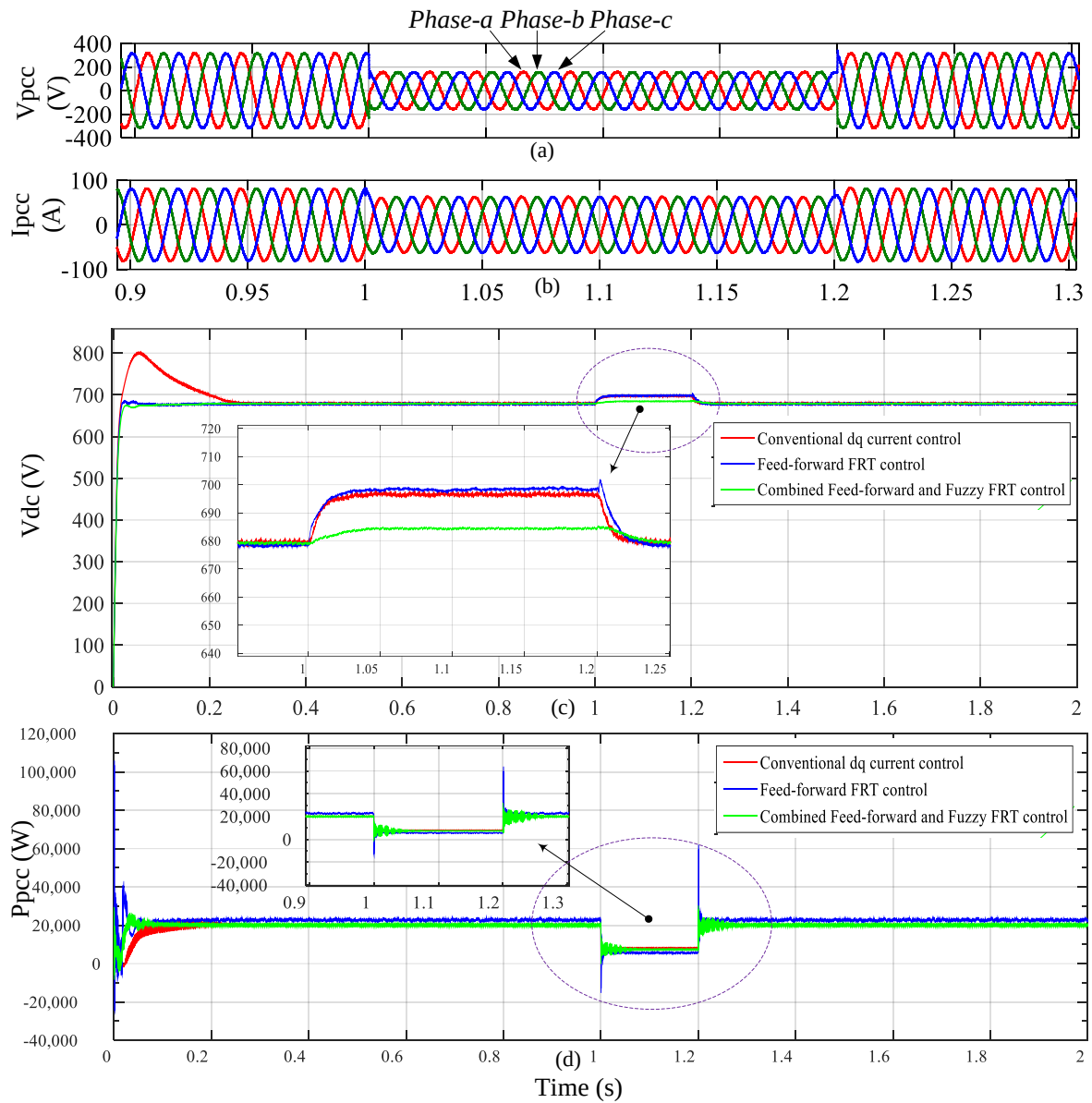


Fig. 4.10. Parameters at PCC during 3-phase sag, (a) PCC voltage, (b) PCC current, (c) DC-link voltage, (d) Active power delivered, (e) negative sequence current.

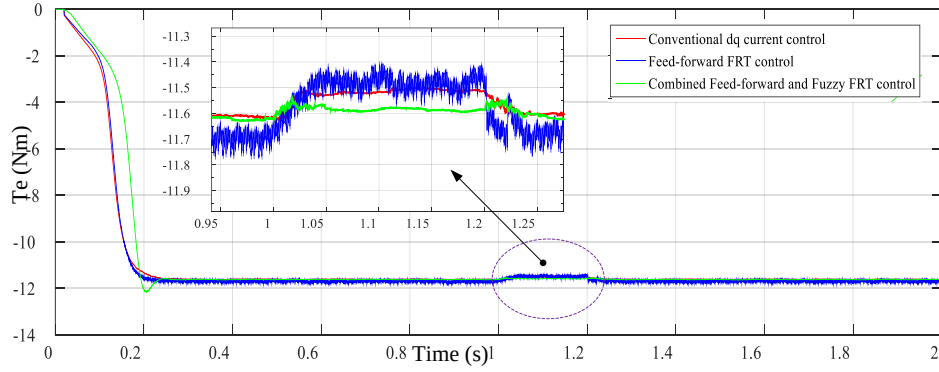


Fig. 4.11. Electromagnetic torque of PMSG.

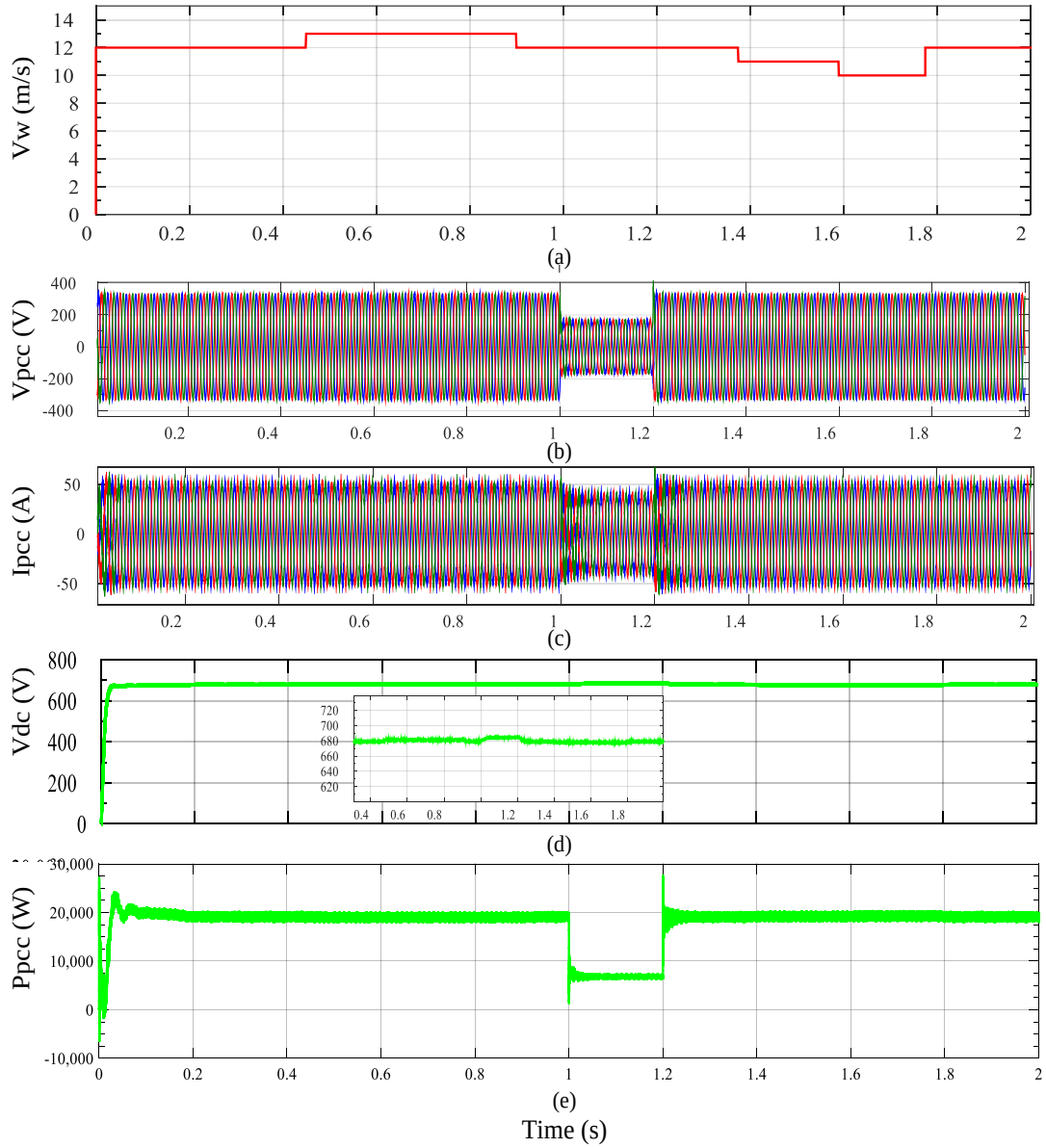


Fig. 4.12. Parameters at PCC during variable wind speed and symmetrical fault, (a) Wind speed V_w , (b) PCC voltage, (c) PCC current, (d) dc-link voltage, (e) Active power delivered, (e) negative sequence current.

4.6.4 System Performance Under Variable Wind Speed and Symmetrical Fault

A variable wind speed profile is considered to evaluate the performance of the hybrid wind/fuel cell system with the proposed feed-forward-fuzzy control. The system is also subjected to a symmetrical fault for the time span of 1 s to 1.2 s. The wind velocity varies between 10 m/s to 14 m/s as per Fig. 4.12(a). The PCC voltage and current profile is depicted in Fig. 4.12 (b)-(c) respectively. The PCC current is well controlled and does not exhibit any over current during the fault span. This aspect is due to effective functioning of the feed-forward-fuzzy FRT control algorithm. While; the waveforms of dc-link voltage as per Fig. 4.12 (d) do not show deviations from its reference value during variable wind speed span. Similarly, the active power profile of the PCC as per Fig. 4.12 (e) does not deviate during variable wind speed, this is due to the presence of fuel cell which enables to nullify the power deviations at the PCC even during variable wind speed. The system simultaneously exhibits the FRT feature during the fault span with the proposed feed-forward-fuzzy FRT control strategy.

4.7 Chapter Summary

The chapter contributes towards the enhancement of the LVRT technology for a grid-connected hybrid sustainable generation system via the design of a new feed-forward FRT control. The presented feed-forward FRT controller's mathematical model is developed based on the extraction of a new set of current references such that the surge in the dc-link voltage, ripples in the active power profile and negative sequence current in the system are minimized. Further, an improvisation to the feed-forward FRT scheme is done with the inclusion of two sets of fuzzy logic controllers to form a feed-forward-fuzzy FRT controller, which is proved to be an improved choice for achieving the FRT capability. The feed-forward-fuzzy control outperformed the conventional dq - controller and feed-forward FRT control, which is justified by categorically comparing the system performance during 1-phase, 2-phase and 3-phase voltage sag. Also, the overall system performance is found satisfactory with the developed control algorithm during simultaneous wind speed variation and symmetrical fault. In other words, it is summarized that the presented feed-forward-fuzzy control scheme can fulfil the FRT requirement of the considered grid-connected hybrid sustainable generation system in an effectual way. Moreover, a smooth profile of the PMSG electromagnetic torque is registered under voltage sag conditions which proves to be an additional advantage of this newly developed feed-forward-fuzzy FRT control scheme.

Integrated Rule Based Power Management and Dynamic Feed-Forward LVRT Scheme for Grid-Connected Hybrid Energy System

5.1 Introduction

In a grid-integrated mode, power generation using hybrid energy system (HES) along with the backup sources possesses convincing features of high efficiency and near zero emissions. Control for facilitating apt power sharing and for providing ancillary services such as low voltage ride through (LVRT) are necessary for the compliance of grid codes. However, the simultaneous control co-ordination for meeting these control objectives is challenging due to dynamic nature of renewable generators and utility grid. Thus, this chapter presents an integrated power management strategy (PMS) and LVRT control scheme for such systems. In this thesis work, a WECS backed up by a battery energy storage system, proton exchange membrane fuel cell (PEMFC) and electrolyzer is considered. A reduced rule-based power management control scheme is proposed for the considered system, where the request made by the grid operator is kept in priority. Further, a dynamic current feed-forward based LVRT control scheme is presented for the grid-interfaced inverter, which is based on minimization of negative sequence current. The inverter control is coupled with an inherent mode selection capability between the grid feeding mode and LVRT mode in order to realize the suggested integrated control objectives. The validation of the presented PMS and LVRT control is justified by detailing relevant mathematical control models, and also by realizing practical case scenarios such as variable wind speed, load demand, grid power request and occurrences of balanced and unbalanced voltage sag. The obtained simulation results show cordial response of the system with the proposed control strategies.

5.2 Related Review and Research Motivation

As discussed in Section 1.2 of the dissertation, HES offers the benefits of high reliability because of uninterruptible operations, good power quality and economic benefits. Backup systems with the use of battery storage is widely acceptable with solar PV as the prime source of power generation [82]. On the other hand, diesel generator sets are also widely adopted as backup systems in the remote areas as they provide reliable power [133]. However, these diesel

generators mainly suffer from the issue of environmental pollution and noise. While; batteries suffer from the problem of high maintenance and low power density. H₂ based storage proves to be a convincing way for creating long term energy backup. As an added flexibility, the excess energy generated from the renewable generators can be used to run an electrolyzer to generate H₂. Therefore, it is planned to develop a HES model with battery and H₂ as back-up sources. Hybrid storage systems using battery and H₂ can complement each other by overcoming the technical barriers of each other during transient and steady state conditions respectively [134].

As per Section 1.2.4, it is established that power management is an essential aspect in HES, which involves the appropriate sharing of power from various sources and design of a power management controller (PMC). Depending on HES configuration, viz., grid interfaced mode or stand-alone mode power management algorithms are established. Standalone systems are well investigated by the researchers and in fact numerous combinations of sources and various PMCs are suggested in the reported articles [135]-[141]. The existing literature solves the power management aspect by considering specific objectives; like load leveling [135], nonlinear load compensation [136], and unbalanced load compensation [137]. In hybrid energy system, the aspect of power coordination between the hybrid storage is achieved by employing supervisory control based on states [138], or by using droop-based control. Besides the conventional approach, intelligent controllers like fuzzy logic and adaptive neuro-fuzzy based control are also applied for performing the energy management and inverter control in a micro-grid [139]-[141]. These intelligent controllers show cordial performance under various system dynamics like sudden change in generation, load demand or the grid side dynamics etc. Intelligent control also shows fast response in grid connected PV based DER under variable generation and loading conditions [142].

The grid integration of HES has evolved with the changing power system paradigm as there might be a scenario where a grid is largely dependent on the power generated by a specific region's micro-grid. In such cases, the grid is controlled by a system operator who can make a request of power demand from the interconnected microgrid based on the energy dispatch schedule. In such case, a power management logic requires special design and considerations which are elucidated in the work of [143]-[148]. These works present the power coordination in a grid-connected micro-grid by considering specific objective cases. Criteria such as dc-link voltage regulation, ac voltage regulation at the PCC, appropriate power sharing from individual sources under grid connection remains a common objective in most of the works. With the changing grid codes and architecture of the power system, if renewable energy generators

participate in bulk towards the injection of power to the grid, then these renewable generators must stay connected with the grid for specific duration. This aspect is termed as LVRT capability [149]. Generally, the simultaneous objective of power management and LVRT capability is rarely attempted in previous works. Although in [150], the power management and LVRT control is proposed for a fuel cell (FC), super capacitor and battery system, but the interconnection of the battery with dc-bus is performed directly without any interfacing dc-dc converter. Such integration is not desirable since the charging and discharging cycle of the battery gets affected, and this hampers its life time. Looking into these aspects, this chapter contributes toward the coordination control strategy for a grid connected HES consisting of wind/ FC/ battery/electrolyzer system. The improvisation towards the control logic of the HES is executed by the following ways:

1. A new simplified PMC is presented for the considered grid-connected wind/ FC/ battery/ electrolyzer system which accounts for the power request made by the grid operator and power demand of the loads at PCC simultaneously.
2. In particular, the PEMFC is used to improve the overall generation efficiency for the hybrid system as well as it puts favorable impact over the reduction in greenhouse gases emission.
3. An effort is made to reduce the number of *if-else* case for making decision on the power-references for the FC, battery, electrolyzer in the proposed PMC. This enhances the transient response of the considered HES.
4. Desired objectives such as minimum dc-link voltage fluctuation, low active power fluctuations for generation and loading transients are ensured with the considered power management algorithm.
5. Along with the power sharing control, a dynamic feed-forward based LVRT control scheme is embedded with the grid-interfaced voltage source inverter (VSI).
6. The proposed LVRT control scheme uses less computations and it is based on the positive sequence power tracking scheme so as to mitigate the negative sequence current profiles in the PCC.

The remaining chapter is organized as follows; Section 5.3 describes the architecture of and design of the considered HES. A brief discussion on the modeling of individual system components is detailed in Section 5.4. The proposed PMC used in this chapter is explained in Section 5.5, while; the suggested converter controllers for the WECS, PEMFC, battery,

electrolyzer and VSI are described in Section 5.6. Section 5.7 presents the detailed validation of the proposed integrated rule-based PMC along with the discussion on exchange capacities. The section also presents the validation of the dynamic feed-forward LVRT control for 50% and 90% voltage sag conditions with the support of extensive simulations. Finally, the concluding remarks of the chapter are deliberated in Section 5.8.

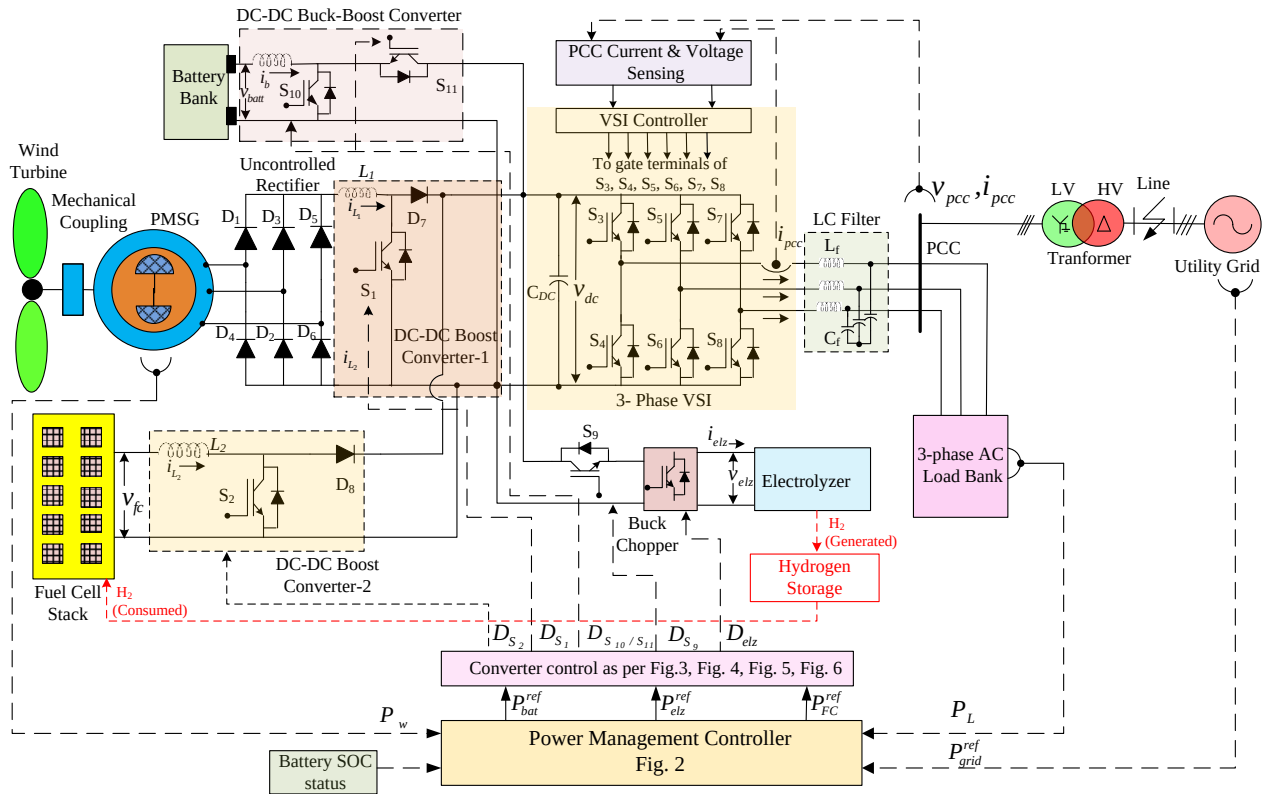


Fig. 5.1. Schematic of the considered grid connected hybrid generation system.

5.3 System's Architecture and Design

In this chapter, the hybrid energy system is considered as depicted in Fig. 5.1, which consists of PMSG based WECS as the primary source of power generation. An uncontrolled bridge rectifier and a controlled dc-dc boost converter-1 arrangement facilitates the conversion of uncontrolled ac voltage generated at the PMSG terminal to a controllable dc voltage. The storage system consisting of batteries acts as the primary storage system which, is designed to meet the load transition for shorter duration while a FC- electrolyzer combination is used as the secondary back-up system for long-term backup in case of worst-case power outage. A H_2 storage system is assumed as indicated in red colour and the corresponding channel of the H_2 circuit is shown in dotted red line. In this work, the dynamics and the modeling of H_2 storage system has not been considered to simplify the simulation-based modeling. However, it is

ensured that the working of FC and electrolyzer must complement each other by introducing a new power management algorithm. An appropriate power sharing logic is designed so as to safeguard the life span of the battery and FC. The same is elucidated in Section 5.6.2 where, the battery system's life span is ensured by keeping its state of charge (SOC) within 20% to 80%. Whereas, for the PEMFC system, the prolonged life span is confirmed by restricting its utilization factor within 80% to 90%. A dc-dc buck-boost converter is interfaced with the battery system, whereas dc-dc boost converter-2 is interfaced with the PEMFC system. A brief detail regarding the unit sizing and modeling of individual system components is described in the next subsections.

5.3.1 Unit Sizing

The work considers a situation where, the grid is accessible and the available wind potential enables the WECS to meet an average annual load of 14 kW. Therefore, the sizing of WECS is done by considering its plant load factor (PLF). In general, the wind power plants operate at a PLF of 35%, thus as per (5.1), the power rating for the wind generator is estimated as 40 kW.

$$Plant\ capacity = \frac{\text{Average annual load}}{PLF} = \frac{14,000}{0.35} = 40\text{ kW} \quad (5.1)$$

The rating of FC is based on the grid side peak demand; it is intended to meet the peak grid demand of 15 kW. Therefore, a total of 12 numbers of 1.2 kW size PEMFC units are connected in cascade to attain the total rated power of 15 kW. While; the sizing of the battery is done by considering the grid operator's demand. The battery backup system intends to support the load demand of 40 kW for a maximum span of 15 minutes. Considering an ideal depth of discharge of 60% and battery terminal voltage as 300 V, the Ah rating of the battery is determined from (5.2).

$$Battery\ rating = \frac{\text{Load demand} \times \text{Backup time}}{\text{Battery terminal voltage} \times \text{Depth of discharge}} = \frac{40,000 \times 0.25}{300 \times 0.6} \approx 55\text{Ah} \quad (5.2)$$

Further, the rating of electrolyzer is done on the basis of available surplus power [16]. Assuming an ideal generation of 40 kW from the WECS and a constant demand of 20 kW, the surplus power is 20 kW. Looking into the aspect of high cost associated with an aqua electrolyzer, the final rating of electrolyzer is selected as 60% of the available surplus power available in the system which is calculated per (5.3).

$$\begin{aligned} \text{Electrolyzer}^{\text{rating}} &= 60\% \times (\text{surplus power}) \\ &= (40-20) \times 0.6 = 12 \text{ kW} \end{aligned} \quad (5.3)$$

5.4 Modeling of the Proposed Hybrid Sustainable Energy System

A brief modeling of the presented hybrid energy system is explicated which is a combination of PMSG based WECS, PEMFC, battery bank, and electrolyzer respectively.

5.4.1 Modeling of Wind Turbine and PMSG

The 40 kW wind turbine is selected as the primary source of energy generation whose mechanical power is modeled as per equations (3.1) -(3.3) deliberated in Subsection 3.2.1. The considered PMSG is a salient pole whose stator voltage equations are modeled on parks transformation according to equations (3.5) -(3.6) reviewed in Section 3.2.2.

5.4.2 Modeling of PEMFC

A 1.2 kW PEMFC system is modeled as per the mathematical expressions (3.20) -(3.22) presented as in Section 3.3. Parameters like cell internal potential, partial pressure of the reactants at anode and cathode of the PEMFC and the quantity of reacted H₂ in the FC are primarily considered for modeling the FC system.

5.4.3 Modeling of Battery

The considered 55 Ah battery is modeled as per the equations (3.23) and (3.24) presented in Section 3.4. The terminal voltage and battery SOC are the critical parameters for a battery model.

5.4.4 Modeling of Electrolyzer

A 12 kW electrolyzer forms the supporting system for PEMFC where H₂ gets generated with the help of excess power for the WECS. The cell voltage and current in an electrolyzer is related as per (3.27). Electrolyzer generates H₂ as a function of electrolyzer's current whose mathematical expression is already deliberated as per (3.29) and (3.30) in Section 3.7 of Chapter-3. In this work, a 12 kW electrolyzer is designed by keeping its current rating to 120 A. The 5 kW, 120 A and 43 V electrolyzer is used obtain a 12 kW electrolyzer by fixing a voltage of 100 V at the terminal of electrolyzer. Therefore, a total of 75 numbers of cells are connected in series in order to obtain the rated terminal voltage from the electrolyzer model. As the electrolyzer is maintained at a lower voltage as that of the dc-bus, a buck converter is

used to step down the voltage. Detailed parameters of this electrolyzer system are mentioned in the Table 5.1.

5.5 Proposed Power Management Controller

The power sharing algorithm is developed among the generators, backup devices and the utility grid with the help of proposed PMC. The adopted PMC logic is depicted as per Fig. 5.2 where, the control logic is divided into three section namely input power sensing (IPS), PMC and output power reference (OPR) generation unit. The IPS senses the available power generation of the WECS denoted by P_w , power demand from the grid P_g^{ref} , power demand of the load connected at the PCC denoted by P_L . The PMC performs the arithmetical and logical computations with the sensed inputs and channelizes its result to the OPR generation unit. Four status conditions, namely, *Status-1*, *Status-2*, *Status-3* and *Status-4* respectively, are considered with in the centralized PMC for determining various power reference for the converters interfaced with FC, battery and electrolyzer (ELZ). *Status-1* and *Status-2* are activated when the system encounters excess power due to lesser demand and higher wind power generation whereas *Status-3* and *Status-4* are activated when the system encounters higher power demand and deficient wind power generation.

Status-1: In scenarios where the surplus power (denoted by P_{net}) is available in the system even after fulfilling the demand of grid and load, the SOC criteria of the battery is monitored. If the battery is fully charged; the extra power is dumped to the aqua-electrolyzer by controlling the switch S_9 and buck chopper.

Status-2: For situation of surplus power availability in the system, if the battery has its SOC less than 80% then this power is used to charge the battery. The calculated power reference P_{batt}^{ref} is used to drive the buck switch S_{11} of the buck-boost converter interfaced with the battery. The process of charging continues until the battery reaches the upper SOC limit.

Status-3: For situations when there is a power deficiency in the system, the coordination of battery and FC is performed by the PMC. The condition of battery's SOC is checked and if it is at the lower limit, FC is used to supply the deficit power. The power exchange with electrolyzer and battery is not performed in the system, this is ensured by fixing $P_{elz}^{ref} = 0$ and $P_{batt}^{ref} = 0$.

Status-4: It is the state of power deficiency in the system where the power demand of the utility grid and load is not met by WECS. The deficit power of the system is supplied by the battery provided its SOC, and is above 20%.

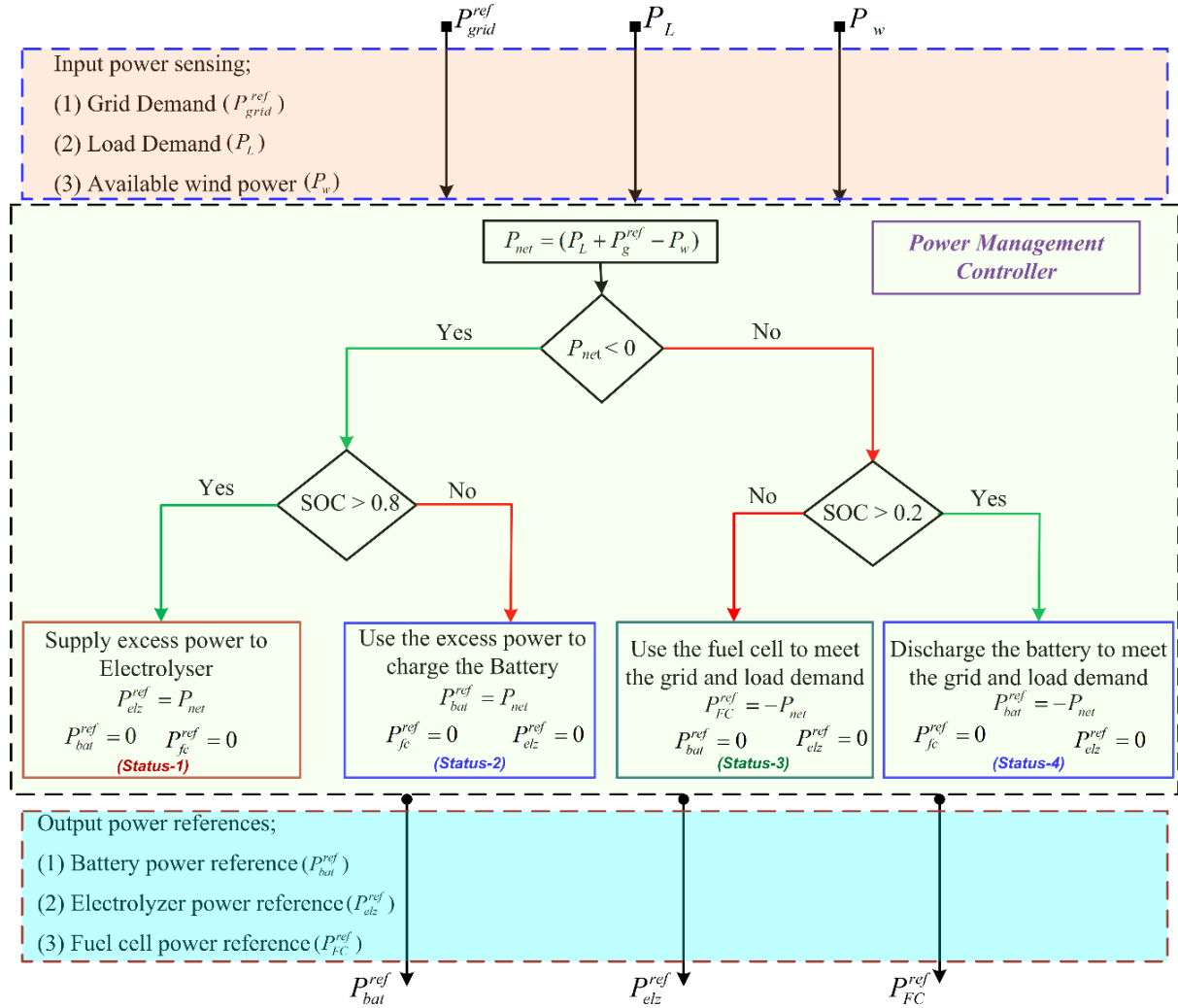


Fig. 5.2. Schematic of the proposed power management controller of HES.

It is interesting to note that fuel cell and electrolyzer's have slow response time and are not suitable for frequent start and stop operation as compared to a battery. But, H₂ based storage systems are very suitable for satisfying the load demand for a long-term basis which can improve the overall system's efficiency. In this work, the above technical constraint exhibited by fuel cell and electrolyzer system has been mitigated via the adoption of battery storage. As depicted in Fig. 5.2, the battery storage always helps in meeting the transient generation, and loading power profiles in the system via the adoption of reduced rule-based power management controller (PMC). In fact, with the help of deliberated PMC the merits of battery storage have been judiciously used to overcome the slow dynamic nature of fuel cell and electrolyzer.

As shown in Fig. 5.2, it is observed that the battery can support either the electrolyzer system or the FC system depending on the criteria of P_{net} and SOC of the battery. During excess power generation inside the hybrid system, the electrolyzer consumes this excess power to generate H_2 whereas, the battery consumes this excess power to replenish its SOC if the battery SOC is less than 80%. Thus, either the electrolyzer or the battery participates whenever there is an excess power generation in the considered system. While; the FC- battery combination participates in meeting the deficit load demand whenever the system encounters power deficiency. Thus, in all cases the support from battery either as an energy source or as an energy sink is available. The SOC criteria for the battery have been intentionally applied as this will ensure that the battery is always available whenever the FC and electrolyzer system ceases to deliver or absorb their respective power. Moreover, this SOC criteria helps in reducing the frequent start and stop cycles of the H_2 -based devices (FC and electrolyzer). The power references generated from the OPR unit are controlled by the respective interfacing power electronic converters whose control algorithms are discussed in the next section.

5.6 Proposed Control Schemes of Power Electronic Converters

The power references for the PEMFC converter P_{FC}^{ref} , battery converter P_{batt}^{ref} , electrolyzer converter P_{elz}^{ref} are generated from the OPR unit of the proposed PMC as it was deliberated in the previous section. Since, this chapter keeps a holistic approach for meeting the objective of power management and also the aspect of LVRT capability in the system, the design for dc-dc boost converter-1 that is interfaced with WECS is done by keeping both of these objectives. Hence, in this regard a MPPT control and off-MPPT control is used and the control methodology of the same is deliberated in the following subsection.

5.6.1 Control of WECS Converter

As shown in Fig. 5.1, the dc-dc boost converter-1 is used for MPPT purpose from the WECS. This controller senses the wind speed denoted by V_w in order to calculate the optimum value of the rotor speed ω_r^{opt} , this rotor speed will correspond to the maximum power to be fetched from the turbine. The optimum rotor speed changes with the instances in wind speed variation and is tracked via a PI controller bearing proportional and integral gain as k_p^{mppt} and k_i^{mppt} respectively. The PI controller adaptively generates a reference current for the dc-dc boost converter-1 denoted by $i_{L_1}^*$ containing the information of maximum power. The error between

the generated reference current $i_{L_1}^*$ and measured current i_{L_1} is applied to adjust the duty cycle d_{pmsg} of the boost converter via a hysteresis current controller in order to operate the turbine at optimum speed.

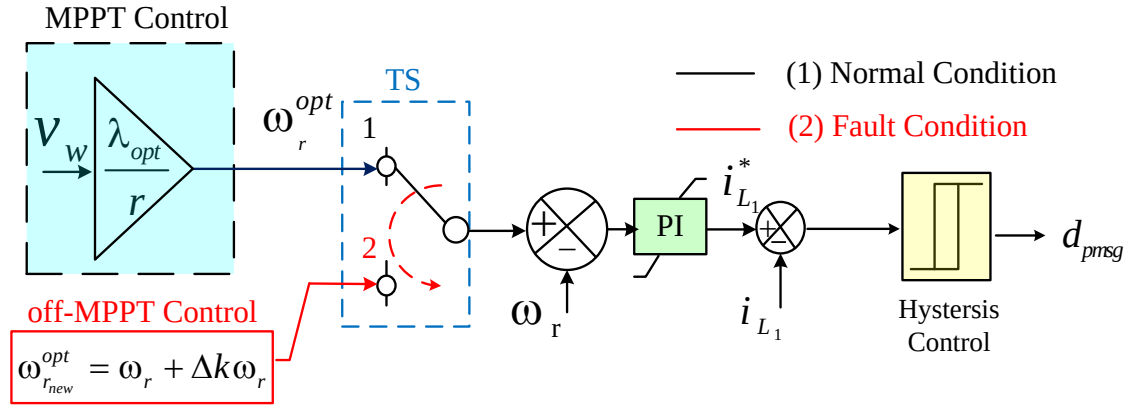


Fig. 5.3. MPPT and off-MPPT based control for WECS.

In case of grid fault, there is a power imbalance generated in the system as there is a sharp drop in the magnitude of active power at the PCC while; the power generated from WECS remains unchanged. If this imbalance is not nullified, then the magnitude of active power shoots up at the dc-link which, is visible in the form of surge of dc-link voltage. Thus, the PMSG based WECS needs to be disconnected from the MPPT mode during the detection of fault at the PCC and must be switched to off-MPPT mode. Since, this work also aims to integrate the LVRT capability in the considered system; an off-MPPT control is also proposed in this regard as depicted in Fig. 5.3. The toggle switch (TS) changes the turbine's reference speed from ω_r^{opt} to a new optimum reference speed denoted by $\omega_{r_{new}}^{opt}$. The basic idea of generating the new speed reference is to momentarily increase the speed of the turbine as per (5.4) for the time span of the fault where, n stands for quantity of velocity samples, ΔT denotes the fault/ voltage sag span duration, T_{s_speed} represents the MPPT controller's sampling period, $\Delta\omega$ expresses the increase in PMSG's speed and H stands for generators inertia constant.

$$\left. \begin{aligned} \omega_{r_{new}}^{opt} &= \omega_r + \Delta k \omega_r \\ \Delta k &= \sqrt[n]{1 + \frac{\Delta\omega}{100}}; n = \frac{\Delta T}{T_{s_speed}}; \Delta\omega = \frac{\Delta T}{H} \end{aligned} \right\} \quad (5.4)$$

The tracking of the new speed reference as per (5.4) enables to decrease the power generated from the turbine according to the wind turbine power and rotor speed characteristics.

In this process, some portions of the energy stored in the system in form of inertia denoted as per (5.5) [151], where J denotes the moment of inertia of the rotor mass.

$$\Delta KE = 0.5J \left[\left(\omega_{r_{new}}^{opt} \right)^2 - \left(\omega_r \right)^2 \right] \quad (5.5)$$

5.6.2 Battery Converter Control Scheme

A bidirectional dc-dc buck-boost converter is interfaced between the battery and dc-link, as the battery is expected to release and absorb its energy for balancing the deficit power as per the power sharing algorithm. The representation of the controller is shown in Fig. 5.4 where, the battery is controlled to either in buck mode when the excess power is to be dumped or in boost mode when the deficit power is to be met.

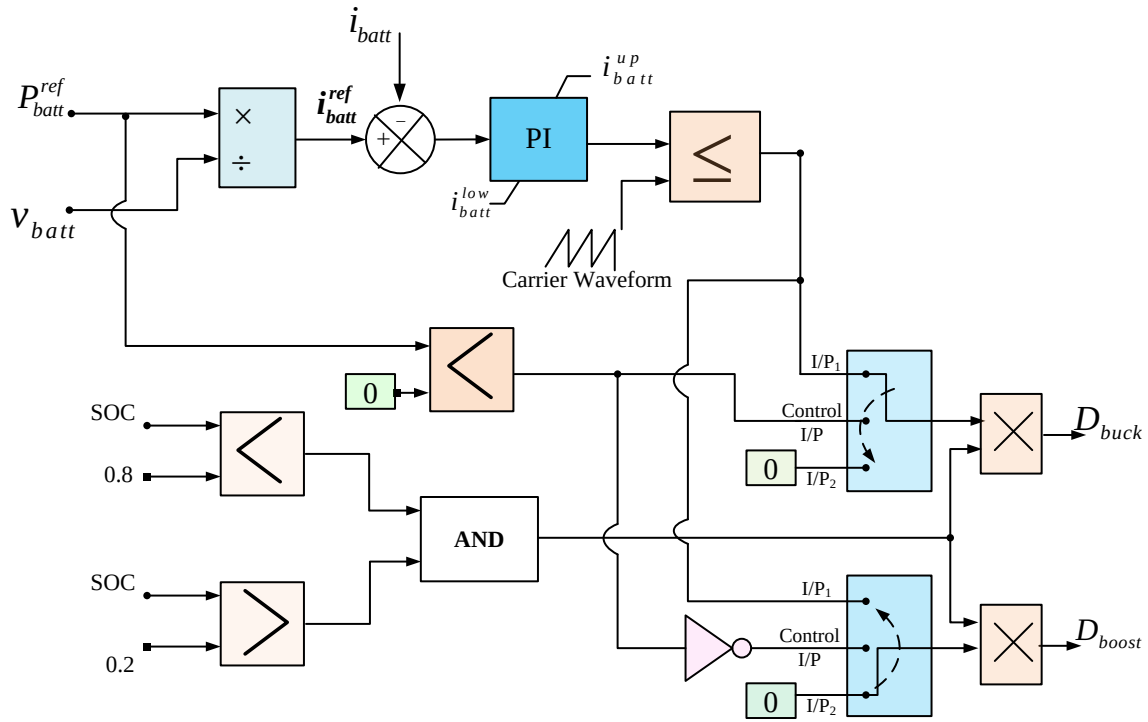


Fig. 5.4. Schematic showing the battery converter control scheme of the proposed HES model.

The battery reference power P_{batt}^{ref} which, is derived from the PMC is mathematically divided by the battery terminal voltage in order to generate the battery reference current i_{batt}^{ref} . This reference current is tracked by the PI controller bearing proportional and integral gain as k_p^{batt} and k_i^{batt} respectively. The entire control scheme is designed in such a way that it is ensured that the battery operates within its lower and upper SOC limits of 20% and 80%

respectively. Thus, an additional check loop is added to take care of the above condition which, ensures that the battery always works in the specified SOC condition.

Additionally, the condition of buck operation or boost operation is ensured by applying a conditional two-way switch that selects either of the inputs, that is, I/P₁ or I/P₂ based on the value of control input.

5.6.3 Fuel Cell Converter Control Scheme

The fuel cell (FC) converter participates in meeting the deficit power when the battery SOC reaches its lower value. The control of switch S₂ in dc-dc converter-2 is done in such a manner that the utilization factor of FC stays in the range of 80% to 90%, as this criterion ensures the optimum life span of the FC. The desired limits of utilization factor are converted to lower and upper limits of the current to be supplied by the FC denoted by i_{fc}^{low} and i_{fc}^{up} correspondingly.

$$i_{fc}^{up} = \frac{0.9q_{H_2}^{in}}{2K_r}; i_{fc}^{low} = \frac{0.8q_{H_2}^{in}}{2K_r} \quad (5.6)$$

The value of the current limits is calculated as per (5.6) where, K_r is the cell constant and $q_{H_2}^{in}$ is the quantity of hydrogen which enters the FC.

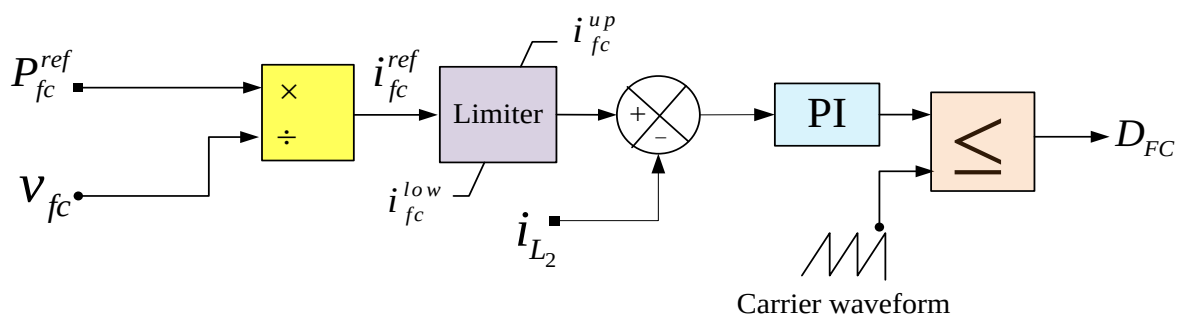


Fig. 5.5. FC converter control scheme.

The current reference of the FC converter i_{fc}^{ref} is obtained by dividing the fuel cell reference power P_{fc}^{ref} with FC terminal voltage v_{fc} . The magnitude of i_{fc}^{ref} is controlled between its limits by the help of a limiter block and the inductor current i_{L2} is controlled via a PI controller whose proportional and integral gains are k_p^{fc} and k_i^{fc} respectively. The corresponding duty cycle for the FC converter D_{FC} is generated as per Fig. 5.5.

5.6.4 Electrolyzer Converter Control Scheme

The electrolyzer is controlled by a buck converter, as the required terminal voltage for the electrolyzer is less than the rated dc-link voltage. The control schematic for the switch S_9 and buck converter connected in front of the electrolyzer is presented in Fig. 5.6. The control ensures the operation of electrolyzer is in operation only when the battery upper limit is reached, and at the same time the desired excess power is absorbed by the electrolyzer. Here, k_p^{elz} and k_i^{elz} represents the proportional and integral gain constant of the PI controller used in the electrolyzer converter control.

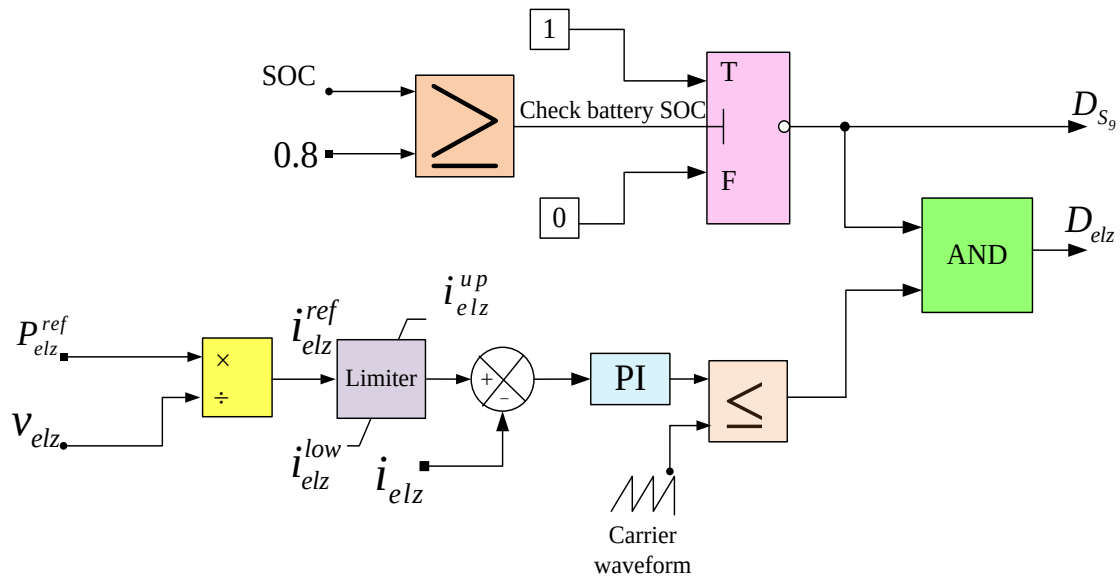


Fig. 5.6. Control of switch S_9 and buck converter for electrolyzer.

5.6.5 Control Scheme for Grid Connected VSI for Integrating LVRT Capability

The control schematic for the grid connected VSI is as per Fig. 5.7. The VSI is controlled in grid feeding mode when the preliminary role of the converter is to deliver the power generated from the WECS as per the grid operator's request. Besides the grid feeding feature, a new converter control for attaining the LVRT feature is proposed as well. In fact, when a grid fault is detected, the VSI control does the switching between its generated current references. The calculation of current reference during grid feeding operation mode and during the LVRT mode is discussed in the following sub-sections.

(a) Grid Feeding Mode Operation

The power balance in the system is represented as per (5.7) where, the total power generated from WECS P_w , PEMFC P_{fc} and battery P_{bat} is distributed among the dc-link P_{dc} ,

electrolyzer P_{elz} , inverter P_{inv} , load demand P_l and to the grid demand P_g^{ref} . This power balance helps in determining the required reference power of the inverter P_{inv}^{ref} which, is translated to a current reference by the current reference generation block as shown in Fig. 5.7.

$$P_w + P_{fc} \pm P_{bat} - P_{elz} = P_{dc} + P_{inv} + P_l + P_g^{ref} \quad (5.7)$$

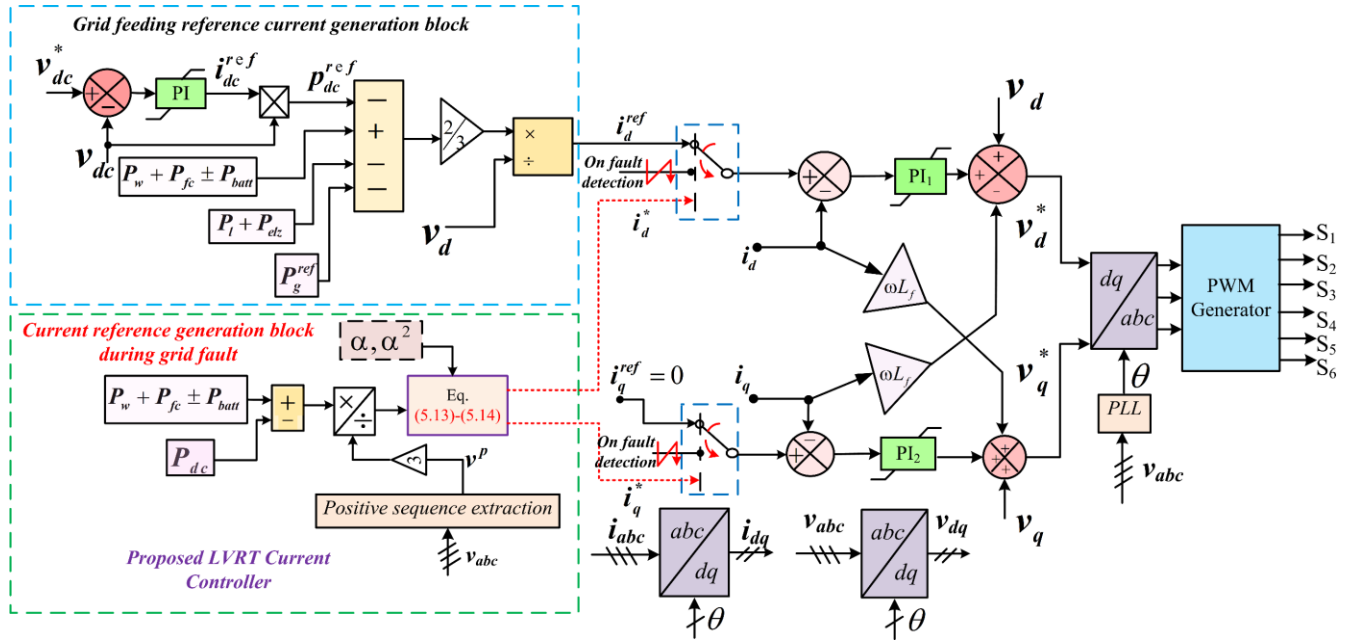


Fig. 5.7. Grid interfaced VSI control.

The dc-link power reference P_{dc}^{ref} is obtained by the product of dc-link reference current i_{dc}^{ref} and dc-link voltage v_{dc} which is generated as per (5.8) and (5.9) respectively where v_{dc}^* and v_{dc} are the reference and actual value of dc-link voltage, k_p^v and k_i^v are the proportional and integral gain constant of the voltage controller. As the inverter is controlled in dq -reference frame and under unity power factor condition, the reference d -axis current i_d^{ref} is obtained as per (5.10) while the default q -axis current reference i_q^{ref} is fixed to zero.

$$i_{dc}^{ref} = k_p^v (v_{dc}^* - v_{DC}) + k_i^v \int (v_{dc}^* - v_{dc}) dt \quad (5.8)$$

$$P_{dc}^{ref} = v_{dc} \times i_{dc}^{ref} \quad (5.9)$$

$$i_d^{ref} = \frac{2}{3} \left(\frac{P_w + P_{fc} \mp P_{bat} - P_{elz} - P_{dc}^{ref} - P_l - P_g^{ref}}{v_d} \right) \quad (5.10)$$

The current references i_d^{ref} and i_q^{ref} are tracked by the PI controllers PI_1 and PI_2 in order to generate the direct and quadrature axis voltage references denoted by v_d^* and v_q^* respectively.

(b) LVRT Mode Operation

The mode selection switch performs the switching of current reference from the grid feeder current generation block to LVRT current controller block depending upon the detection of grid fault. The mathematical modeling of the proposed LVRT control scheme is described in this subsection. The reference current is generated during LVRT mode via tracking the positive sequence power of the system as per (5.11) where, P_{hs} is the total power generated from the hybrid system as per (5.12), v^p is the positive sequence voltage component, C_{dc} is value of dc-link capacitance. As per (5.11), the reference current i^{p*} does not contain the component of negative sequence power and thus, if this reference current is successfully tracked by the inverter control, then, the FRT functionality is effectually unified in the system.

$$i^{p*} = \frac{\left(P_{hs} - v_{dc} C_{dc} \frac{dv_{dc}}{dt} \right)}{3 \times v^p} \quad (5.11)$$

$$P_{fc} + P_w + P_{bat} = P_{hs} \quad (5.12)$$

The current reference in positive sequence component which is obtained as per (5.11). Further, it is converted to current variables i_a^* , i_b^* , i_c^* of a 3-phase stationary circuit using Fortescue operators, α and α^2 as per (5.13).

$$i_a^* = \frac{\left(P_{hs} - v_{dc} C_{dc} \frac{dv_{dc}}{dt} \right)}{3 \times v^p} \quad (5.13.1)$$

$$i_b^* = \alpha^2 \left(\frac{P_{hs} - v_{dc} C_{dc} \frac{dv_{dc}}{dt}}{3 \times v^p} \right) = (-0.5 - j0.866) \left(\frac{P_{hs} - v_{dc} C_{dc} \frac{dv_{dc}}{dt}}{3 \times v^p} \right) \quad (5.13.2)$$

$$i_c^* = \alpha \left(\frac{P_{hs} - v_{dc} C_{dc} \frac{dv_{dc}}{dt}}{3 \times v^p} \right) = (-0.5 + j0.866) \left(\frac{P_{hs} - v_{dc} C_{dc} \frac{dv_{dc}}{dt}}{3 \times v^p} \right) \quad (5.13.3)$$

$$\begin{bmatrix} i_d^* \\ i_q^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos \theta & \cos(\theta - 120^\circ) & \cos(\theta + 120^\circ) \\ -\sin \theta & -\sin(\theta - 120^\circ) & -\sin(\theta + 120^\circ) \end{bmatrix} \begin{bmatrix} |i_a^*| \\ |i_b^*| \\ |i_c^*| \end{bmatrix} \quad (5.14)$$

Since, it is intended to regulate the inverter current references by PI controllers but it is generated in the abc -frame obtained as per (5.13), these current references are converted to SRF using (5.14). Moreover, the current references obtained from (5.13) are complex terms bearing their real and imaginary components because of the presence of sequence factors, their corresponding magnitude are extracted and the same is applied to (5.14) for obtaining the further current references in dq -frame. The current reference terms of d -axis i_d^* and that of q -axis i_q^* enables for the FRT attainment. The reference current of q -axis i_q^* is compared with the actual q -axis current and the corresponding error is regulated by the PI controllers PI₁ and PI₂ to generate an intermediate voltage reference term. The final voltage reference in the dq -frame is obtained by including the cross-coupling voltage terms which finally generates the dq -axis reference voltages v_d^* and v_q^* according to (5.15) -(5.16) respectively. k_i^c and k_p^c denotes the integral and proportional gains of PI-regulators PI₁ and PI₂, the entire control schematic is included in Fig. 5.7. The method described above is one of the significant contributions done in terms of the system modeling.

$$v_d^* = k_p^c \left\{ (i_d^* \text{ or } i_d^{ref}) - i_d \right\} + k_i^c \int \left\{ (i_d^* \text{ or } i_d^{ref}) - i_d \right\} dt + v_d - \omega L_f i_q \quad (5.15)$$

$$v_q^* = k_p^c (i_q^* \text{ or } i_q^{ref} - i_q) + k_i^c \int (i_q^* \text{ or } i_q^{ref} - i_q) dt + v_q + \omega L_f i_d \quad (5.16)$$

5.7 Results and Interpretations

The validation of the deliberated system's modeling and its control is performed by considering series of simulation experimentation in MATLAB/Simulink platform. The detailed simulation parameters are presented in Table. 5.1. Following case studies are undertaken to validate the dynamic and transient performance of the system under various power generation and demand scenarios.

5.7.1 Case-1: WECS Generated Power Greater than the Grid Request

A situation is considered where; the power generated from the wind generator P_w remains constant at 18.3 kW per Fig. 5.8 (a) because of nearly constant wind speed. The battery SOC is considered more than 80% while, the produced power from the WECS is larger than the power demand of the grid operator. The power demand of the grid denoted by P_g^{ref} as shown in Fig. 5.8 (e) varies in the following way; a demand of 3 kW for the span of 0 s – 0.5 s, 7 kW from 0.5 s – 1.5 s, 15 kW for the peak demand span of 1.5 s – 3 s and 10 kW for the remaining duration. The demand from the grid acts as the input power reference for the grid connected inverter controller.

Table 5.1
Parameters of the system used for simulation

PMSG- WECS	
Rated power of the wind turbine	40 kW
Rated electromagnetic torque of the PMSG	126 N-m
Rated speed of the PMSG	314 rad/s
Base wind speed of the turbine	12 m/s
Pitch angle (β)	0°
Optimal tip speed ratio (λ_{opt}) for MPPT	8.1
k_p^{mppt} , k_i^{mppt} of the DC-DC MPPT converter (Boost Converter-1)	82, 650
Battery Bank	
Type	Lithium ion
Rating	55 Ah
Rated terminal voltage	300 V
Internal resistance	0.1 Ω
k_p^{batt} , k_i^{batt} of the DC-DC buck-boost converter	0.0153, 2
PEMFC System	
Power rating of individual stack	1.2 kW
e_o	1.229 V
Rated voltage of a single stack	26 V
Rated stack current	46 A
Number of cells in a single stack	48
Nominal stack efficiency	46 %
Operating temperature	55°C
Universal gas constant	8314.47 J/(k-mol-K)
Faradays constant	96485 C/mol
Cell constant	9.94×10^{-7}
Nominal supply pressure of H ₂	1.5 Bar
Nominal supply pressure of O ₂	1 Bar

Number of series connected stacks	12
Overall rating of the PEMFC array	15 kW
k_p^{fc} , k_i^{fc} of the DC-DC boost converter (Boost Converter-2)	3.5, 350
Electrolyzer System	
Rating of the electrolyzer	12 kW
r_1	$1.5 \times 10^{-5} \Omega \text{ m}^2$
r_2	$-6.019 \times 10^6 \Omega \text{ m}^2 \text{ } ^\circ\text{C}$
t_1	$0.214 \text{ A}^{-1} \text{ m}^2$
t_2	$-9.870 \text{ A}^{-1} \text{ m}^2 \text{ } ^\circ\text{C}$
t_3	$119.1 \text{ A}^{-1} \text{ m}^2 \text{ } ^\circ\text{C}^2$
N	75
V_{therm}	1.1647 V
T	70 $^\circ\text{C}$
A	873 cm^2
k_p^{elz} , k_i^{elz} of the DC-DC buck converter	6, 82
Parameters of the Inverter Control System	
Base voltage (Peak of line to ground)	338 V
Switching frequency	20 kHz
dc-link voltage reference; v_{dc}^*	690 V
Simulation sample time	20- μs
Voltage controller parameters; k_p^v , k_i^v	0.02, 267
Current controller parameters; k_p^c , k_i^c	2.67, 0.002

As presented in Fig. 5.8 (d) net power P_{net} is negative which implies the presence of excess power in the system. The efficacy of the PMC is seen where the excess power is stored in electrolyzer as per Fig. 5.8 (b) and dc-link is regulated near its reference value. Further, the power injected to the grid by the inverter follows the grid demand reference as evident from Fig. 5.8 (f). The PCC voltages are well regulated at 1 P.U by the inverter control while the currents at the PCC are regulated as per the grid power demand as inferred from Fig. 5.8 (g) and Fig. 5.8 (h). The generated H_2 (mol/s) profile of the electrolyzer is shown as per Fig. 5.8 (i). The profile of generated H_2 clearly gives an inference that H_2 production is directly related to the availability of the excess power in the system whose profile is as per Fig. 5.8 (d). During instances, when the system has excess power, then the H_2 generation is more while; during the situation when the magnitude of excess of power decreases then the generation of H_2 also decreases.

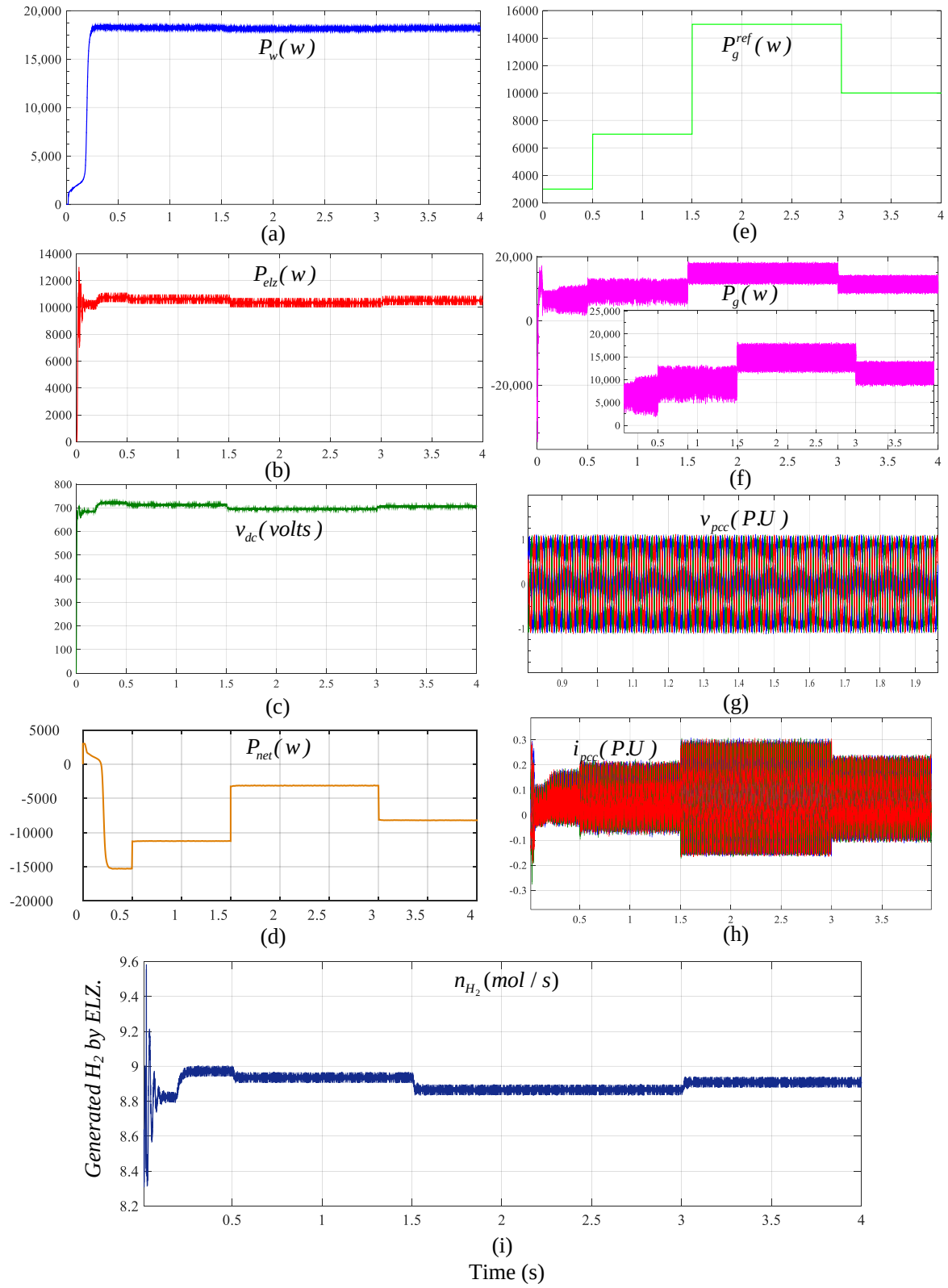


Fig. 5.8. (a) Power generated by WECS, (b) power generated by electrolyzer, (c) dc-link voltage, (d) net power in the system, (e) grid demand reference, (f) power delivered to the grid, (g) voltage at the PCC, (h) current at the PCC, (i) hydrogen generated by the electrolyzer.

5.7.2 Case-2: WECS Generated Power Lesser than the Grid Request and Load Demand

In this case, a situation is considered where the power generated from the WECS is constant but the sum of the load demand and the demand coming from the grid operator is constantly varying. The variation of P_g^{ref} is as per the previous case, while the load power P_L varies as 5 kW for the span of 0 s to 2.1 s, 10 kW for the time range of 2.2 s to 3 s and 30 kW from 3.1 s to 4 s. For this criterion, the net power constantly varies and takes the positive and negative values as shown in Fig. 5.9 (b). The profile of wind power, load demand, grid demand and the response of the inverter P_{inv} is depicted as per Fig. 5.9 (a), where it is seen that the inverter responds according to the demand of load and grid. For instance, during 3 s to 4 s, the total demand of the system ($P_L + P_g^{ref}$) is 40 kW which is delivered by the inverter.

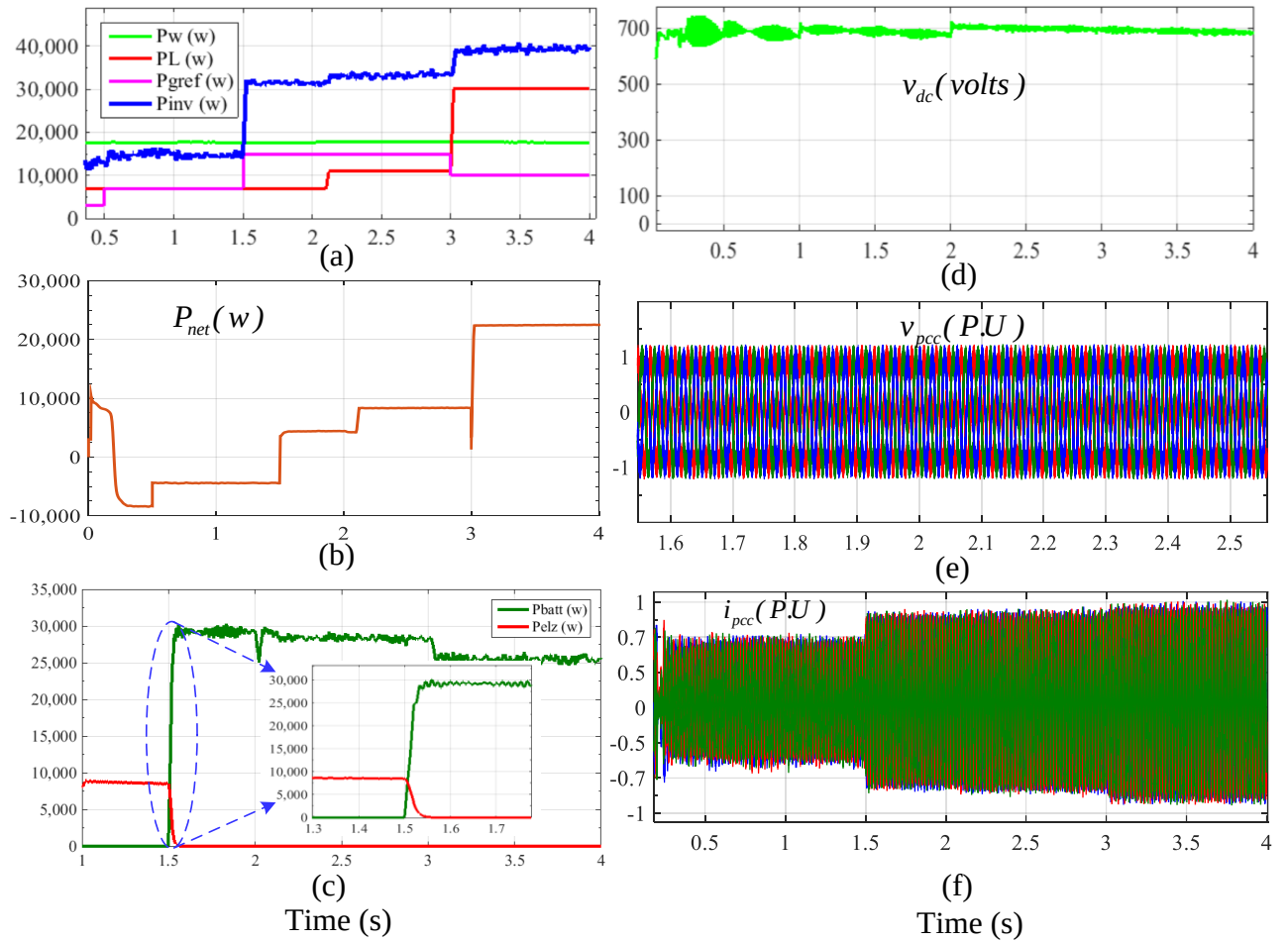


Fig. 5.9. (a) Power generated by WECS, load demand, grid demand, inverter generated power, (b) net power in the system, (c) power shared by battery and electrolyzer along with its zoomed version, (d) dc-link voltage, (e) voltage at the PCC, (f) current at the PCC.

The power delivered by the inverter is derived by the participation of battery and electrolyzer in the power sharing which is evident from Fig. 5.9 (c). The power management controller (PMC) directs the battery to participate in meeting the deficit power of 21.7 kW in the system since the generation from WECS is only 18.3 kW at that instant. The SOC of the battery is considered in the range of 20% to 80%. As per the zoomed version of active power response of electrolyzer and battery as per Fig. 5.9 (c), before 1.5 s the excess power in the system is absorbed by the electrolyzer, however after 1.5 s the electrolyzer goes to shut-down mode and due to the slow dynamics of the electrolyzer it switches OFF completely ($P_{elz} = 0$ W) at 1.55 s. The battery storage instantly supports the system at 1.5 s itself and thus it mitigates the power imbalance in the system created due to the slower dynamics of the electrolyzer. Although, the system experiences transition during 0.5 s, 1.5 s, 2 s and at 3 s respectively, proper regulation is performed by the proposed dc-ac converter control. The dc-link voltage is regulated around its reference value of 690 V, while the PCC voltages are maintained at 1 P.U and the PCC currents reacts as per the load demand. The profiles of the discussed parameters are depicted as per Fig. 5.9 (d), (e) and (f) respectively.

5.7.3 Case-3: Variable Power Generated by WECS and Variable Grid Request and Load Demand

The robustness of the proposed system and its control is also validated by considering variable wind generation, variable load demand and variable grid demand as depicted in Fig. 5.10 (a). The battery SOC is fixed less than 20%, because of variable power profile the system experiences both surplus and deficient power. The profile of net power is as per Fig. 5.10 (b) while the power shared by fuel cell and battery as per Fig. 5.10 (c). During the time span of 0.5 s to 1.5 s, the system possesses excess power but the SOC of battery is less than 20%, hence, the battery works in charging mode. Power of around 5 kW is received by the battery during the span 1 s to 1.5 s, negative magnitude of battery power P_{bat} validates the charging mode. After 1.5 s, net power in the system shift from excess power mode to deficient power mode where the fuel cell starts up and delivers the deficient power according the overall system demand. For instance, 10 kW of deficit power is conveniently delivered by the fuel cell during the span of 2 s to 3 s as per the PMC logic. The apt regulation of the dc-link voltage around its reference and regulation of PCC voltage at 1 PU is depicted as per Fig. 5.10 (d) and Fig. 5.10 (e) respectively. The inset version of PCC currents during the transients encountered at 1.5 s and 2.1 s is shown in Fig. 5.10 (f) where, it is inferred that the current regulation is well visualized by the inverter control.

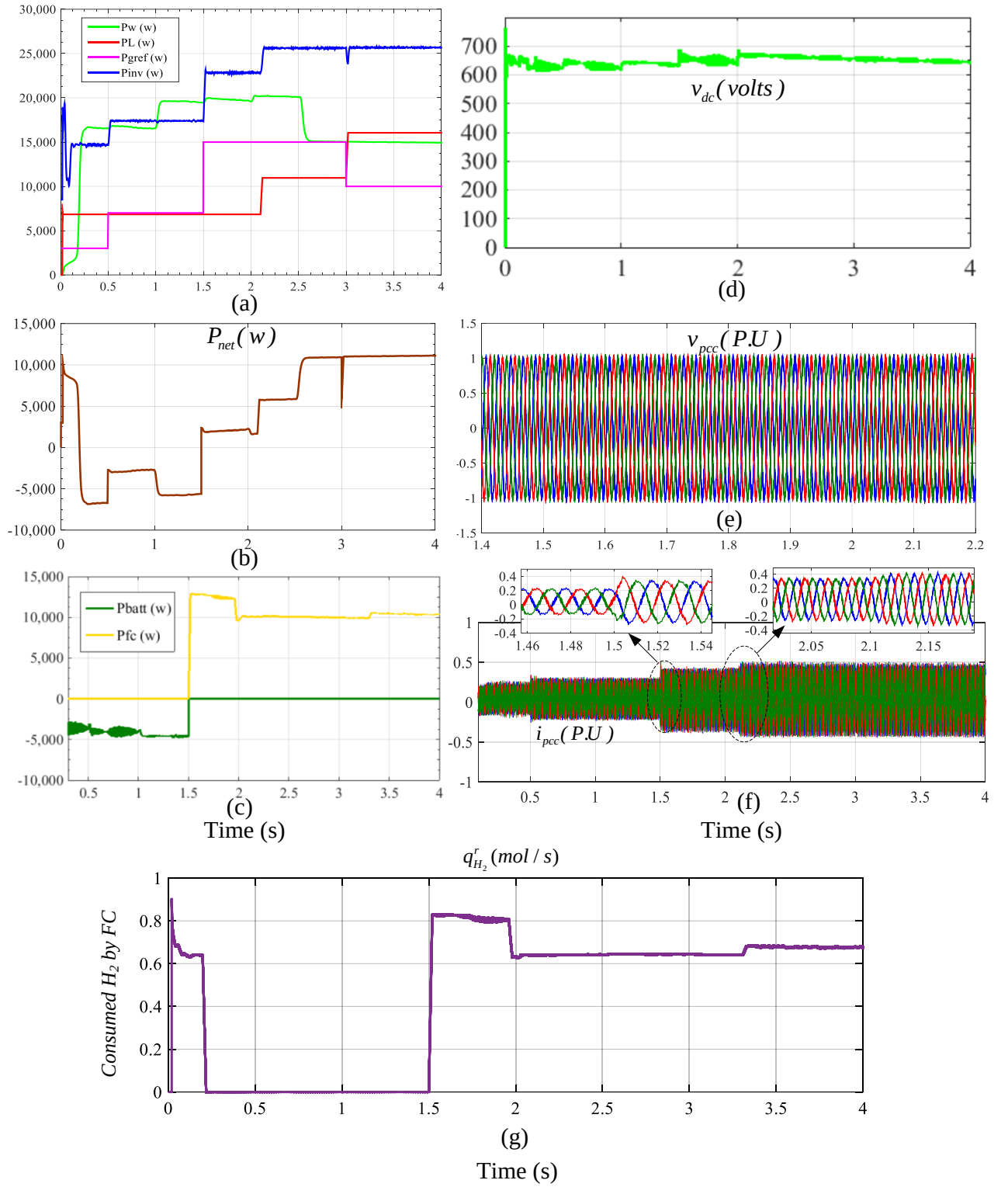


Fig. 5.10. (a) Power generated by WECS, load demand, grid demand, inverter generated power, (b) net power in the system, (c) power shared by battery and FC, (d) dc-link voltage, (e) voltage at the PCC, (f) current at the PCC and its corresponding zoomed versions, (g) Consumed H_2 by the FC.

The consumed/ reacted H_2 profile in the fuel cell is as per Fig. 5.10 (g) where, the corresponding changes in the H_2 consumption are observed whenever there is a change in the

fuel cell's power delivery magnitude. For instance, the system experiences a power deficiency during the span of 1.5 s – 1.9 s, hence, the H₂ consumption also surges and registers a value around 0.8 mol/s during this span. While; after 1.9 s, the H₂ consumption gets regularized within the range of 0.65 mol/s and 0.7 mol/s respectively as per the fuel cell's power delivery requirement.

5.7.4 Energy Exchange Analysis of the Grid-Connected Hybrid Generation System

In order to understand the energy balance in the system, the dynamics of power associated in the dc-link and inverter is ignored for simplicity. Hence, the power balance inside the system is stated as per expression:

$$P_w + P_{fc} \pm P_{bat} - P_{elz} = P_l + P_g^{ref} \quad (5.17)$$

where, P_w is the power generated from the WECS, P_{fc} is the power delivered by the FC, P_{bat} is the power delivered or absorbed by the battery, P_{elz} is the power absorbed by the electrolyzer, P_l is the power demand of the ac load connected at the point of common coupling while P_g^{ref} is the power demand of the grid. The energy balance is derived from (5.17) and is expressed as per (5.18)

$$\int P_w dt + \int P_{fc} dt \pm \int P_{bat} dt - \int P_{elz} dt = \int P_l dt + \int P_g^{ref} dt \text{ or}$$

$$E_w + E_{fc} \pm E_{bat} - E_{elz} = E_l + E_g \quad (5.18)$$

where, E_w is the energy supplied by the WECS, E_{fc} is the energy provided by fuel cell, E_{bat} is the energy absorbed or supplied by battery, E_l is the energy demand of the load, while E_g denotes the energy demand of the grid. Since the validation of power management algorithm is performed for a shorter simulation span, the demonstrated values of energy exchange capacities will be of lower magnitudes. In each simulation cases the energy exchange associated with battery, FC and electrolyzer are discussed on the basis of (5.18), and the same is enumerated below;

Simulation Case-1: In this case (discussed as per Subsection 5.7.1) the system has energy abundance as $E_w > E_g$, the excess energy is consumed by electrolyzer (E_{elz}) to generate more H₂. At this condition the FC and battery does not participate in energy exchange thus; $E_{fc} = 0$ kWh and $E_{bat} = 0$ kWh. Considering the average power consumption of electrolyzer as 10-kW

for the duration of 4 s (evident from Fig. 5.8 (b)), the average energy consumption of the electrolyzer (E_{elz}^{avg}) is calculated as per (5.19).

$$E_{elz}^{avg} = P_{elz}^{avg} \times t = 10kW \times \frac{4}{3600} hr = 0.012 \quad kWh \quad (5.19)$$

Simulation Case-2: In this case (discussed as per Subsection 5.7.2) the system has energy deficiency since $E_w < (E_g + E_l)$ hence, the deficient energy is supplied by the battery storage system. As per the results of Fig. 5.9 (c) of the manuscript, the battery supplies an average power of 27 kW for the duration of 2.5 s, hence the average energy exchanged by the battery (E_{bat}^{avg}) is calculated as per (5.20) while the energy exchanged with the fuel cell $E_{fc} = 0$ kWh.

$$E_{bat}^{avg} = P_{bat}^{avg} \times t = 27kW \times \frac{2.5}{3600} hr = 0.01875 kWh \quad (5.20)$$

Simulation Case-3: In this case (discussed as per Subsection 5.7.3) the system encounters variable loading hence the condition of energy deficiency and energy surplus are created. During energy surplus condition, the excess energy is absorbed by the battery while during the energy deficiency the FC participates in meeting the demand. As per the results of Fig. 5.10 (c), the FC supplies an average power of 10 kW for the duration of 2.5 s, hence the average energy exchanged by the FC (E_{fc}^{avg}) is calculated as per (5.21) while the energy exchanged by the electrolyzer $E_{elz} = 0$ kWh.

$$E_{fc}^{avg} = P_{fc}^{avg} \times t = 10kW \times \frac{2.5}{3600} hr = 0.006944 kWh \quad (5.21)$$

5.7.5 Case-4: LVRT Capability of the Considered Hybrid Power Generation

The LVRT capacity is added to the system by appending the presented LVRT controller discussed in Subsection 5.6.5(b), and also by using the off-MPPT control discussed in Section 5.6.1. The validation for the LVRT control is undertaken by considering three sub-cases namely 1-phase sag, 2-phase sag and 3-phase sag. The system response for all the three voltage sag cases are depicted as per Fig. 5.11. For all the cases, PCC voltage (v_{pcc}), PCC current (i_{pcc}), dc-link voltage (v_{dc}), power delivered by the inverter (P_{inv}) and the mean power from the inverter P_{inv}^{mean} are calculated. The voltage sags are simulated for the duration of 2 s to 2.15 s respectively, and the inverter is operated to meet the grid active power demand of 5 kW.

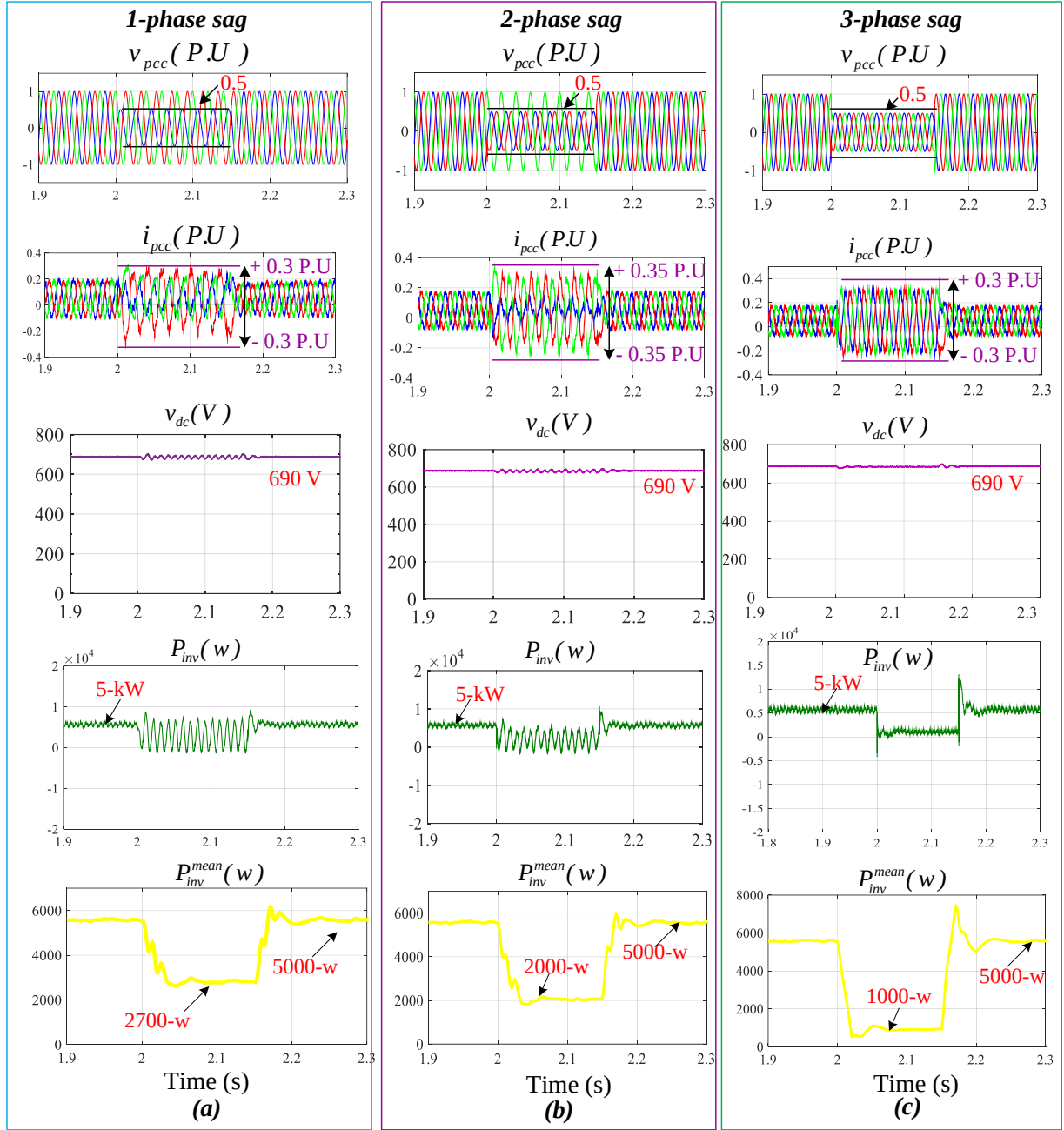


Fig. 5.11. (a) system parameters under 50% 1-phase voltage sag, (b) system parameters under 50% 2-phase voltage sag, (c) system parameters under 50% 3-phase voltage sag.

(a) 1-Phase Voltage Sag

In case of single-phase sag, a voltage dip of 50% is simulated at one phase correspondingly, the dynamics of the inverter control and the off-MPPT control are actuated enabling the ride through characteristics in the considered system. As per the results in Fig. 5.11. (a), the overshoot of i_{pcc} is controlled within the range of ± 0.1 P.U., while the profile of v_{dc} is controlled in a smooth manner due to simultaneous the actuation of off-MPPT control, operation of the negative sequence current control and also due to effective power sharing

performance with the proposed power management controller. The generation of negative sequence currents attributes to the ripple content in the instantaneous active power oscillations in the system while the proposed FRT control is unable to completely eliminate these oscillations. However, the dip in the active power profile is minimized to a great extent. This aspect is visible by visualizing the P_{inv}^{mean} profile delivered by the inverter under various voltage sag conditions where the mean value of the inverter active power is maintained up to 2.7 kW during the voltage dip span.

(b) 2-Phase Voltage Sag

The system is subjected to a double phase sag of 50% and the corresponding system's behaviour is projected as per Fig. 5.11 (b). Due to the increase in quantum of unbalancing, the overshoot of i_{pcc} is within the increased range of ± 0.15 P.U. while; the profile of dc-link voltage well stabilized within its rated value of 690 V with minute number of ripples. The active power profile delivered by the inverter registers a dip up to 2 kW from the rated power reference of 5 kW.

(c) 3-Phase Voltage Sag

The systems investigation for the LVRT capability is performed for a symmetrical fault case study where a uniform voltage dip by 50% is created in the utility grid in order to observe the ride through performance in the system. The corresponding parameters are showcased in Fig. 5.11 (c) where, the current surge is limited within the range of ± 0.1 P.U. Further, the dc-link voltage profile and the instantaneous active power profile does not register any double frequency oscillations due to the absence of negative and zero sequence components of current and voltage. Since, such type of sag condition is considered to be the most severe one, the dip in the mean value of active power profile is up to 1 kW from the rated value of 5 kW.

(d) Severe voltage sag ride through capability

In general, a typical electric power system mostly registers a 1-phase voltage sag and the magnitude of voltage at the PCC or at the inverter terminals generally lies within 0.9 P.U. to 0.5 P.U. This typical range of voltage magnitude at the PCC during the voltage sag span is due to inherent availability of impedance existing between the line connecting the utility grid and inverter terminals. In this work, the robustness of the discussed LVRT algorithm is also brought out by validating it for the considered system during 90% voltage sag events where the magnitude of respective PCC voltages is registered up to 0.1 P.U.

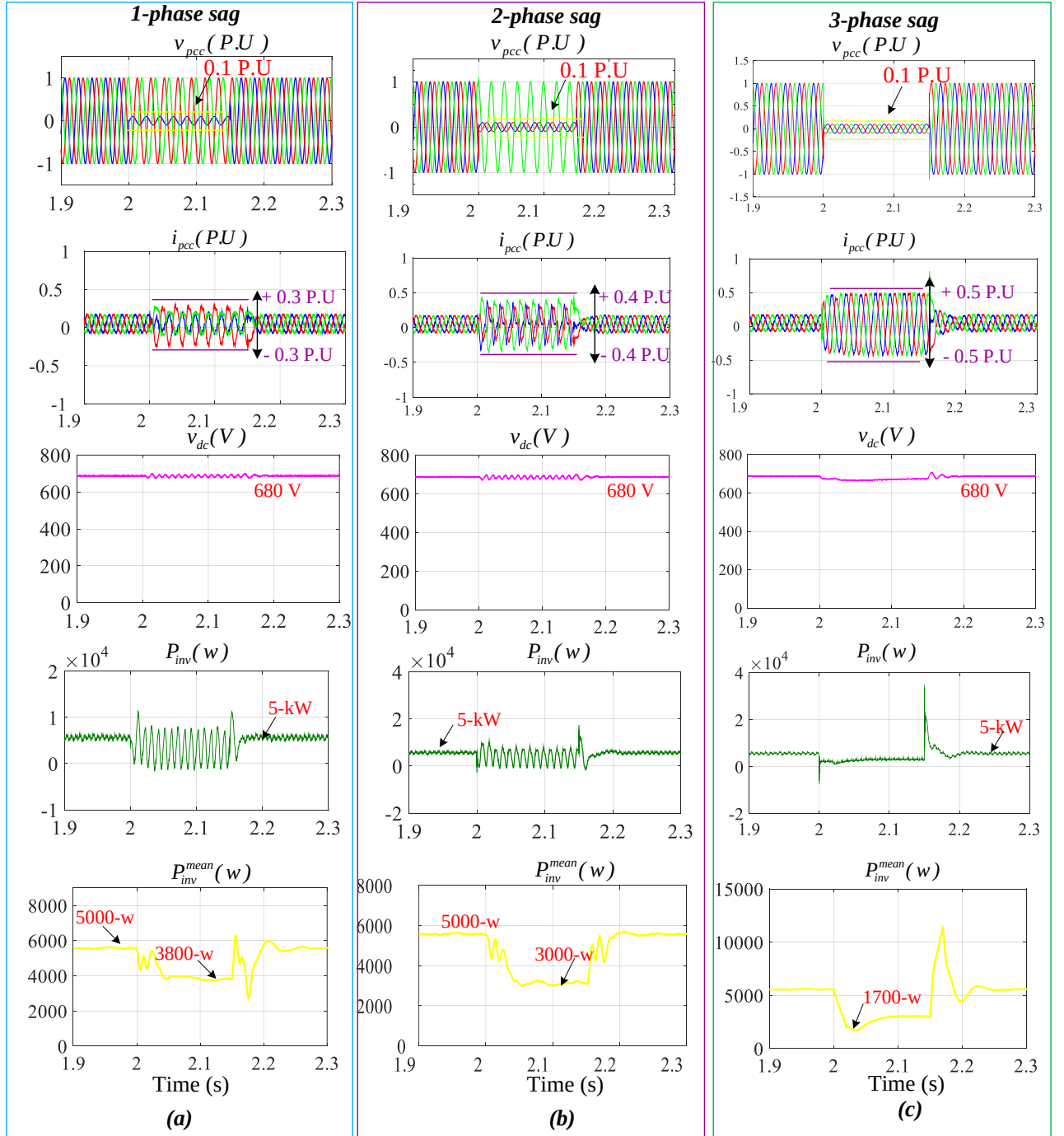


Fig. 5.12. (a) system parameters under 90% 1-phase voltage sag, (b) system parameters under 90% 2-phase voltage sag, (c) system parameters under 90% 3-phase voltage sag.

The system ride through performance is portrayed as per Fig. 5.12 where the respective considered subcases of 90% 1-phase, 2-phase and 3-phase voltage sag are depicted as per Fig. 5.12 (a), Fig. 5.12 (b) and Fig. 5.12 (c) respectively. As seen from Fig. 5.12, there is a gradual increase in the magnitude of PCC current from 0.3 P.U. to 0.5 P.U. as the voltage sag events shift from 1-phase, 2-phase and 3-phase sag respectively. Hence, in all the cases the magnitude

of PCC currents i_{pcc} is within the range of rated current carrying capability of the inverter's power electronic switches. The profile of dc link voltage registers oscillation during 1-phase and 2-phase voltage sag due to presence of negative sequence currents. However, similar to the response of 50% voltage sag event the registered oscillations in v_{dc} has negligible peaks and does not portrays magnitude surge because of effective action of the presented feed-forward LVRT control action in the VSI control discussed as per Subsection 5.6.5 (b). As far the profile of instantaneous power at the inverter terminal P_{inv} is concerned, the double frequency oscillations persist during 1-phase and 2-phase sag, while; steep spike is visualized during the end of 3-phase sag which can be considered as a limitation of the adopted LVRT strategy. Nevertheless, the mean value of inverter's active power profile P_{inv}^{mean} lies above 1500 W for all the cases which is due to effective support from the off-MPPT control of the PMSG-WECS discussed as per Section 5.6.1.

5.8 Chapter Summary

This chapter has addressed the simultaneous power management and LVRT control of a grid connected hybrid WECS based renewable energy generation system which, is primarily backed up by battery and PEMFC. The behaviour of the presented reduced rule-based power management control is found satisfactory for various power generation and demand scenarios. The proposed PMC takes into account the request of grid, power demand of the loads at PCC and available generation from the WECS during the entire system's operation. Most importantly in all cases, the dc-link voltage and PCC voltages are regulated around 690 V and 1 P.U. respectively. The discussed PMC also ensures the apt energy balance in the system. Further, the life span enhancement of the storage devices is ensured with the considered PMC by the allocation of proper coordination control and current limits within the various interfacing dc-dc converter control. As an added feature of the system, a dynamic current feed-forward control based on the regulation of negative sequence PCC current is appended in the inverter control which ensures the LVRT functionality. The ride through functionality is found satisfactory for 50% and 90% 1-phase, 2-phase and 3-phase voltage sag cases. The profiles of PCC voltages, currents and the dc-link voltage exhibit firm regulation under all the considered transient events. Overall, the proposed system and its control is well suitable where the grid operator is dependent in fetching reliable and clean power.

A Unified Central Power Management and LVRT Control for a Grid-Integrated Hybrid Energy System

6.1 Introduction

In continuations to Chapter-5, in this chapter, the aspects of *power management control and LVRT* is now presented for DFIG based hybrid energy systems. The work presented in this chapter considers a hybrid system consisting of DFIG based WECS as primary power generator along with hybrid storage units consisting of super capacitor (SC), fuel cell (FC)-electrolyzer (ELZ) pair as back up sources. The power-sharing characteristic is fulfilled with the proposal of reduced rule-based central power management controller (PMC). As per research objectives, the design of proposed PMC takes into account regarding the power demand from the grid operator. While; the low-voltage ride through (LVRT) capability of the system is enhanced via a new multi-dimensional control approach. Firstly, a control for the rotor side converter (RSC) is performed for torque ripple nullification in DFIG during grid voltage sag. Secondly, a mode selection-based switching control for the dc-dc converter interfaced with SC is adopted for smoothening the dc-link voltage transients under voltage sag scenario. Thirdly, a feed-forward-adaptive neuro-fuzzy inference system (FF-ANFIS) based control for the grid side converter (GSC) of DFIG is presented. The FF-ANFIS based control for GSC, helps in regulating the newly generated current references from the LVRT block under grid voltage sag condition. The unified operation of discussed PMC and LVRT control is validated in MATLAB/Simulink based testbed for varied generation, loading and voltage sag conditions.

6.2 Related Review and Motivation

The merits of a DFIG based WECS were briefed in Section 1.2. To reiterate the same, a DFIG offers high energy conversion efficiency, flexible controllability and requirement of lower ratings of the power converters [20]. A DFIG system has the flexibility to perform additional control functionalities such as reactive power support, harmonic compensation and FRT capability as per the grid-operator requirements [21]. The practice of connecting a DFIG system with one or more number of storage systems at the point of common coupling (PCC) proves be beneficial in terms of energy efficiency and facilitation of reliable power [23]. Many studies shown the integration of energy storage devices at the common dc-link created by the

back-to-back converter arrangement in DFIG systems. Here, the integration of such storage devices provides the advantage of control flexibility, simplicity and cost effectiveness in the overall system [136], [152]-[153]. The use of SC as a storage device in conjunction with DFIG-WECS has proven advantages for facilitating various technical objectives in the resultant HES. In [85], SC is being employed along with a PMSG based wind farm to compensate the slow dynamic response of FC due to change in WECS output. In the work of [154]-[157], a SC is also used with a DFIG for rendering multiple tasks like, mitigation of power fluctuation, nullification of transient power mismatch and also for power smoothening in a WECS. SC is also a favourable choice for LVRT enhancement, the same is demonstrated in [156]-[157]. In [157], a SDBR is also used with SC to enhance the transient response of the DFIG system during 3-phase fault condition. In case of a DFIG machine, trapped flux is induced under low voltage situation due to the rapid change of voltage at its stator terminals. This phenomenon further causes larger induced voltage at the rotor windings at the slip frequency and causes a loss of control of the RSC. Devices like fault current limiter (FCL) with battery energy storage, switch typed FCL are used to weaken the rotor emf and also to limit the rotor overcurrent during low voltage situation at the DFIG as per [167]-[168]. An approach to include an additional transformer between the GSC and grid transformer is discussed in [169]. Here, the stator voltage is controlled towards its nominal magnitude irrespective of any potential changes in the grid voltage. The inclusion of more than one power generation sources like PV, batteries and FC along with SC in a DFIG-WECS are attempted in various literatures [23], [103]. However, these referred work considers only grid independent architecture. From the above discussions, it is apt to state that a SC attributes an immense potential towards the enhancement of the dynamic response in a hybrid system.

From the discussions of Subsection 1.2.4, it was emphasised that in HES, a PMC is essential for maintaining the balance of power in hybrid system and also for voltage and frequency regulation. The aspect of power management is equally essential in a DFIG based hybrid systems. For instance, the work of [25], [136] and [158] considers grid independent mode of operation with special consideration towards power quality improvement in the system. The PMC algorithm in grid- connected environment find its practical feasibility, when a DFIG based hybrid generation system operates in a smart grid-based frame work. It is reiterated that LVRT control is equally essential for grid integrated hybrid energy system considering the latest grid code requirements. References [159]-[160] proposes PMC in a DFIG based HES for grid integrated environment, however, these works did not address the LVRT

mode of operation in the system. The simultaneous objective of power management control and LVRT enhancement are sparsely attempted in the existing literature involving DFIG based HES. For instance, the work of [152] and [161] attempts the LVRT and energy management control in a cost effective DFIG hybrid system architecture. However, detailed information regarding the profile of generator's electromagnetic torque is missing in these studies. Moreover, the validations for LVRT schemes are done by considering only balanced 3-phase faults which might not be practical as 3-phase faults rarely occur in a power system and does not involve the negative sequence currents or voltages. Considering the above cited research gaps, this chapter attempts to highlight the following contribution in the proposed work.

1. This chapter demonstrates an architecture to integrate the back-up devices in the presented hybrid system, viz, FC-ELZ and SC at the common dc-link created in DFIG. Due to the very configuration, the requirement of an additional inverter to integrate the hybrid system with the grid is eliminated. Instead, the already existing converter in DFIG system, which is the GSC is utilized for this purpose.
2. The aspect of FRT is embedded in the proposed system by the use of SC, which is already available with the considered system. Thus, the investment for additional passive devices such as crow bar, breaking chopper etc. for LVRT enhancement is eliminated.
3. The proposed system achieves an apt power management with the implementation of a new PMC. The PMC offers the determination of power references for SC, FC and ELZ with reduced number of “if-else” based rules. This enhances the dynamic response of the considered grid-integrated HES. Moreover, the described power management strategy takes into account the power demand of the grid operator in priority while determining these power references.
4. An effort is made to integrate the LVRT scheme along with the PMC. The LVRT schemes includes; (a) demonstration of special control for the RSC within DFIG which is referred as ‘off-MPPT’ control, (b) mode selection based control for power dispatching mode and LVRT mode for the dc-dc converter interconnected with the SC, and (c) FF-ANFIS based LVRT control for the GSC in the DFIG.
5. The merit of including a SC in the system is utilized in dual modes. Firstly, the SC is controlled to balance the transient power mismatch within the system during power fluctuations. Secondly, it is utilized to render the LVRT capability in the system by stabilizing the dc-link voltage under fault span.

The chapter is organized as per the following; Section 6.3 discusses the considered system's schematic, its related component ratings and their respective modeling. The converter control for RSC along with the integrated grid feeding and FF-ANFIS based LVRT control for the GSC is deliberated in Section 6.4. The related control for various dc-dc converters interfaced with SC, FC and ELZ are also discussed in this section. Section 6.5 describes the considered reduced rule based central PMC responsible for actuating the magnitude of power references for SC, FC and ELZ. The validation of discussed control philosophies in the considered HES is showcased in Section 6.6 under various generation, demand and grid fault conditions. Finally, the important conclusions are drawn in Section 6.7.

6.3 System's Configuration, Component Ratings and Mathematical Modeling

The considered system is shown in Fig. 6.1. The system is configured in such a way that it is intended to meet the maximum demand of 15 kW for its local loads. At the same time, it must meet the demand of 5 kW of renewable power obligation imposed by the grid operator. The DFIG delivers power from both the stator and rotor circuit during super synchronous mode of operation [115]. Therefore, the benefit of lower kVA rating requirement of RSC and GSC is realized in the hybrid system configuration with the use of a DFIG system.

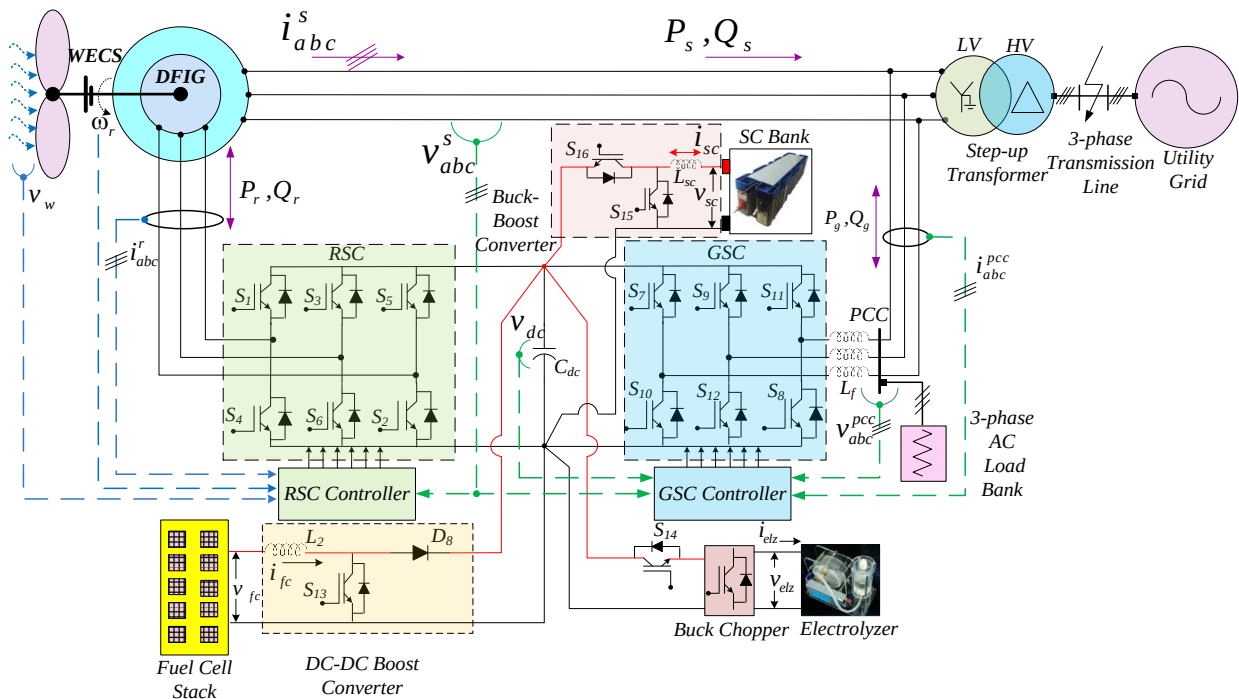


Fig. 6.1. DFIG based Grid connected hybrid system configuration.

FC and ELZ forms the H₂ energy support system where, FC helps in providing the long-term power backup in case of any power deficiency. While; the excess power if generated is absorbed by the ELZ. Fuel cells are characterized by the problem of slow starting time [103], and thus, it becomes an unsuitable candidate to meet the intermittent or transient power demands. In order to overcome this limitation, a SC is placed in the system. The SC is controlled by interfacing it with a bi-directional buck-boost converter. A switching mode selection-based control algorithm is utilised to enable the SC to meet the high frequency power demands. Simultaneously, the SC is also utilized as a compensating device during grid voltage sag events. The presented mode selection-based control for the SC assists in maintaining the smooth dc-link voltage profile under grid voltage sag events. Moreover, the control of GSC is strategically switched to a feed-forward based negative sequence current quenching mode during grid voltage sag thus, enhancing the LVRT capability of the overall system.

6.3.1 Modeling of WECS

The wind turbine is rated at 20 kW in order to fulfill the total demand of the chosen location (micro-grid). Considering a variation of slip between ± 0.3 in the DFIG, the power rating of DFIG P_{DFIG} is determined as per (6.1) where, P_{wt} is the wind turbine's rating, s_m is the maximum slip of the induction machine during generating mode. Considering converter power losses, the DFIG is rated marginally higher from the value obtained from (6.1) which is at 15.5 kW.

$$P_{DFIG} = \frac{P_{wt}}{1 + |s_m|} = \frac{20 \times 10^3}{1 + |-0.3|} = 15.38 \text{ kW} \quad (6.1)$$

The model of WECS comprises of a prime mover, gear box and a wind generator. The modeling of the gear box has been neglected for design simplicity, whereas the modeling of wind turbine is as per (3.1) discussed in Section 3.2. The output of the wind turbine drives the wind generator which is a DFIG for the considered system. The modeling of DFIG is done in synchronously rotating reference frame as per (3.9)- (3.19) which was discussed in Section 3.2.3.

6.3.2 Modeling of PEMFC

The considered hybrid system requires a constant generation of 5 kW as back up in order to meet its renewable power obligation towards the utility grid. Consequently, suitable series and parallel arrangements of a 1.2 kW PEMFC stack is done in order to build an entire 5 kW

PEMFC array. The modeling of stack is done as per the modeling equations (3.20) -(3.21) detailed in Section 3.3.

6.3.3 Modeling of SC

SCs are characterized by rapid transient response, low start up time, large power density, rapid discharging and charging cycles and does not require of extra cryogenic cooling systems as in case of a super-conducting energy storage device [155]-[156]. The sizing of SC is done by considering the fact that, it must support the transient power demand up to 5 kW from the load or grid for a minimum span of 10 s. The terminal voltage across the SC bank is considered as 300 V. The sizing equation is as per (6.2) [9], where, C_{sc}^{bank} denotes the capacitance of the resultant SC bank, P_{sc} is the power demand from the SC bank, t_1 is the duration of backup in s, v_{term}^{sc} is the rated terminal voltage of the SC bank.

$$C_{sc}^{bank} = \frac{2 \times P_{sc} \times t_1}{(v_{term}^{sc})^2} = \frac{2 \times 5 \times 10^3 \times 10}{300^2} = 1.12 \text{ F} \quad (6.2)$$

The modeling of SC is done via the utilization of the equivalent circuit discussed as per Fig. 3.3 and as per the modeling equations (3.25) -(3.26) detailed in Section 3.5.

6.3.4 Modeling of Electrolyzer

The 6 kW ELZ forms the supporting system for the PEMFC where, H_2 gets generated when the WECS generates excess power. The cell voltage and current relation in an ELZ is and the related modeling relations are as per (3.27) -(3.30) detailed in Section 3.7.

6.4 Control of Various Converters used in the Hybrid Energy System

This section discusses the control techniques adopted for the various interfacing power electronic converters used in the considered grid-connected hybrid system. At first, the controls of converters used in DFIG-WECS namely RSC and GSC are discussed. Thereafter, the controllability of GSC for integrated grid feeding and LVRT mode is presented, while; the control of dc-dc converters interfaced with SC, FC and ELZ are discussed subsequently.

6.4.1 Control Algorithm for RSC

The objective of RSC is to control the active and reactive power from the DFIG stator terminals. In this work, stator voltage-oriented control (VOC) is selected for the control of power since VOC has the flexibility of easy estimation of stator voltage space vector [159]. In VOC, the d -axis of the reference frame is aligned along stator voltage position, as a result, the

term $v_{qs}=0$. The control of stator active power and reactive power is directly proportional to i_{dr} and i_{qr} respectively. The controller consists of an outer loop responsible for MPPT and reactive power control in the WECS. The first outer loop derives the reference d -axis rotor current i_{dr}^* after the error between reference rotor speed ω_r^* and actual rotor speed ω_r is processed by the PI controller. The MPPT block generates ω_r^* based on the magnitude of wind speed v_w , turbine radius r and the optimum tip speed ratio λ_{opt} of the wind turbine. The second outer loop derives the value rotor q -axis reference current i_{qr}^* by processing the error between reference reactive power Q_s^* and actual reactive power Q_s via a PI controller. In this presented work, an effort is made to integrate the FRT capability in DFIG via a modified RSC control which is depicted as per Fig. 6.2.

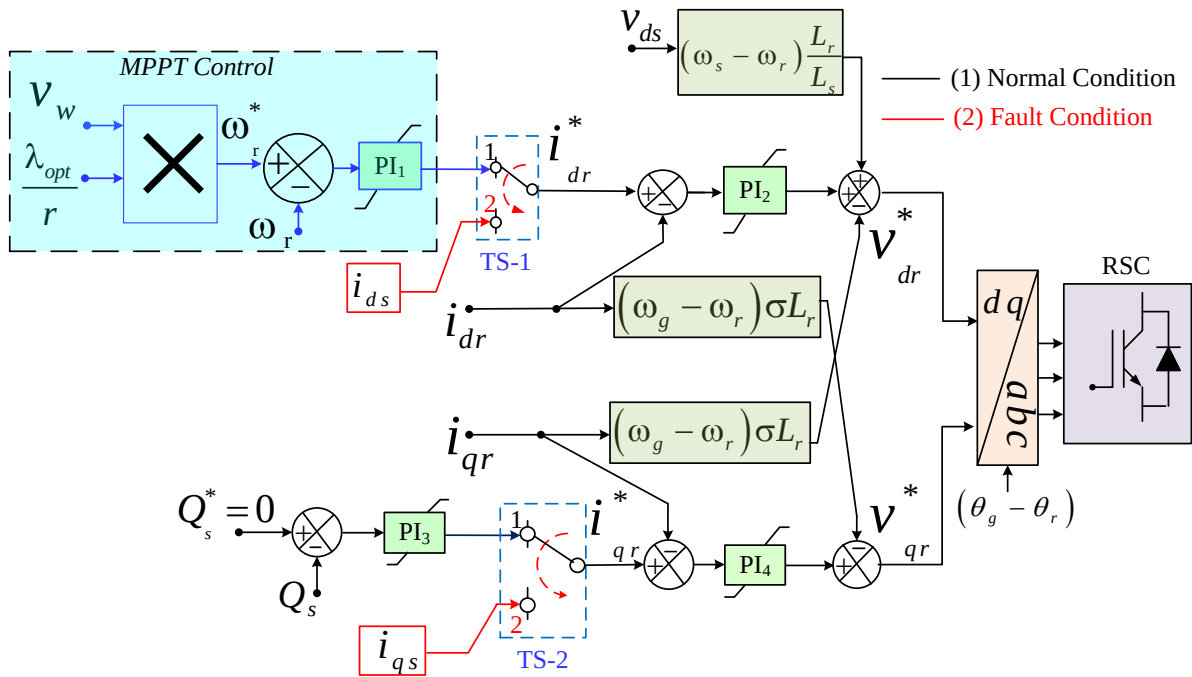


Fig. 6.2. Control of the RSC during normal condition and during fault.

Firstly, when fault is detected, the toggle switches TS₁ and TS₂ makes a switching from their normal position ‘1’ to position ‘2’ which denotes the fault condition. This control process helps in minimisation of generator’s electromagnetic torque T_e as it tries to reduce its magnitude to zero under the faulted span. The toggle switches TS₁ and TS₂ in the inner control loop sets the current references i_{dr}^* and i_{qr}^* equal to i_{ds} and i_{qs} respectively. When the currents i_{dr}

and i_{qr} of the rotor are regulated to the new reference value set by TS₁ and TS₂, the magnitude of stator's electromagnetic torque can be pulled down towards zero which is justified as per (6.3) [166].

$$T_e = 1.5L_m (i_{qs}i_{dr} - i_{ds}i_{qr}) \quad (6.3)$$

6.4.2 GSC Control Algorithm

The objective of GSC is to exchange the dc-link power with the grid, to maintain the dc-link voltage and also to participate in providing ancillary service if desired. In this work, the discussed GSC control algorithm is used to facilitate the power exchange between the hybrid generation, local loads and grid. An ancillary facility of LVRT is incorporated by the incorporation of new ANFIS based FF current controller. The idea of using the better regulation capability of ANFIS control is utilised in this work. The proposed GSC control is established as per Fig. 6.3 where, the purpose of the '*grid feeding reference current generation block*' is to facilitate active power exchange between the GSC and the utility grid. Further, the '*current reference generation block during grid fault*' renders the LVRT capability via an integrated FF-ANFIS based current controller. This controller is solely proposed to mitigate the power oscillations from the output of GSC, deliver balanced currents at the PCC, limits the over currents at the PCC during grid voltage sag events by regulating the current references via the ANFIS based control.

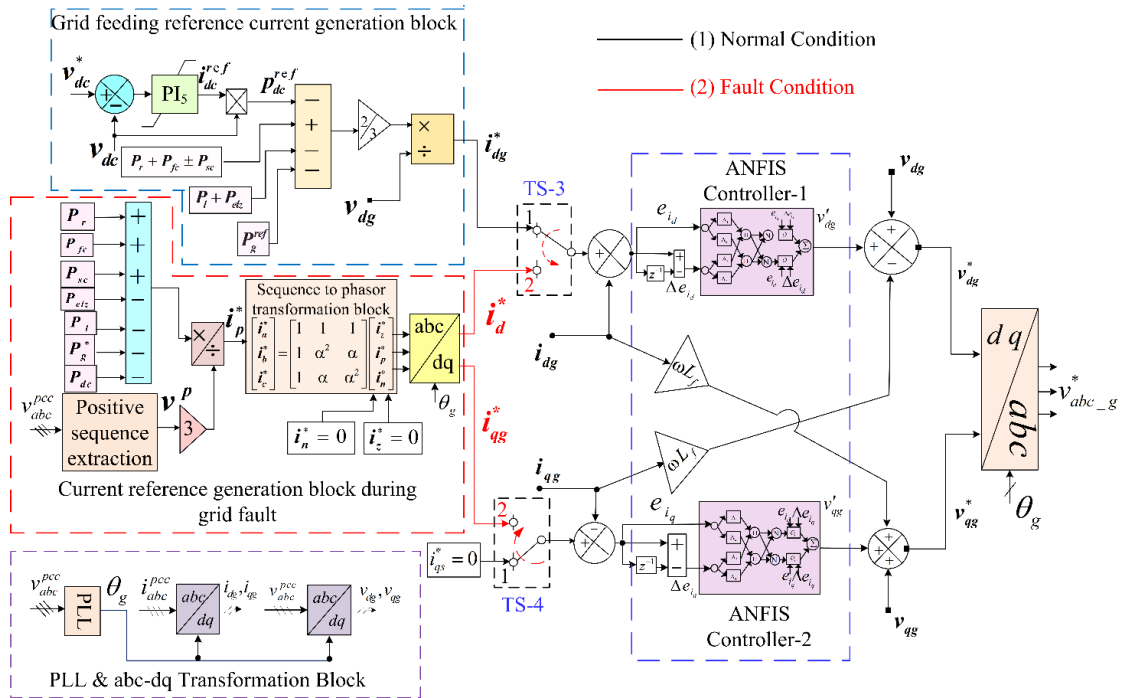


Fig. 6.3. Control of the GSC during normal condition and during fault.

6.4.2.1 Grid Feeding Reference Current Generation Block

The grid feeding mode of inverter control is adopted for the GSC in order to effectually evacuate the required power from the HES to the load and grid. The current control is established in the SRF where, the control of d -axis current controls the active power from the GSC. This d -axis current reference is calculated as per the system's power balance equation (6.4), where, P_{fc} denotes the power delivered by fuel cell, P_{sc} is the power generated or absorbed by the SC, P_{elz} is the power dumped to the ELZ, P_l is the power delivered to the load, P_g^{ref} is the fixed power demanded from the grid operator, P_{dc} is power flowing through the dc-link and P_{inv} refers to the power dispatched by the GSC respectively.

$$P_r + P_{fc} \pm P_{sc} = P_{elz} + P_l + P_g^{ref} + P_{dc} + P_{inv} \quad (6.4)$$

The dc-link power is regulated by a dc-link PI controller to a fixed value denoted by P_{dc}^{ref} , while the power delivered by the GSC is articulated as per (6.5),

$$P_{inv} = 3/2 (v_{dg} i_{dg} + v_{qg} i_{qg}) \quad (6.5)$$

where v_{dg} , v_{qg} refers to the voltage of the PCC transformed in dq - frame, similarly i_{dg} and i_{qg} refers to the PCC current referred in dq - frame. Since, i_{qg} is regulated to zero under normal condition, the required value of the d -axis reference current i_{dg}^* is determined as per (6.6).

$$i_{dg}^* = \frac{2}{3} \left\{ \frac{P_r + P_{fc} \pm P_{sc} - P_{elz} - P_l - P_g^{ref} - P_{dc}^{ref}}{v_{dg}} \right\} \quad (6.6)$$

6.4.2.2 Current Reference Generation Block During Grid Fault

The function of this block is to provide the current reference whenever the system operates in the LVRT mode during the occurrence of grid fault. The toggle switch TS₃ and TS₄ operates from their default position-1 to position-2 upon fault detection. The method for determining the new current references at position-2 is discussed now. The current reference generation block during grid fault generates the current references in such a manner such that the flow of negative sequence power is nullified. The d -axis current reference term of position-2 denoted by i_d^* is pushed to the summer block via TS₃ giving a feed-forward schematic. The resultant current reference is tracked by the ANFIS controller-1. A same methodology is adopted for the q -axis current reference as well where the switch TS₄ channelizes the current reference i_{qg}^* at position-2. This current reference is tracked by ANFIS controller-2. The

generation of current references i_d^* and i_{qg}^* is done as per the modeling equations (6.7) -(6.10). Here, the power balance is expressed in sequence components where v_p , v_n , v_z denotes the positive, negative and zero sequence voltage at the PCC respectively, while; i_p , i_n and i_z represents the positive, negative and zero sequence components of PCC current respectively. As the considered system is a 3-phase, 3-wire system the zero-sequence power component is inherently absent. The negative sequence power component is nullified which leads to the expression of desired positive sequence reference current i_p^* as per (6.8).

$$P_r + P_{fc} \pm P_{sc} - P_{elz} - P_l - P_g^{ref} - P_{dc} = 3 \times (v_p i_p + v_n i_n + v_z i_z) \quad (6.7)$$

$$i_p^* = \frac{1}{3} \left\{ \frac{(P_r + P_{fc} \pm P_{sc} - P_{elz} - P_l - P_g^{ref} - P_{dc})}{v_p} \right\} \quad (6.8)$$

For the ease of tracking this positive sequence current reference, it is transformed to corresponding d -axis and q -axis current references i_d^* and i_{qg}^* as per (6.9) -(6.10) after it has been transformed using the sequence to phasor transformation block and is pushed to the terminal-2 of switches TS₃ and TS₄ respectively.

$$i_d^* = \left(\frac{2}{3} \right) \left[\cos(\theta_g) \times i_p^* + \alpha^2 \times \cos\left(\theta_g - \frac{2\pi}{3}\right) \times i_p^* + \alpha \times \cos\left(\theta_g + \frac{2\pi}{3}\right) \times i_p^* \right] \quad (6.9)$$

$$i_{qg}^* = \left(\frac{2}{3} \right) \left[\sin(\theta_g) \times i_p^* + \alpha^2 \times \sin\left(\theta_g - \frac{2\pi}{3}\right) \times i_p^* + \alpha \times \sin\left(\theta_g + \frac{2\pi}{3}\right) \times i_p^* \right] \quad (6.10)$$

6.4.2.3 Current Reference Tracking by ANFIS Controller

The generated current reference as per (6.9) and (6.10) is made to track by ANFIS controllers and this resultant control arrangement is termed as “*FF-ANFIS based control*”. In fact, the intention of using an ANFIS controller is to ensure the effective tracking of the current references even during system dynamics. ANFIS control is a superior candidate as compared to the conventional PI control when the exact system’s mathematical model is hard to predict and the system encounters repeated dynamic conditions [162]-[163]. Meanwhile, an occurrence of grid fault is unpredictable, and it is characterized with varying magnitude. Thus, the utilization of ANFIS control is apt for the considered system in this work. In general, the ANFIS structure comprises of 5-layers whose elaborative details can be referred from [164].

As per Fig. 6.3, the training pattern for the neural net part of ANFIS is generated by simulating the GSC control using PI control instead of ANFIS controller for different fault types and voltage dip level. A total set of 15 different training data is obtained for the purpose training data generation. This data is imported from the work space via using the neuro-fuzzy design application available in MATLAB software. Further, for the fuzzy rule-based section of ANFIS, gaussian membership functions (MF) are selected, and rules base is evaluated using Takagi-Sugeno fuzzy inference system model. The conventional error back propagation algorithm assists in the adjustment of the MF's span. The output of ANFIS controller -1, 2 are v_{dg}^* and v_{qg}^* respectively. The d -axis reference current i_d^* is tracked by ANFIS controller-1, while the reference current of q -axis as per (6.10) is tracked by ANFIS controller-2. A brief model of the proposed ANFIS control in this work is discussed in brief. The inputs to ANFIS controller-1 are error and change in error of the d -axis current denoted as per (6.11); where, $e_{dq}(k)$ denotes the error of d -axis or q -axis current at the k^{th} instant, while $\Delta e_{dq}(k)$ represents the change of error of the corresponding quantity.

$$\left. \begin{aligned} e_d(k) &= i_d^*(k) - i_{dg}(k) \\ \Delta e_d(k) &= e_d(k) - e_d(k-1) \end{aligned} \right\} \quad (6.11)$$

The inputs to the ANFIS controller-2 are error and change in error of the q -axis current denote as per (6.12);

$$\left. \begin{aligned} e_q(k) &= i_{qg}^*(k) - i_{qg}(k) \\ \Delta e_q(k) &= e_q(k) - e_q(k-1) \end{aligned} \right\} \quad (6.12)$$

where, $e_q(k)$ denotes the error of q -axis current at the k^{th} instant, while $\Delta e_q(k)$ represents the change of error of the corresponding quantity.

6.4.3 Control of Super Capacitor Interfaced Converter

In this work, a SC bank is utilized to perform dual tasks. Firstly, to support the transient power demand generated in the system. Secondly, the SC is additionally used to regulate the dc-link voltage during an occurrence of grid fault. Thus, the functionality of LVRT is also addressed by the SC. The recommended control for the SC-interfaced dc-dc converter facilitates the above tasks. Then the charging and discharging mechanisms can occur inside a SC system, a buck-boost converter is utilized for its interfacing with the dc-bus as shown in Fig. 6.1. The switch S_{16} denotes the buck switch and S_{15} is the boost mode switch. The discharge process of

SC is via the control of boost switch where power is transferred to the dc-bus, which is maintained at a higher voltage level with respect to the SC terminal voltage. A reverse operation is performed by the control of buck switch during charging process. The controller schematic is portrayed as per Fig. 6.4 where, the projected control scheme is capable to govern the SC so as to fill the transient power mismatch in the system. The SC current reference during normal mode i_{sc}^* is generated as per the power balance equation outlined as per (6.13).

$$P_{sc}^* = P_g^* + P_l - P_r - P_{fc} \quad (6.13)$$

The reference power of SC denoted by P_{sc}^* is determined from the PMC and then the corresponding current reference i_{sc}^* is generated by dividing P_{sc}^* with SC terminal voltage V_{term}^{sc} . The PI controller nullifies the error between i_{sc}^* and the actual SC current i_{sc} in order to generate the duty cycle D_{S16} and D_{S15} for the buck and boost switches respectively. It is to be noted that the SC must be operated within the nominal state SOC range which is between 20% to 80% under all conditions. This has been ensured by an AND logic gate in the control algorithm as per Fig. 6.5.

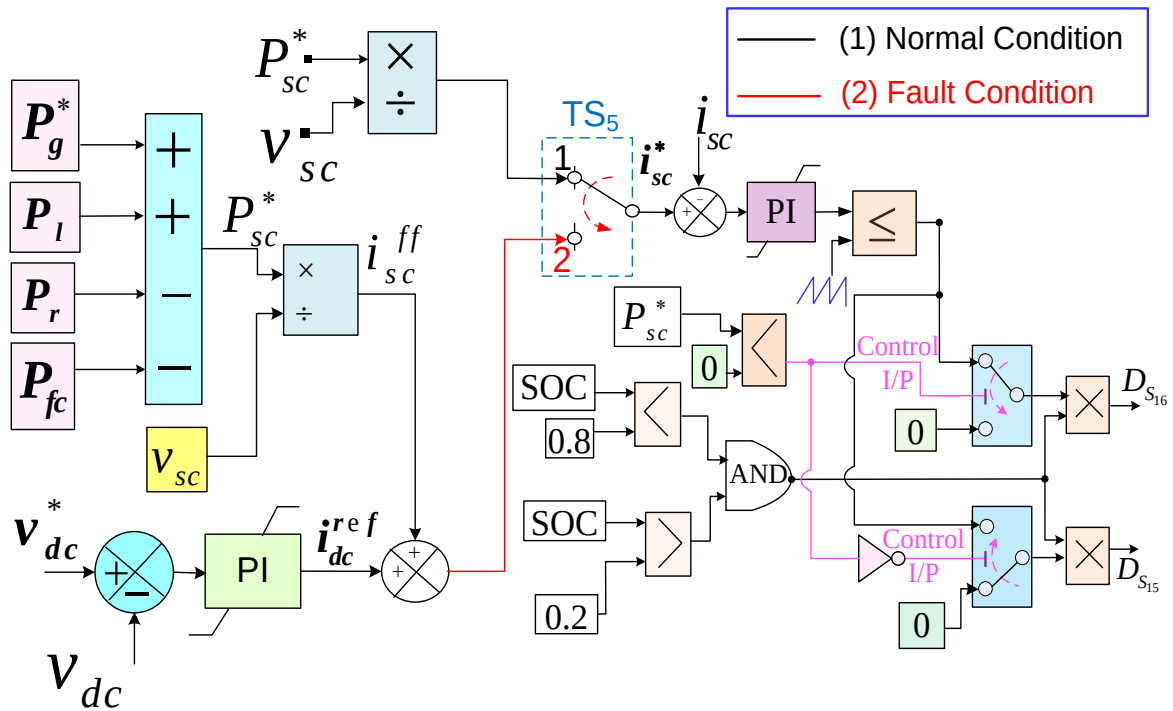


Fig. 6.4. Control of the SC-interfaced buck-boost converter.

For LVRT enhancement, a mode selection-based switching control is developed upon occurrence of voltage sag, which is performed by operating the toggle switch TS_5 . As shown in Fig. 6.4 from position-1 denoting normal condition to position-2 denoting fault condition.

As FF control schemes enhance the dynamic response of the control loop [165], an FF control schematic is adopted in the proposed control loop structure of the converter interfaced with SC. The SC assists in mitigating the dc-link voltage transients by generation of FF-current reference i_{sc}^{ff} as per (6.14). With the help of PI controller, the new current reference ($i_{dc}^{ref} + i_{sc}^{ff}$) is tracked in order to achieve the dc-link voltage regulation under fault condition.

$$\left. \begin{aligned} P_r + P_{fc} + P_{sc} &= P_{dc} + P_l + P_{elz} + P_g^* \\ i_{sc} v_{term}^{sc} &= (P_{dc} + P_l + P_{elz} + P_g^*) - (P_r + P_{fc}) \\ i_{sc} v_{term}^{sc} &= \left(v_{dc} C_{dc} \frac{dv_{dc}}{dt} + P_l + P_{elz} + P_g^* \right) - (P_r + P_{fc}) \\ i_{sc}^{ff} &= \frac{1}{v_{term}^{sc}} \left\{ (P_l + P_{elz} + P_g^*) - (P_r + P_{fc}) \right\} \end{aligned} \right\} \quad (6.14)$$

6.4.4 Control of Fuel-Cell Interfaced Converter

The FC is controlled by interfacing it with a boost converter whose control is structured as per Fig. 6.5. The current control scheme is placed for the FC interfaced dc-dc boost converter. The FC current reference i_{fc}^* is being tracked by the PI controller which in turn determines the duty cycle $D_{S_{13}}$ of the boost switch S_{13} by regulating the error between i_{fc}^* and FC current i_{fc} . The current i_{fc}^* is determined by dividing the FC terminal voltage v_{fc} with the power reference P_{fc}^* . The magnitude of i_{fc}^* is limited within its maximum and minimum limits denoted by i_{fc}^{max} and i_{fc}^{min} respectively. The determination of P_{fc}^* is as per the power management logic discussed in Section 6.5.

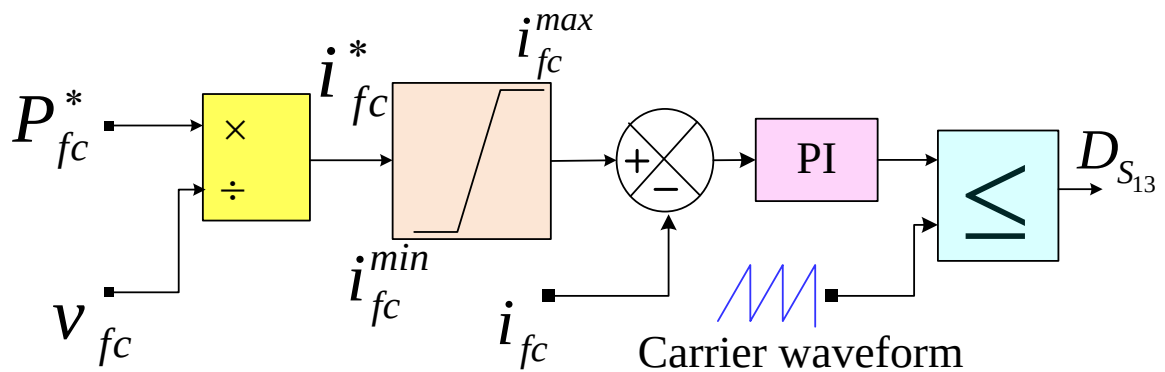


Fig. 6.5 Control of the fuel cell interfaced boost converter.

6.4.5 Control of Electrolyzer Interfaced Converter

The converter control for the electrolyzer (ELZ) is as per Fig. 6.6 where the switch S_{14} ensures that the ELZ operates only when the system has excess power. The sign convention of the net available power P_{net} in the system is utilized for the generation of duty ratio $D_{S_{14}}$ for the switch S_{14} . The purpose of the ELZ is to accept the excess available power generated by the DFIG-WECS. The buck converter control of ELZ ensures the tracking of the ELZ reference power P_{elz}^* indirectly by controlling the ELZ current i_{elz} with its reference value i_{elz}^* . The PI controller regulates the duty ratio D_{elz} of the buck converter by regulating the ELZ's current within the maximum and minimum rated value denoted by i_{elz}^{max} and i_{elz}^{min} respectively.

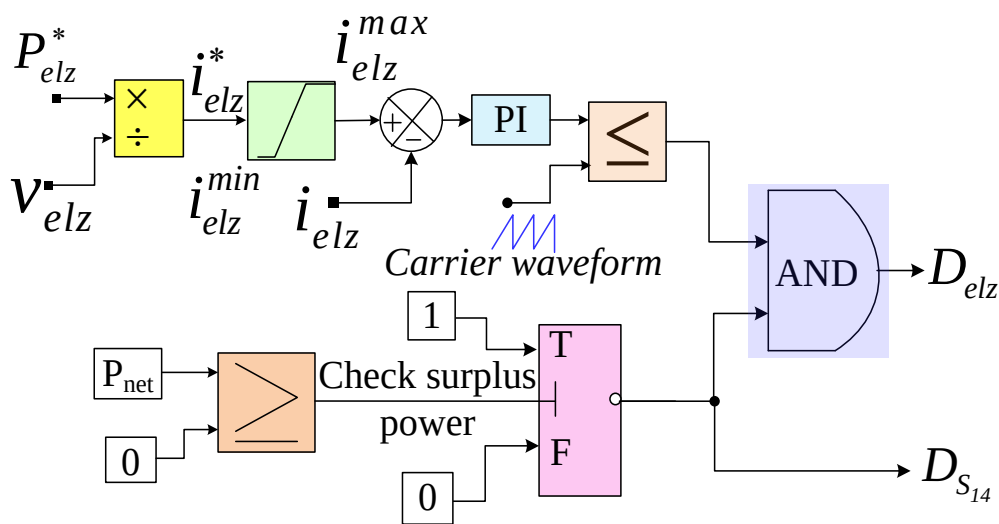


Fig. 6.6. Control of the buck converter and switch S_{14} interfaced with electrolyser.

6.5 Proposed Power Management Algorithm

A power management logic is being followed in order to derive the power references for the dc-dc converters interfaced with SC, FC and ELZ, it is detailed as per Fig. 6.7. It is assumed that the system holds sufficient generation to always cater the power request demanded by the grid operator P_g^* hence the condition of islanding mode of operation is not considered in the present scope of the study. Also, it is further assumed that the SOC of SC is well within its maximum and minimum limits of 20% and 80% respectively. As the load power dynamics is considered rapid, the SOC criteria is not considered for the algorithm. In this algorithm, input power quantities such as the power produced by DFIG P_{DFIG} , power demand of the grid operator P_g^* and the power demand of the load P_l are sensed. The difference between the

generated power of DFIG and the total demand is considered and is denoted by P_{diff} as per (6.15) which further guides the operating criterion of SC, FC and ELZ as per the following operating modes.

$$P_{diff} = (P_{DFIG}) - (P_g^{ref} + P_l) \quad (6.15)$$

- **Mode (a):** In this mode, the generated power from DFIG is lesser than the load and grid demand, and thus, FC and SC have to meet this deficit power. If this deficit power is not greater than the rated capacity of the FC denoted by P_{fc}^{rating} then FC is allowed to be operated to meet the power deficiency, while the remaining power is met by DFIG.
- **Mode (b):** In this mode, power deficiency exists in the system since the magnitude of P_{DFIG} is less than the total demand. The magnitude of the deficient power exceeds P_{fc}^{rating} . Thus, the FC is utilised up to its rating while the remaining power is supplied by the SC.

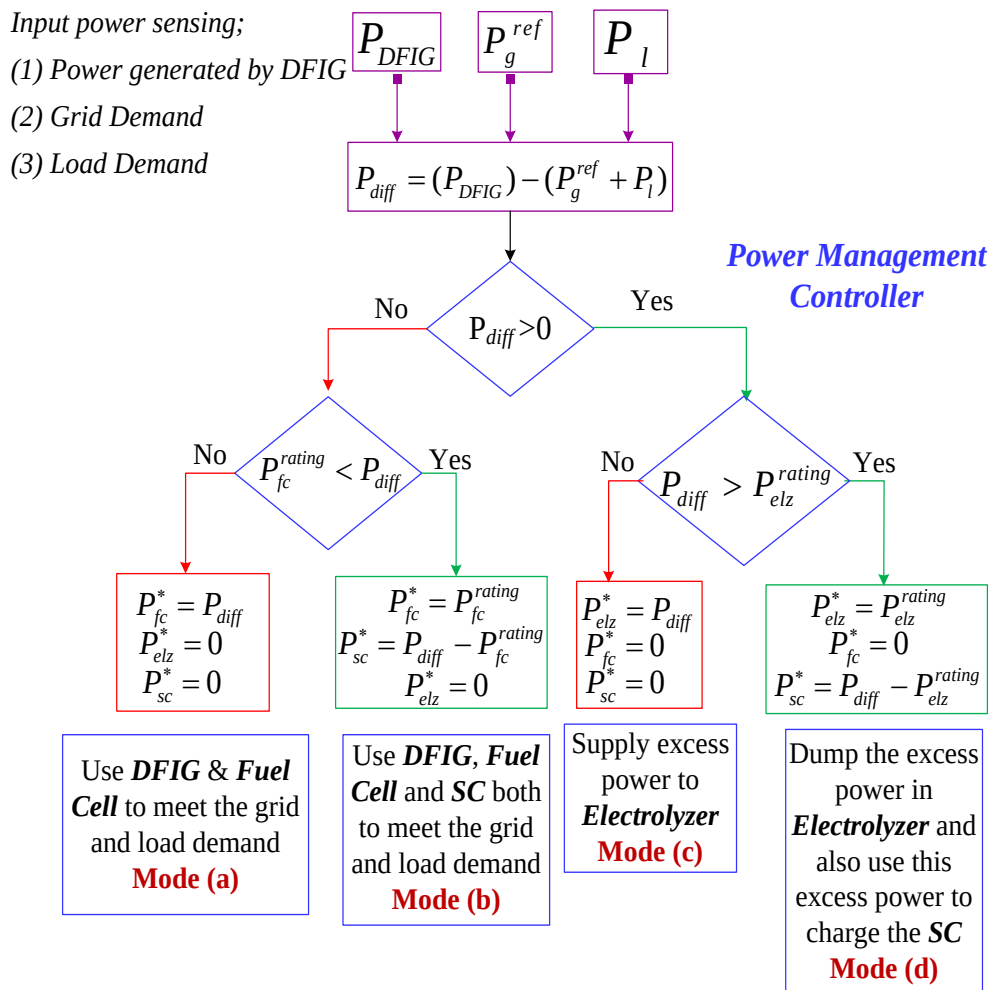


Fig. 6.7. Power management control logic.

- **Mode (c):** Under this mode, the power produced from DFIG is greater than the load and grid demand. Thus, the excess power which is available in the system is diverted either to ELZ or SC as per the following criteria. If the rating of the ELZ denoted as P_{elz}^{rating} is greater than the available excess power, then this particular power is absorbed by the ELZ else **Mode (d)** is selected.
- **Mode (d):** This is counter part of Mode (c), where the available excess power is greater than P_{elz}^{rating} . The ELZ absorbs the power up-to its rated power and the remaining power is used to charge the SC.

The flow chart as per Fig. 6.7 summarises all the above operating modes.

6.6 System's Performance Validation

The validation of the presented control algorithms is done in the MATLAB/Simulink environment using the Sim-power and ANFIS tool boxes. The system parameters are listed in Table. 6.1. Different types of case studies are undertaken and discussed in order to justify the effectiveness of the proposed PMC and LVRT control.

Table. 6.1
Parameters of DFIG-WECS based grid-connected hybrid system

DFIG-WECS	
Turbine power rating	20 kW
DFIG's power rating	15.5 kW
Radius of the turbine blade	R = 3.65 m
Optimal tip speed ratio	$\lambda_{opt} = 8.1$
Base wind speed, Pole pairs (p), Stator's terminal rated voltage	12 m/s, 3, 415 V
FC System	
FC array rating	5 kW
Single FC stack rating	1.26 kW
Stack's terminal voltage and current	24 V, 52.5 A
Number of series connected stack	4
SC Bank	
Single SC cell's voltage	2.7 V
Number of series connected unit cell	112
Temperature of each cell	25°C
Electrolyzer	
n= 64, T= 70 °C, A= 873 cm ² , $v_{therm} = 1.1647$ V, $r_1 = 1.5 \times 10^{-5} \Omega \text{ m}^2$, $r_2 = -6.019 \times 10^6 \Omega \text{ m}^2\text{C}$, $t_1 = 0.214 \text{ A}^{-1}\text{m}^2$, $t_2 = -9.870 \text{ A}^{-1}\text{m}^2\text{C}$, $t_3 = 119.1 \text{ A}^{-1}\text{m}^2\text{C}^2$	
Inverter control	
Simulation sample time	20 μs
Peak of line to ground magnitude of Base voltage	338 V
Switching frequency of the Inverter	20 kHz
Reference voltage of dc-link (V_{dc}^*)	680 V

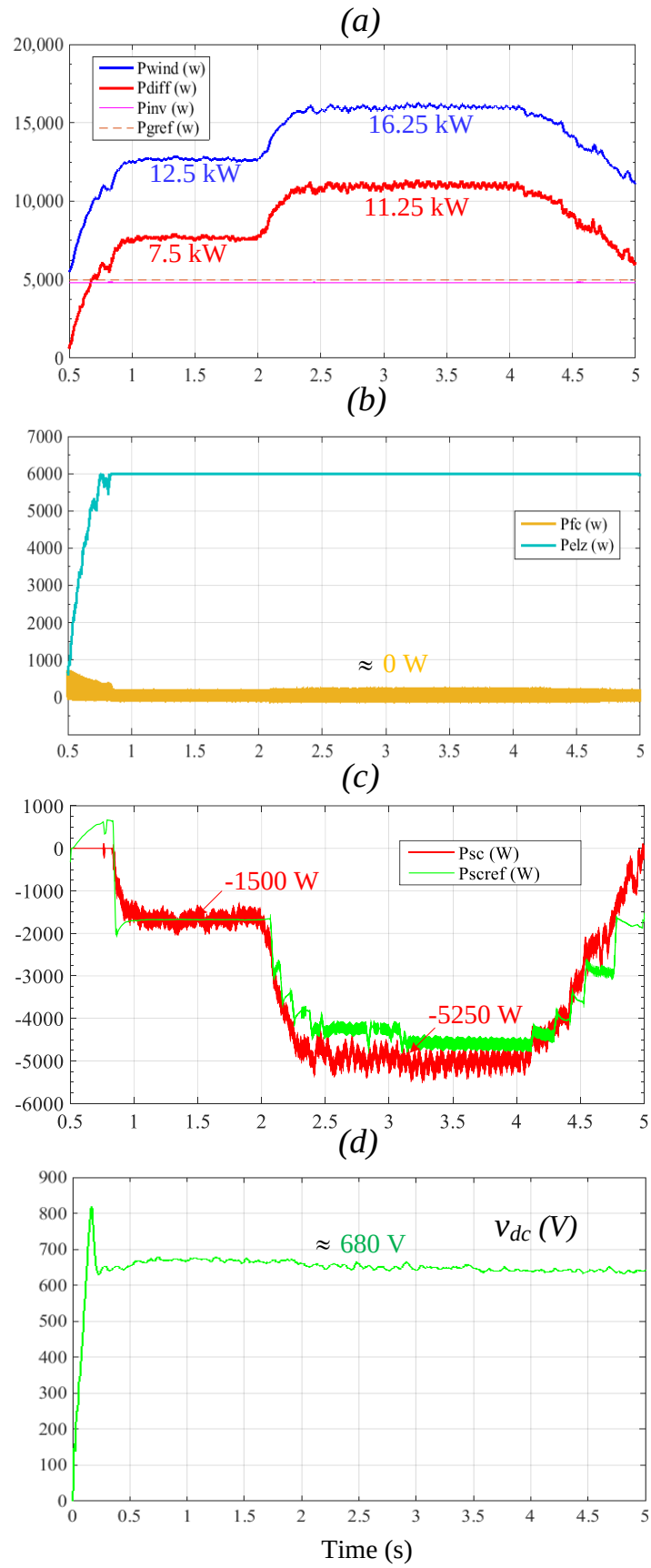


Fig. 6.8. Results for variable wind and constant grid demand; (a) P_{DFIG} , P_{diff} , P_{inv} , P_g^{ref} (b) P_{fc} , P_{elz} (c) P_{sc}^* , P_{sc} (d) V_{dc}

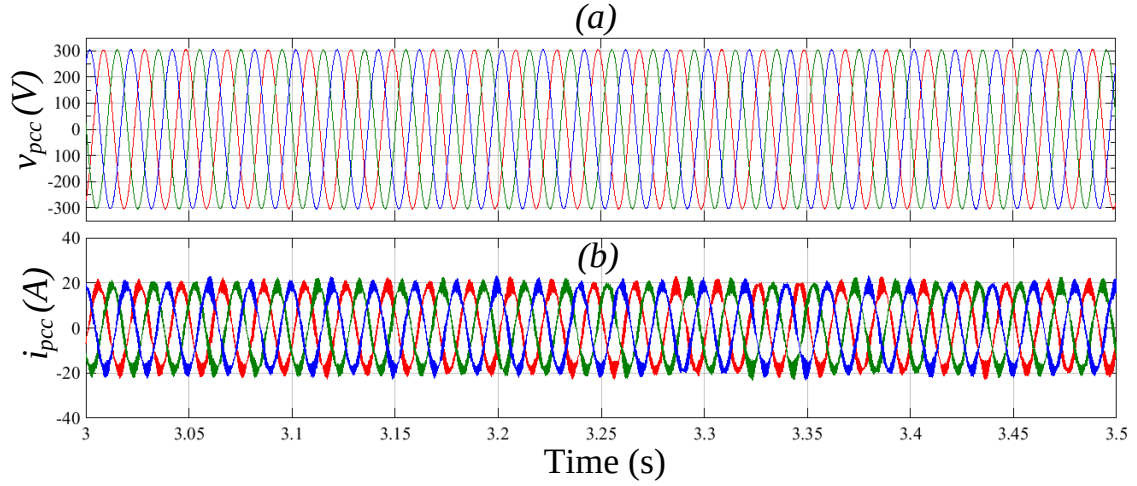


Fig. 6.9. Results for variable wind and constant grid demand (cont.); (a) v_{pcc} (b) i_{pcc} .

6.6.1 Case-(i): Variable Wind and Constant Grid Demand

The validation of power management controller (PMC) in the considered system is showcased by taking a situation where the power demand from the grid is kept constant at 5 kW but the generation from WECS varies. The objective of the proposed PMC is to maintain the power balance by applying the power management logic discussed as per Section. 6.5. As evident from Fig. 6.8 (a), the power generated by WECS is greater than the grid demand for the entire span of 5 s. However, the power imbalance is aptly nullified via the mutual coordination of SC and ELZ. The FC is turned OFF in this case as it does not contribute to the power balance process, while ELZ absorbs the excess power in the system up to its rating of 6 kW as per Fig. 6.8 (b). As the excess power is beyond the ELZ rating, it is diverted to SC and hence, the system operates in Mode (d). Since, the SC receives power, the sign convention of SC's active power is negative as per Fig. 6.8 (c). The apt regulation of dc-link voltage near to its reference value of 680 V as per Fig. 6.8 (d) also indicates the effective power balancing between the generation and demand in the considered hybrid system offered by the proposed PMC. The results shown in Fig. 6.9 (a) and Fig. 6.9 (b) represents the apt regulation of voltage and current at the PCC even during the power variations within the system.

6.6.2 Case-(ii): Variable Wind with Variable Load and Grid Demand

The proposed PMC's logic is also validated for variable wind generation, variable load and variable grid demand simultaneously. As per the results of Fig. 6.10 (a), the power profiles of WECS, load and grid demand are presented while the power difference in the system is registered as per (6.15).

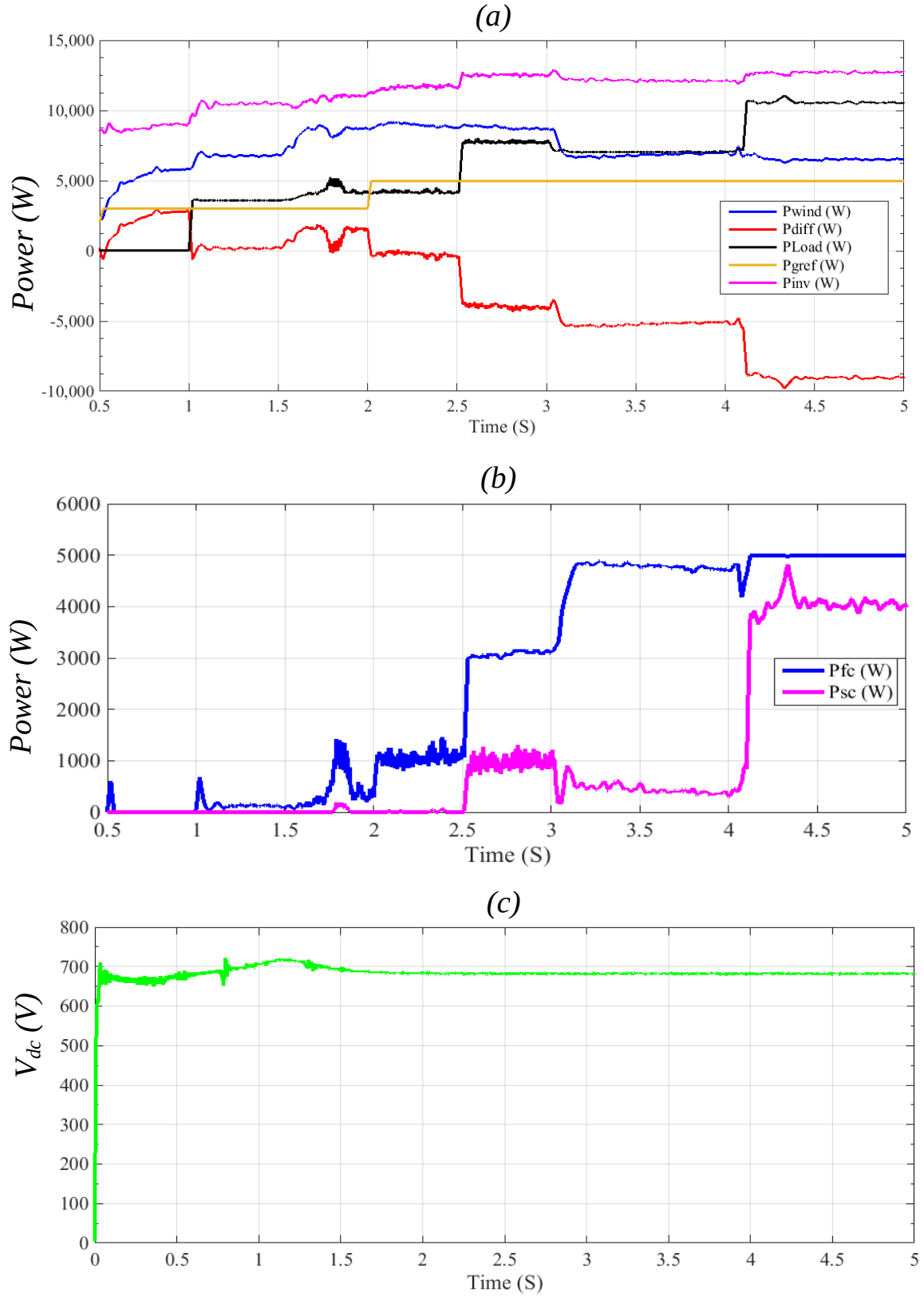


Fig. 6.10. Results for variable wind with variable load and grid demand; (a) P_{DFIG} , P_{diff} , P_{load} , P_g^{ref} , P_{inv} (b) P_{fc} , P_{sc} (c) v_{dc}

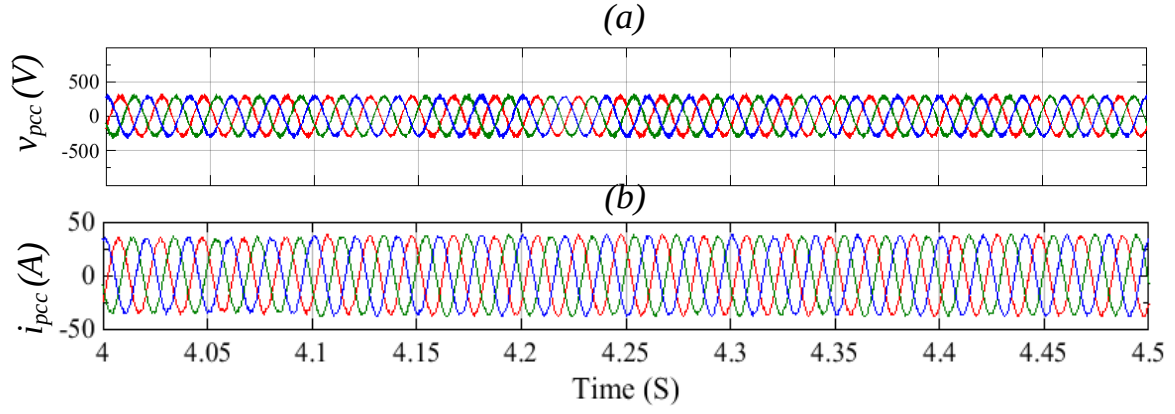


Fig. 6.11. Results for variable wind with variable load and grid demand (cont.); (a) v_{pcc} (e) i_{pcc}

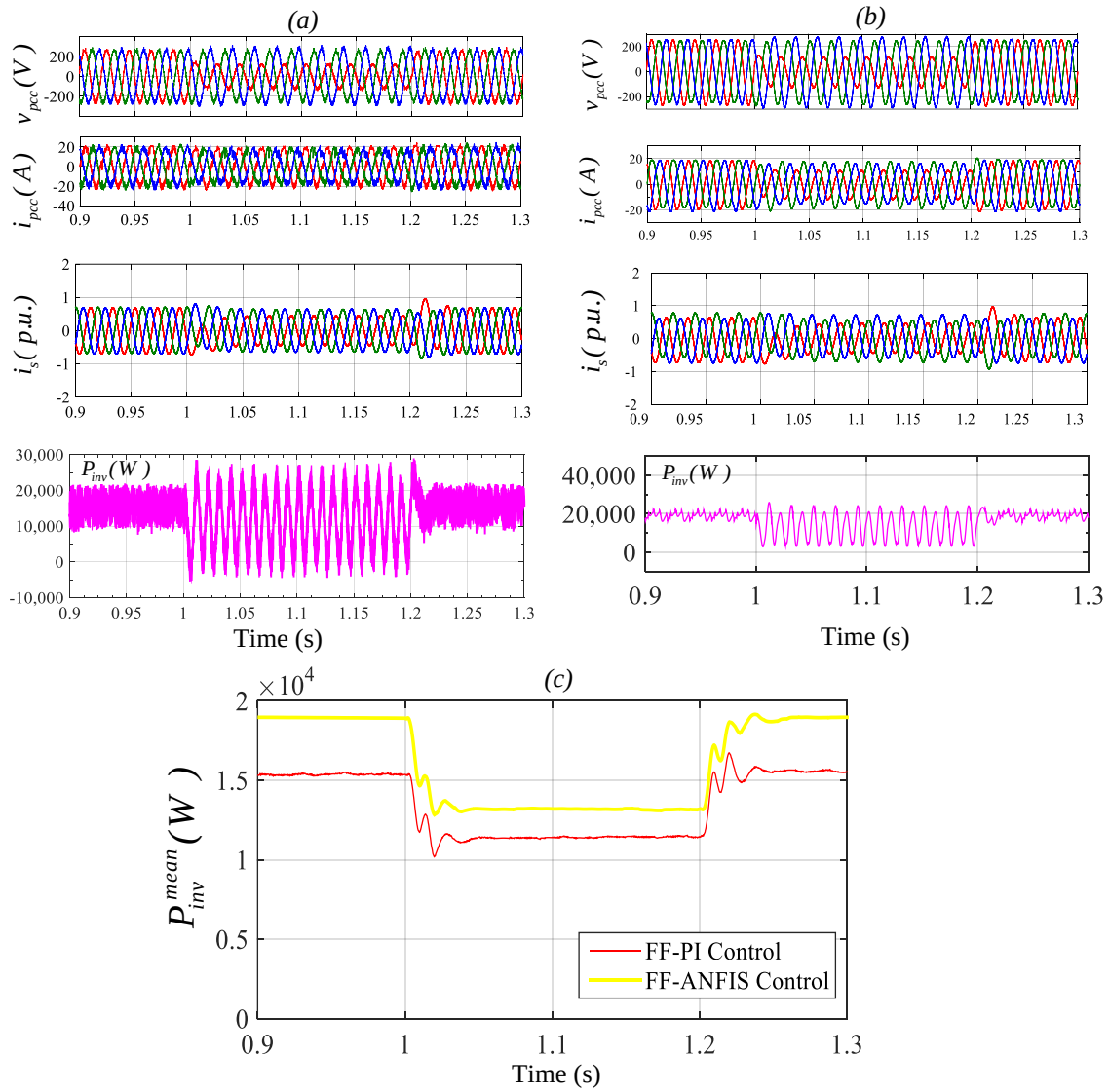


Fig. 6.12. Results for LVRT control validation under 1-phase sag; (a) v_{pcc} , i_{pcc} , i_s , P_{inv} with FF-PI control, (b) v_{pcc} , i_{pcc} , i_s , P_{inv} with FF-ANFIS control, (c) P_{inv}^{mean}

The GSC delivers its power P_{inv} as the sum of demand of load and grid. The power transitions are experienced at 1 s, 2.5 s, 3 s and at 4 s respectively. As per the profile of P_{diff} the system experiences power deficiency beyond 2.5 s. The sharing of power to meet this power deficiency is effective by the participation of SC and FC as per *Mode (b)* of the PMC. For instance, beyond 4.2 s, the power deficiency in the system is around 9 kW where 5 kW is supplied by the FC while the remaining power comes from the SC as evident from Fig. 6.10 (b). The profile of the dc-link voltage is as per Fig. 6.10 (c) while; the profile of PCC-voltages and currents are as per Fig. 6.11 (a)-(b) respectively which are well regulated within their set points.

6.6.3 Case-(iii): Operation Under 1-Phase Voltage Sag Condition

As the GSC is designed to unify the power feeding control and LVRT control, its validation for LVRT enhancement with the presented FF-ANFIS based current control discussed as per Section 6.4.2 is performed in this case. For validations, 1-phase and 2-phase sag conditions are simulated with a voltage sag of 50% for the span of 1 s- 1.2 s. In fact, a comparative validation between the FF-PI based and FF-ANFIS based LVRT control is depicted as per Fig. 6.12 (a)–(b) respectively in order to establish the efficacy of the proposed LVRT control in this chapter. In clearer terms, the result of Fig. 6.12 (a) is replicated when the ANFIS controller-1 & 2 as per Fig. 6.3 are replaced by PI controllers. The merits of FF-ANFIS LVRT control are exhibited in terms of more balanced PCC currents i_{pcc} and lesser oscillation for instantaneous active power delivered by the GSC P_{inv} at the PCC as per Fig. 6.12 (b). This is due to effective tracking of the current references and minimization of the negative sequence currents by the presented FF-ANFIS LVRT control. The profile for the mean value of GSC's active power P_{inv}^{mean} as per Fig. 6.12 (c) depicts that the drop in its magnitude is less in case of FF-ANFIS control as compared to the FF-PI control. This justifies the enhanced ride through capability attributed by the proposed FF-ANFIS control.

6.6.4 Case-(iv): Operation Under 2-Phase Voltage Sag Condition

The LVRT enhancement validation with the presented FF-ANFIS LVRT control is performed for 2-phase sag where voltage sag by 50% is simulated for phase-a and phase-b for the span of 1 s to 1.2 s. Fig. 6.13 (a) shows the ride through profile of the system when FF- PI control is applied while Fig. 6.13 (b) presents the ride through validation with the proposed FF-ANFIS control. Balanced PCC currents, less oscillation in the instantaneous power, lower dip in the mean value of GSC active power are the notable merits of the proposed FF-ANFIS-

LVRT control over the FF-PI-LVRT control. The profile of stator's terminal current i_s shown as per Fig. 6.13 (a)-(b) depicts its regulated behaviour even under fault span due to minimization of negative sequence current by the LVRT control action.

The profile of DFIG's electromagnetic torque T_e shows its minimization towards the null value as per Fig. 6.14 (a) due to the effective control action of RSC under the fault span as explained in Section 6.4.1. While the profile of systems dc-link voltage is well regulated with its reference value of 680 V as per Fig. 6.14 (b) even during the fault span which is due to the effective control of SC. In fact, the profile of T_e and v_{dc} are similar with both PI and ANFIS-LVRT control as the regulation of these quantities are dependent on the control functionality of RSC and SC respectively. Explicitly, it is concluded that a satisfactory LVRT behaviour is achieved in the considered system even under 2-phase sag with FF-ANFIS-LVRT control.

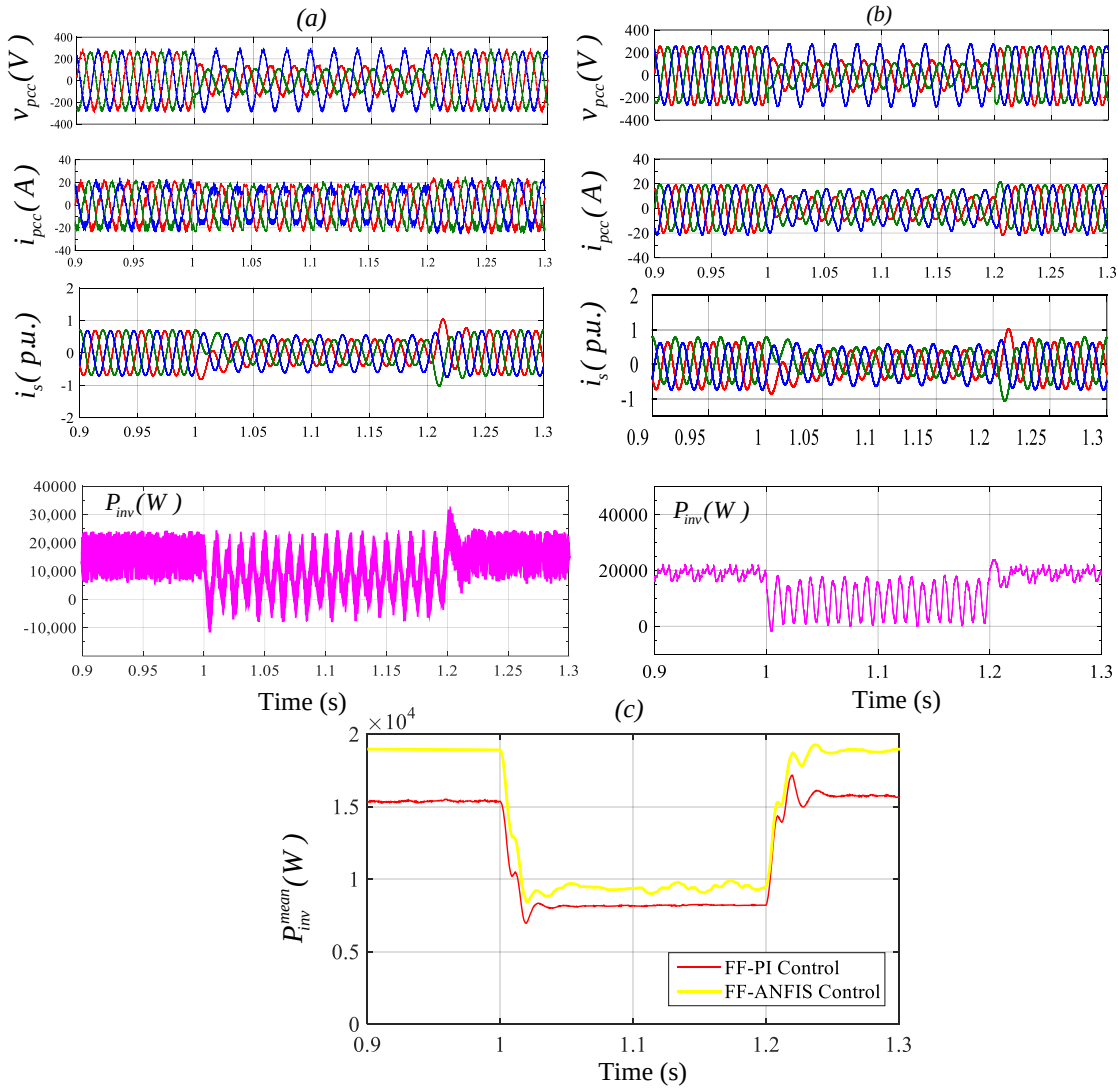


Fig. 6.13. Results for LVRT control validation under 2-phase sag; (a) v_{pcc} , i_{pcc} , i_s , P_{inv} with FF-PI control, (b) v_{pcc} , i_{pcc} , i_s , P_{inv} with FF-ANFIS control, (c) P_{inv}^{mean}

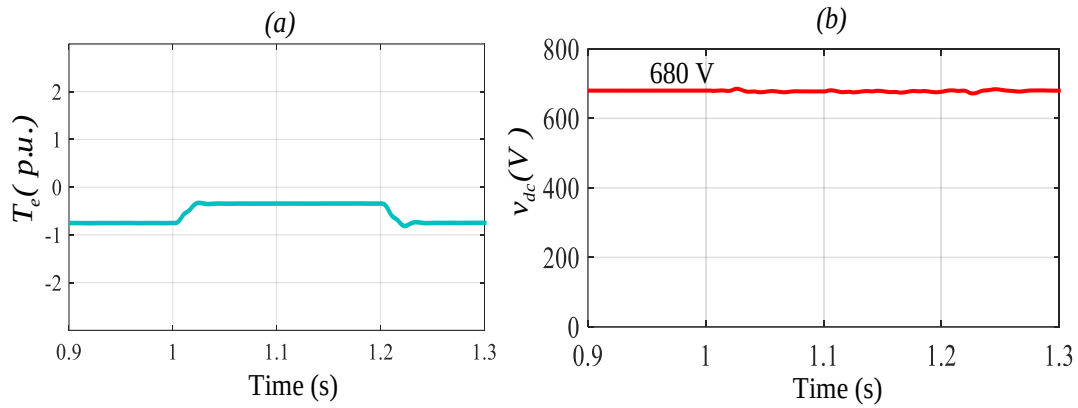


Fig. 6.14. LVRT control validation under 2-phase sag (cont.); (a) T_e , (b) v_{dc} .

6.7 Chapter Summary

The chapter presented a holistic approach to address the issue of power management control and LVRT control for a grid connected hybrid generation system considering DFIG based WECS as the primary source of power generation. The control coordination for regularized power dispatch is performed and validated with the utilization of reduced rule-based central power management algorithm. The power demand from utility grid operators is kept in priority in the discussed PMC, while; bearing four different operational modes. Further, the LVRT control is also unified into the system by the proposal of torque magnitude minimization through the RSC control, FF based control for the SC's dc-dc converter and also with the implementation of FF-ANFIS control at the GSC. Several simulation cases studies for varied power generation/ demand scenarios and also for varied voltage sag conditions demonstrated the validation of the proposed control algorithms for apt power management and LVRT enhancement of the considered system.

Conclusion and Future Scope

7.1 Conclusion

This thesis has considered different feasible architectures of hybrid sustainable energy systems (HSES). In all the considered HSES, wind energy has been considered as the primary source of power generation and fuel-cell is used as an important backup source. The major contributions of this research work are to equip the presented HSES with new control schemes for realizing low voltage ride through (LVRT) capability and for performing power management control. The objectives set towards design, modeling, control and for investigation under fault conditions are successfully achieved in the considered hybrid system architectures. All the hybrid system architectures are termed sustainable as these systems meet the power demand of present and future electrical loads. The concept of hybridization of one or more backup sources with renewable energy generators proved to be a promising solution for enhancing the reliability, efficiency and energy security. In all the hybrid energy system models, WECS is an integral choice for the primary power generator while; FC is an essential back-up source. The grid integration of HSES reveals control challenges towards LVRT and power management. Thus, this research work focused towards the methodologies of design, modeling and control of HSES. Prime contributions have been made towards LVRT control and power management control in various grid integrated hybrid system architectures. PMSG based WECS and DFIG based WECS are selected as primary energy source while; hybrid storage in form of either PEMFC-Electrolyzer-Battery or PEMFC-Electrolyzer-SC are utilized for achieving sustainable power from the proposed hybrid energy systems. The suggested power management schemes demonstrated satisfactory performance for various generation and loading conditions. Also, the LVRT enhancement schemes exhibited a good ride through behavior under various voltage sag conditions.

The major contributions of this research are briefed as follows:

- **Design & Modeling:** The methodologies essential to design and model a stand-alone and grid connected HES are presented successfully. Brief and significant discussions on the aspect of inverter control are also given. Preliminary and comparative investigations under ideal and fault conditions in HES helped to identify various technical challenges towards the control of HES.

- LVRT Enhancement Strategies:

(a) The proposal of feed-forward (FF) based FRT control, combined FF and fuzzy logic based FRT control achieved the LVRT enhancement in hybrid PMSG-WECS/PEMFC system. The combined FF-fuzzy FRT controller has been proved to be an improved choice than the conventional dq - controller or by only applying FF- FRT control. Justifications have been showcased by categorically comparing the system performance during 1-phase, 2-phase and 3-phase voltage sag. Also, the system's performance during simultaneous wind speed variation and symmetrical fault is found satisfactory with the proposed control. Important results implicated that, the surge in dc-link voltage, dip and ripples in the active power profile and negative sequence current in the system are minimised. Further, a smooth profile of the PMSG electromagnetic torque under the voltage sag conditions proved to be an additional merit of this enhancement scheme.

(b) Multi-dimensional LVRT enhancement strategies are performed in grid integrated DFIG/SC/FC-electrolyzer system. The strategies include the application of FF-ANFIS based control for GSC. New control schemes for the dc-dc converter interfaced with SC and WECS. The improvement in LVRT capability of this hybrid system is justified for several simulation-based case studies for varied voltage sag conditions.

- Power Management Strategies:

(a) The dynamic rule-based power management controller for a grid integrated PMSG/FC-Electrolyzer-Battery hybrid system exhibits the efficacy of developed power management control. The reduction in the number of *if-else* cases for determining the dynamic power-references shows smooth transient response in achieving power balance in the system. The power demand from the grid operator is also considered for designing the power management controller. Along with the power sharing control, a dynamic FF based LVRT control scheme is successfully embedded with the control of grid-interfaced VSI in the considered PMSG/FC-Electrolyzer-Battery based HES.

(b) A reduced rule-based central power management controller is successfully presented and validated for a grid integrated DFIG/FC-Electrolyzer-SC based hybrid system. The control coordination for regularized power dispatch and the generation of

power references is performed by the mutual operation of power management controller and various dc-dc converter control in the system. The LVRT control based on FF-ANFIS based current control is effectively unified with the central controller. Exhaustive simulation-based case studies demonstrate the efficacy of proposed power management strategies for the considered HES.

7.2 Future Scope of Research

The research work is significant, as the aspect of LVRT enhancement and unification of power management schemes in hybrid energy systems helps in establishing a reliable and sustainable power generation system. However, the identified challenges in this research work opens up some broader opportunities of research which are detailed as per the following:

- Consideration of real time yearly power generation and demand profile towards the validation of power management algorithms requires enormous computational algorithms. This aspect can be investigated further.
- Validation of control algorithms in real time simulators and in experimental hardware-based test beds.
- Hybrid system has varied operating points, thus application of advanced control like model predictive control could be a promising towards control enhancement in hybrid energy systems.

References

- [1] D. Rekioua, *Hybrid Renewable Energy Systems: Optimization and Power Management Control*, Switzerland: Springer Nature, 2019.
- [2] M. K. Deshmukh and S. S. Deshmukh, "Modeling of hybrid renewable energy systems," *Renew. Sustain. Energy Rev.*, vol. 12, pp. 235-249, Jan. 2008.
- [3] S. Hajiaghahi, A. Salemnia, and M. Hamzeh, "Hybrid energy storage system for microgrids applications: A review," *J. Energy Storage*, vol. 21, pp. 543-570, Feb. 2019.
- [4] M. H. Nehrir *et al.*, "A review of hybrid renewable/alternative energy systems for electric power generation: configurations, control, and applications," *IEEE Trans. Sustain. Energy*, vol. 2, no. 4, pp. 392-403, Oct. 2011.
- [5] M. Dali, J. Belhadj, and X. Roboam, "Hybrid solar-wind system with battery storage operating in grid-connected and standalone mode: Control and energy management – Experimental investigation," *Energy*, vol. 35, no. 6, pp. 2587-2595, Jun. 2010.
- [6] F. Blaabjerg, Z. Chen, and S.B. Kjaer, "Power electronics as efficient interface in dispersed power generation systems," *IEEE Trans. Power Electron.*, vol. 19, no. 5, pp. 1184-1194, Sep. 2004.
- [7] K. S. Krishna and K. S. Kumar, "A review on hybrid renewable energy systems," *Renew. Sustain. Energy Rev.*, vol. 52, pp. 907-916, Dec. 2015.
- [8] Y. J. Reddy, Y. V. P. Kumar, K. P. Raju, and A. Ramsesh, "Retrofitted hybrid power system design with renewable energy sources for buildings," *IEEE Trans. Smart Grid*, vol. 3, no. 4, pp. 2174-2187, Dec. 2012.
- [9] X. Liu, P. Wang, and P. C. Loh, "A hybrid AC/DC microgrid and its coordination control," *IEEE Trans. Smart Grid*, vol. 2, no. 2, pp. 278-286, Jun. 2011.
- [10] *IEEE Interconnecting Distributed Resources with Electric Power Systems*, IEEE Standard 1547, 2003.
- [11] M. Tsili and S. Papathanassiou, "A review of grid code technical requirements for wind farms," *IET Renew. Power Gener.*, vol. 3, no. 3, pp. 308-332, Sept. 2009.
- [12] K. Ma, W. Chen, M. Liserre, and F. Blaabjerg, "Power controllability of a three-phase converter with an unbalanced ac source," *IEEE Trans. Power Electron.*, vol. 30, no. 3, pp. 1591-1604, Mar. 2015.
- [13] *Central Electricity Regulatory Commission Ministry of Power Government of India (Indian Electricity Grid Code)* New Delhi, Apr. 2010.
- [14] P. Basak, S. Chowdhury, S.H. Dey, and S.P. Chowdhury, "A literature review on integration of distributed energy resources in the perspective of control, protection and stability of micro-grid," *Renew. Sustain. Energy Rev.*, vol. 16, pp. 5545-5556, Oct. 2012.
- [15] Central Electricity Authority, (2020 Nov.), Installed capacity report. [Online]. Available: <https://cea.nic.in/installed-capacity-report/?lang=en>
- [16] C. N. Bhende, S. Mishra, and S. G. Malla, "Permanent magnet synchronous generator- based standalone wind energy supply system," *IEEE Trans. Sustain. Energy*, vol.2, no.4, pp. 361-373, Oct. 2011.
- [17] B. Subudhi and R. Pradhan, "A Comparative Study on Maximum Power Point Tracking Techniques for Photovoltaic Power Systems," *IEEE Trans. Sustain. Energy*, vol. 4, no. 1, pp. 89-98, Jan. 2013.
- [18] M. Hussein, T. Senjyu, M. Orabi, M. Wahab, and M. Hamada, "Control of a stand-alone variable speed wind energy supply system," *Applied Sciences*, vol. 3, no. 2, pp. 437-456, Apr. 2013.
- [19] N. Mendis, K. M. Muttaqi, S. Sayeef, and S. Perera, "Standalone operation of wind turbine-based variable speed generators with maximum power extraction capability," *IEEE Trans. Energy Convers.*, vol. 27, no. 4, pp. 822-834, Dec. 2012.

- [20] S. Muller, M. Deicke, and R. W. De Doncker, "Doubly fed induction generator systems for wind turbines," *IEEE Ind. Appl. Magazine*, vol. 8, no. 3, pp. 26-33, Jun. 2002.
- [21] V. C. Ganti, B. Singh, S. K. Aggarwal, and T. C. Kandpal, "DFIG-based wind power conversion with grid power levelling for reduced gusts," *IEEE Trans. Sustain. Energy*, vol. 3, no. 1, pp. 12-20, Jan. 2012.
- [22] A. Hamadi, S. Rahmani, K. Addoweesh, and K. Al-Haddad, "A modeling and control of DFIG wind and PV solar energy source generation feeding four wire isolated load," *39th Annual Conf. IEEE Indus. Electron. Society*, Vienna, 2013, pp. 7778-7783.
- [23] A. Kadri, H. Marzougui, A. Aouiti, and F. Bacha, "Energy management and control strategy for a DFIG wind turbine/fuel cell hybrid system with super capacitor storage system," *Energy*, vol. 192, Feb. 2020.
- [24] L. W. Chong *et al.*, "Hybrid energy storage systems and control strategies for stand-alone renewable energy power systems," *Renew. Sustain. Energy Rev.*, vol. 66, pp. 174-189, Dec. 2016.
- [25] N. Mendis, K. M. Muttaqi, and S. Perera, "Management of low- and high-frequency power components in demand-generation fluctuations of a DFIG-based wind-dominated RAPS system using hybrid energy storage," *IEEE Trans. Indus. Appl.*, vol. 50, no. 3, pp. 2258-2268, Jun. 2014.
- [26] F.J. Vivas, A. De las Heras, F. Segura, and J.M. Andújar, "A review of energy management strategies for renewable hybrid energy systems with hydrogen backup," *Renew. Sustain. Energy Rev.*, vol. 82, pp. 126-155, Feb. 2018.
- [27] J. Larminie and A. Dicks, *Fuel Cell Systems Explained*, 2nd edn., Chichester, U.K: Wiley, 2003.
- [28] C. Wang, M.H. Nehrir, and S.R. Shaw, "Dynamic models and model validation for PEM fuel cells using electrical circuits," *IEEE Trans. Energy Convers.*, vol. 20, no. 2, pp. 442- 451, Jun. 2005.
- [29] C. Wang and M.H. Nehrir, "A physically based dynamic model for solid oxide fuel cells," *IEEE Trans. Energy Convers.*, vol. 22, no. 4, pp. 887-897, Dec. 2007.
- [30] G. R. Biswal, R. P. Maheshwari, and M. L. Dewal, "Modeling, control and monitoring of S3RS-based hydrogen cooling system in thermal power plant," *IEEE Trans. Indus. Electron.*, vol. 59, no. 1, pp. 562-570, Jan. 2012.
- [31] O. C. Onar, M. Uzunoglu, and M.S. Alam, "Dynamic modeling, design and simulation of a wind/fuel cell/ ultra-capacitor-based hybrid power generation system," *J. Power Sources*, vol. 161, pp. 707-722, Oct. 2006.
- [32] B. Madaci, R. Chenni, E. Kurt, and K. E. Hemsas, "Design and control of a stand-alone hybrid power system," *Int. J. Hydrogen Energy*, vol. 41, no. 29, pp. 12485-12496, Aug. 2016.
- [33] R. S. Bhatia, S. P. Jain, D. K. Jain, and B. Singh, "Battery Energy Storage System for Power Conditioning of Renewable Energy Sources," *Int. Conf. on Power Electron. and Drives Systems*, Kuala Lumpur, 2005, pp. 501-506.
- [34] C. Wang and M. H. Nerir, "Fuel cell and load transients," *IEEE Power & Energy Magazine*, 2007.
- [35] K. Jin, X. Ruan, M. Yang, and M. Xu, "A Hybrid Fuel Cell Power System," *IEEE Trans. Indus. Electron.*, vol. 56, no. 4, pp. 1212-1222, Apr. 2009.
- [36] D. Somayajula and M. L. Crow, "An integrated active power filter-ultracapacitor design to provide intermittency smoothing and reactive power support to the distribution grid," *IEEE Trans. Sustain. Energy*, vol. 5, no. 4, pp. 1116-1125, Oct. 2014.
- [37] R. K. Sharma and S. Mishra, "Dynamic power management and control of a PV PEM fuel-cell-based standalone ac/dc microgrid using hybrid energy storage," *IEEE Trans. Indus. Appl.*, vol. 54, no. 1, pp. 526-538, Feb. 2018.
- [38] A. Yazdani and R. Iravani, *Voltage-Sourced Converters in Power Systems: Modeling, Control, and Applications*, vol. 34, Hoboken, NJ, USA: Wiley, 2010.

- [39] M. J. Khan and M. T. Iqbal, "Dynamic modelling and simulation of a small wind-fuel cell hybrid energy system," *Renew. Energy*, vol. 30, pp. 421-439, Mar. 2005.
- [40] B. Singh and S. Singh, "Single-phase power factor controller topologies for permanent magnet brushless DC motor drives," *IET Power Electron.*, vol. 3, no. 2, pp. 147-175, Mar. 2010.
- [41] E. Haque, M. Negnvitsky, and K. M. Muttaqi, "A novel control strategy for a variable speed wind turbine with a permanent magnet synchronous generator," *IEEE Trans. Indus. Appl.*, vol. 46, no. 1, pp. 331-339, Feb. 2010.
- [42] S.G. Malla and C.N. Bhende, "Voltage control of stand-alone wind and solar energy system," *Int. J. Electr. Power Energy Syst.*, vol. 56, pp. 361-373, Mar. 2014.
- [43] M. Y. Sharkh, A. Rahman, M. S. Alam, A. A. Sakla, P. C. Byrne, and T. Thomas, "Analysis of active and reactive power control of a stand-alone PEM fuel cell power plant," *IEEE Trans. Power Syst.*, vol. 19, no. 4, pp. 2022-2028, Nov. 2004.
- [44] I. Vechiu, O. Curea, and H. Camblong, "Transient operation of a four-leg inverter for autonomous applications with unbalanced load," *IEEE Trans. Power Electron.*, vol. 25, no. 2, pp. 399-407, Feb. 2010.
- [45] A. M. Howlader, N. Urasaki, and A. Y. Saber, "Control strategies for wind-farm-based smart grid system," *IEEE Trans. Indus. Appl.*, vol. 50, no. 5, pp. 3591-3601, Oct. 2014.
- [46] F. Blaabjerg, R. Teodorescu, M. Liserre, and A.V. Timbus, "Overview of control and grid synchronization for distributed power generation systems," *IEEE Trans. Indus. Electron.*, vol. 53, no. 5, pp. 1398- 1409, Oct. 2006.
- [47] A. Timbus, M. Liserre, R. Teodorescu, P. Rodriguez, and F. Blaabjerg, "Evaluation of current controllers for distributed power generation systems," *IEEE Trans. Power Electron.*, vol. 24, no. 3, pp. 654-664, Mar. 2009.
- [48] M. Singh, V. Khadikar, A. Chandra, and R. K. Varma, "Grid interconnection of renewable energy sources at the distribution level with power quality improvement features," *IEEE Trans. Power Del.*, vol. 26, no. 1, pp. 307-315, Jan. 2011.
- [49] K. Sedghisigarchi, A. Feliachi, "Control of grid-connected fuel cell power plant for transient stability enhancement," in *Proc. Power Engg. Society Winter Meeting*, 2002, vol. 1, pp. 383-388.
- [50] C. J. Hatziaioniu, A.A. Lobo, F. Pourboghra, and M. Daneshdoost, "A simplified dynamic model of grid-connected fuel-cell generators," *IEEE Trans. Power Delivery*, vol. 17, no. 2, pp. 467-473, Apr. 2002.
- [51] O. P. Mahela, N. Gupta, M. Khosravy, and N. Patel, "Comprehensive overview of low voltage ride through methods of grid integrated wind generator," *IEEE Access*, vol. 7, pp. 99299-99326, 2019.
- [52] G. Saccomando and J. Svensson, "Transient operation of grid-connected voltage source converter under unbalanced voltage conditions," in *Proc. IEEE Indus. Appl. Conf.*, 2001, vol. 4, pp. 2419-2424, Oct. 2001.
- [53] M. K. Ghartemani and M. R. Iravani, "A method for synchronization of power electronic converters in polluted and variable- frequency environments," *IEEE Trans. Power Syst.* vol. 19, no. 3, pp. 1263-1270, Aug. 2004.
- [54] V. Kaura and V. Blasko, "Operation of a phase locked loop system under distorted utility conditions," *IEEE Trans. Indus. Appl.*, vol. 33, no. 1, pp. 58-63, Feb. 1997.
- [55] R. Teodorescu and F. Blaabjerg, "Flexible control of small wind turbines with grid failure detection operating in standalone and grid connected mode," *IEEE Trans. Power Electron.*, vol. 19, no. 5, pp. 1323-1332, Sept. 2004.
- [56] P. Rodriguez, J. Pou, J. Bergas, J. I. Candela, R. P Burgos, and D. Boroyevich, "Decoupled double synchronous reference frame PLL for power converters control," *IEEE Trans. Power Electron.*, vol. 22, no. 2, pp. 584-592, Mar. 2007.

- [57] L. Hajidemetriou, E. Kyriakides, and F. Blaabjerg, "A new hybrid PLL for interconnecting renewable energy to the grid," *IEEE Trans. Indus. Appl.*, vol. 49, no. 6, pp. 2709-2719, Dec. 2013.
- [58] P. Rodriguez, A. V. Timbus, R. Teodorescu, M. Liserre, and F. Blaabjerg, "Flexible Active Power Control of Distributed Power Generation Systems During Grid Faults," *IEEE Trans. Indus. Electron.*, vol. 54, no. 5, pp. 2583-2592, Oct. 2007.
- [59] F. Wang, J. L. Duarte, and M. A. M. Hendrix, "Design and analysis of active power control strategies for distributed generation inverters under unbalanced grid faults," *IET Gener. Trans. Distrib.*, vol. 4, no. 8, pp. 905-916, Aug. 2010.
- [60] J. L. Sosa, M. Castilla, J. Miret, J. Matas, and Y. A. Al-Turki, "Control strategy to maximize the power capability of PV three-phase inverters during voltage sags," *IEEE Trans. Power Electron.*, vol. 31, no. 4, pp. 3314-3323, Apr. 2016.
- [61] P. Huang, M. S. El Moursi, W. Xiao, and J. L. Kirtley Jr, "Novel fault ride-through configuration and transient management scheme for doubly fed induction generator," *IEEE Trans. Energy Convers.*, vol. 28, no. 1, pp. 86-94, Mar. 2013.
- [62] S. Alepuz, A. Calle, S. Busquets-Monge, S. Kouro, and B. Wu, "Use of stored energy in PMSG rotor inertia for low-voltage ride-through in back-to-back NPC converter-based wind power systems," *IEEE Trans. Indus. Electron.*, vol. 60, no. 5, pp. 1787-1796, May 2013.
- [63] J. Yao, T. Zhou, W. Hu, Z. Chen, Q. Shen, and M. Yu, "Enhanced control for a direct-driven permanent synchronous generator wind-power generation system with flywheel energy storage unit under unbalanced grid fault," *Electric Power Comp. Sys.*, vol. 43, pp. 982-994, May 2015.
- [64] X. Xiao, R. Yang, X. Chen, Z. Zheng, and C. Li, "Enhancing fault ride-through capability of DFIG with modified SMES-FCL and RSC control," *IET Gener. Trans. Distrib.* vol. 12, no. 1, pp. 258-266, Aug. 2018.
- [65] Y. Yang, F. Blaabjerg, and H. Wang, "Low-Voltage Ride-Through of Single-Phase Transformer-less Photovoltaic Inverters," *IEEE Trans. Indus. Appl.*, vol. 50, no. 3, pp. 1942- 1952, Jun. 2014.
- [66] M. S. El Moursi, W. Xiao, and J. L. Kirtley, "Fault ride through capability for grid interfacing large scale PV power plants," *IET Gener. Trans. Distrib.*, vol. 7, no. 9, pp. 1027-1036, Sept. 2013.
- [67] A.Q.A. Shetwi, M.Z. Sujod, and F. Blaabjerg, "Low voltage ride-through capability control for single-stage inverter-based grid-connected photovoltaic power plant," *Solar Energy*, vol. 159, pp. 665-681, Jan. 2018.
- [68] H. Dehghani Tafti *et al.*, "Low-voltage ride-through capability of photovoltaic grid-connected neutral-point-clamped inverters with active/reactive power injection," *IET Renew. Power Gener.*, vol. 11, no. 8, pp. 1182-1190, Jul. 2017.
- [69] E. Afshari *et al.*, "Control strategy for three-phase grid-connected PV inverters enabling current limitation under unbalanced faults," *IEEE Trans. Ind. Electron.*, vol. 64, no. 11, pp. 8908-8918, Nov. 2017.
- [70] M. Mirhosseini, J. Pou and V. G. Agelidis, "Single- and two-stage inverter-based grid-connected photovoltaic power plants with ride-through capability under grid faults," *IEEE Trans. Sustain. Energy*, vol. 6, no. 3, pp. 1150-1159, Jul. 2015.
- [71] A. Hajizadeh and M. A. Golkar, "Control of hybrid fuel cell/battery distributed power generation system with voltage sag ride-through capability," in *Proc. IEEE PECon.*, pp. 463- 467, 2008.
- [72] A. Hajizadeh and M. A. Golkar, "Control of hybrid fuel cell/energy storage distributed generation system against voltage sag," *Int. J. Electr. Power Energy Syst.*, vol. 32, no. 5, pp. 488-497, June 2010.
- [73] M. J. Morshed and A. Fekih, "A novel fault ride through scheme for hybrid wind/PV power generation systems," *IEEE Trans. Sustain. Energy*, vol. 11, no. 4, pp. 2427-2436, Oct. 2020.
- [74] H. E. Z. Farag and E. F. El-Saadany, "A novel cooperative protocol for distributed voltage control in active distribution systems," *IEEE Trans. Power Syst.*, vol. 28, no. 2, pp. 1645-1656, May 2013.

- [75] S. Lakshmi, S. Vinod, and B.M. Shagar, "Voltage control of hybrid power conversion system under voltage sag condition," *Int. Conf. Comp. Electron. Electr. Tech.*, 2012, pp. 240-247, Mar. 2012.
- [76] E. Dursun and O. Kilic, "Comparative evaluation of different power management strategies of a stand-alone PV/Wind/PEMFC hybrid power system," *Int. J. Electrical Power & Energy Systems*, vol. 34, no. 1, pp. 81-89, Jan. 2012.
- [77] P. Sanjeev, N. P. Padhy, and P. Agarwal, "Autonomous power control and management between standalone DC microgrids," *IEEE Trans. Indus. Inform.*, vol. 14, no. 7, pp. 2941-2950, Jul. 2018.
- [78] S. Saravanan and S. Thangavel, "Electrical power and energy systems instantaneous reference current scheme-based power management system for a solar/wind/fuel cell fed hybrid power supply," *Int. J. Electr. Power Energy Syst.*, vol. 55, pp. 155-170, Feb. 2014.
- [79] P. Gupta, R. S. Bhatia, and D. K. Jain, "Average absolute frequency deviation value based active islanding detection technique," *IEEE Trans. Smart Grid*, vol. 6, no. 1, pp. 26-35, Jan. 2015.
- [80] D. Manna, S. K. Goswami, and P. K. Chattopadhyay, "Optimisation of droop coefficients of multiple distributed generators in a micro-grid," *IET Gener. Trans. Distrib.*, vol. 12, no. 18, pp. 4108-4116, Oct. 2018.
- [81] A. Anvari-Moghaddam, J. M. Guerrero, J. C. Vasquez, H. Monsef, and A. Rahimi-Kian, "Efficient energy management for a grid-tied residential microgrid," *IET Gener. Trans. & Distr.*, vol. 11, no. 11, pp. 2752-2761, Aug. 2017.
- [82] G.K. Singh, "Solar power generation by PV (photovoltaic) technology: A review," *Energy*, vol. 53, pp. 1-13, May. 2013.
- [83] S. A. Belfedhal, E.L.M. Berkouk, and Y. Messlem, "Analysis of grid connected hybrid renewable energy system," *J. Renew. Sustain. Energy*, vol. 11, pp. 014702, Jan. 2019.
- [84] N.B. Halima, S. Ammous, and A. Oualha, "Constant-power management algorithms of a hybrid wind energy system," *J. Renew. Sustain. Energy*, vol. 10, pp. 055102, Oct. 2018.
- [85] S. K. Ayyappa and D. N. Gaonkar, "Performance analysis of a variable-speed wind and fuel cell-based hybrid distributed generation system in grid-connected mode of operation," *Electric Power Comp. Syst.*, vol. 44, no. 2, pp. 142-151, Dec. 2015.
- [86] L. Kong, J. Yu, and G. Cai, "Modeling, control and simulation of a photovoltaic/hydrogen/supercapacitor hybrid power generation system for grid-connected applications," *Int. J. Hydrogen Energy*, vol. 44, no. 46, pp. 25129-25144, Sep. 2019.
- [87] T. Zhou and B. Francois, "Energy management and power control of a hybrid active wind generator for distributed power generation and grid integration," *IEEE Trans. Indus. Electron.*, vol. 58, no. 1, pp. 95-104, Jan. 2011.
- [88] N. Beniwal, I. Hussain, and B. Singh, "Control and operation of a solar PV-battery-grid-tied system in fixed and variable power mode," *IET Gener. Trans. Distrib.*, vol. 12, no. 11, pp. 2633-2641, Jun. 2018.
- [89] R. Kyoungsoo and S. Rahman, "Two loop controllers for maximizing performance of a grid connected photo voltaic fuel cell hybrid power plant," *IEEE Trans. Energy Convers.*, vol. 13, no. 3, pp. 276-281, Sept. 1998.
- [90] C.M Hong and C.H Chen "Intelligent control of a grid connected wind photovoltaic hybrid power systems," *Electr. Power Energy Syst.*, vol.55, pp. 554-561, Feb. 2014.
- [91] A. Hajizadeh and M. A. Golkar, "Intelligent power management strategy of hybrid distributed generation system," *Int. J. Electr. Power Energy Syst.*, vol. 29, no. 10, pp. 783-795, Dec. 2007.
- [92] A. Hajizadeh and M.A. Golkar, "Fuzzy neural control of a hybrid fuel cell/battery distributed power generation system," *IET Renew. Power Gener.*, vol. 3, no. 4, pp. 402-414, Dec. 2009.

- [93] L. Shuhui, M. Fairbank, C. Johnson, D. C. Wunsch, Eduardo Alonso, and J. L. Proaño, "Artificial neural networks for control of a grid-connected rectifier/inverter under disturbance, dynamic and power converter switching conditions," *IEEE Trans. Neural Netw. Learn. Syst.*, vol. 25, no. 4, pp. 738-750, Apr. 2014.
- [94] N. P. Padhy *Artificial Intelligence and Intelligent Systems*, Oxford University Press, 2005.
- [95] A. K. Roy, P. Basak, and G. R. Biswal, "Low voltage ride through capability enhancement in a grid-connected wind/fuel cell hybrid system via combined feed-forward and fuzzy logic control," *IET Gener. Transm. Distrib.*, vol. 13, no. 13, pp. 2866-2876, Jul. 2019.
- [96] H. M. Yassin, H. H. Hanafy, and M. M. Hallouda, "Enhancement low-voltage ride through capability of permanent magnet synchronous generator-based wind turbines using interval type-2 fuzzy control," *IET Renew. Power Gener.*, vol. 10, no. 3, pp. 339-348, Feb. 2016.
- [97] A. Benali, M. Khiat, T. Allaoui, and M. Denai, "Power quality improvement and low voltage ride through capability in hybrid wind-PV farms grid-connected using dynamic voltage restorer," *IEEE Access*, vol. 6, pp. 68634-68648, Nov. 2018.
- [98] S. Vedantham, S. Kumar, B. Singh, and S. Mishra, "Fuzzy logic gain-tuned adaptive second-order GI-based multi-objective control for reliable operation of grid-interfaced photovoltaic system," *IET Gener. Transm. Distrib.*, vol. 12, no. 5, pp. 1153-1163, Mar. 2018.
- [99] A. Calle-Prado, S. Alepuz, J. Bordonau, J. Nicolas-Apruzzese, P. Corts, and J. Rodriguez, "Model predictive current control of grid-connected neutral-point-clamped converters to meet low-voltage ride-through requirements," *IEEE Trans. Ind. Electron.*, vol. 62, no. 3, pp. 1503-1514, Mar. 2015.
- [100] A. Moghadasi *et al.*, "A model predictive power control approach for a three-phase single-stage grid-tied PV module-integrated converter," *IEEE Trans. Indus. Appl.*, vol. 54, no. 2, pp. 1823-1831, Mar. 2018.
- [101] R. K. Agarwal, I. Hussain, and B. Singh, "LMF-based control algorithm for single stage three-phase grid integrated solar PV system," *IEEE Trans. Sustain. Energy*, vol. 7, no. 4, pp. 1379-1387, Oct. 2016.
- [102] B. Wittig, W. Franke, and F. W. Fuchs, "Design and analysis of a DC/DC/AC three phase solar converter with minimized DC link capacitance," *13th European Conf. Power Electron. Appl.*, Barcelona, pp. 1-9, 2009.
- [103] S. Tamalouzt *et al.*, "Performances analysis of WT-DFIG with PV and fuel cell hybrid power sources system associated with hydrogen storage hybrid energy system," *Int. J Hydrogen Energy*, vol. 41, pp. 21006-21021, 2016.
- [104] R. W. Erickson and D. Maksimovic, *Fundamentals of power electronics*, Springer Science & Business Media, 2007.
- [105] P. Sahu, D. Verma and S. Nema, "Physical design and modelling of boost converter for maximum power point tracking in solar PV systems," *Int. Conf. Elect. Power and Energy Syst. (ICEPES)*, pp. 10-15, 2016.
- [106] S. Kewat, B. Singh, and I. Hussain, "Power management in PV-battery-hydro based standalone microgrid," *IET Renew. Power Gener.*, vol. 12, no. 4, pp. 391-398, Mar. 2018.
- [107] P. Mishra, A. K. Pradhan and P. Bajpai, "Voltage control of PV inverter connected to unbalanced distribution system," *IET Renew. Power Gener.*, vol. 13, no. 9, pp. 1587-1594, Jul. 2019.
- [108] *IEEE recommended practices and requirements for harmonic control in electrical power systems*, IEEE Standard 519-1992, 1992.
- [109] R. Teodorescu, M. Liserre, and P. Rodriguez, *Grid Converters for Photovoltaic and Wind Power Systems*, New Jersey, USA: Wiley, 2011.

- [110] A. Yazdani and P. P. Dash, "A control methodology and characterization of dynamics for a photovoltaic (PV) system interfaced with a distribution network," *IEEE Trans. Power Del.*, vol. 24, no. 3, pp. 1538-1551, Jul. 2009.
- [111] Sim Power Systems, Reference, Hydro-Québec, MathWorks, Inc. Natick, MA, 2011.
- [112] A. Soetedjo, A. Lomi, and Widodo Puji Mulayanto, "Modeling of wind energy system with MPPT control," *In Proc. Int. Conf. Electr. Engg. Inform.*, Bandung, pp. 1-6, 2011.
- [113] K. Kim, Y. Jeung, D. Lee, and H. Kim, "LVRT scheme of PMSG wind power systems based on feedback linearization," *IEEE Trans. Power Electron.*, vol. 27, no. 5, pp. 2376-2384, May 2012.
- [114] S. Choudhury and K. B. Mohanty, "Performance analysis of doubly-fed induction generator for wind energy conversion system," M. Tech thesis, Dept. Elect. Eng., NIT Rourkella, Odhisa, India, 2011.
- [115] S. Puchalapalli and B. Singh, "A single input variable FLC for DFIG-Based WPGS in standalone mode," *IEEE Trans. Sustain. Energy*, vol. 11, pp. 595-607, April 2020.
- [116] N. K. S. Naidu and B. Singh, "Experimental implementation of a doubly fed induction generator used for voltage regulation at a remote location," *IEEE Trans. Indus. Appl.*, vol. 52, no. 6, pp. 5065-5072, Nov.-Dec. 2016.
- [117] S. Sahoo, S. Mishra, and N. P. Padhy, "A decentralized adaptive droop based power management scheme in autonomous DC microgrid," *IEEE PES Asia-Pacific Power and Energy Eng. Conf.*, pp. 1018-1022, 2016.
- [118] L. Wang, Q. Vo and A. V. Prokhorov, "Stability improvement of a multimachine power system connected with a large-scale hybrid wind-photovoltaic farm using a supercapacitor," *IEEE Trans. Indus. Appl.*, vol. 54, pp. 50-60, Feb. 2018.
- [119] L. Wang, Q. Vo and A. V. Prokhorov, "Dynamic stability analysis of a hybrid wave and photovoltaic power generation system integrated into a distribution power grid," *IEEE Trans. Sustain. Energy*, vol. 8, no. 1, pp. 404-413, Jan. 2017.
- [120] M. Uzunoglu, O.C. Onar, M.S. Alam, "Modeling, control and simulation of a PV/FC/UC based hybrid power generation system for stand-alone applications," *Renew. Energy*, vol. 34, pp. 509-520, 2009.
- [121] A. Hajizadeh, "Robust power control of microgrid based on hybrid renewable power generation systems," *Iranian J. Elect. and Electron. Engg.*, vol. 10, pp. 58-66, Mar. 2013.
- [122] B. Singh and A. Shrivastava, "Buck converter-based power supply design for low power light emitting diode lamp lighting," *IET Power Electron.*, vol. 7, no. 4, pp. 946-956, Apr. 2014.
- [123] J. Rocabert, A. Luna, F. Blaabjerg, and P. Rodríguez, "Control of Power Converters in AC Microgrids," *IEEE Trans. Power Electron.*, vol. 27, no. 11, pp. 4734-4749, Nov. 2012.
- [124] D. Shin, K. Lee, J. Lee, D. Yoo, and H. Kim, "Implementation of fault ride-through techniques of grid-connected inverter for distributed energy resources with adaptive low-pass notch PLL," *IEEE Trans. Power Electron.*, vol. 30, no. 5, pp. 2859-2871, May 2015.
- [125] M. Nasiri and R. Mohammadi, "Peak current limitation for grid side inverter by limited active power in PMSG-based wind turbines during different grid faults," *IEEE Trans. Sustain. Energy*, vol. 8, no. 1, pp. 3-12, Jan. 2017.
- [126] B. Singh, C. Jain, and A. Bansal, "An improved adjustable step adaptive neuron-based control approach for the grid-supportive SPV system," *IEEE Trans. Indus. Appl.*, vol. 54, no. 1, pp. 563-570, Feb. 2018.
- [127] J. He, L. Huang, D. Wu, C. Zhu, and H. Xin, "Frequency support from PMSG-based wind turbines with reduced DC-link voltage fluctuations," *CES Trans. Electrical Machines and Systems*, vol. 2, no. 3, pp. 296-302, Sep. 2018.

- [128] S. Mohagheghi, G. K. Venayagamoorthy, S. Rajagopalan, and R. G. Harley, "Hardware implementation of a mamdani fuzzy logic controller for a static compensator in a multimachine power system," *IEEE Trans. Indus. Appl.*, vol. 45, no. 4, pp. 1535-1544, Aug. 2009.
- [129] M. A. Hannan, Z. A. Ghani, A. Mohamed, and M. N. Uddin, "Real-time testing of a fuzzy-logic-controller-based grid-connected photovoltaic inverter system," *IEEE Trans. Indus. Appl.*, vol. 51, no. 6, pp. 4775-4784, Dec. 2015.
- [130] H. M. Hasanien and M. Matar, "A fuzzy logic controller for autonomous operation of a voltage source converter-based distributed generation system," *IEEE Trans. Smart Grid*, vol. 6, no. 1, pp. 158-165, Jan. 2015.
- [131] G. Mokryani, P. Siano, A. Piccolo, and Z. Chen, "Improving Fault Ride-Through Capability of Variable Speed Wind Turbines in Distribution Networks," *IEEE Syst. J.*, vol. 7, no. 4, pp. 713-722, Dec. 2013.
- [132] M. H. Nehrir and C. Wang, *Modeling and Control of Fuel Cells: Distributed Generation Applications*, New Jersey: Wiley- IEEE Press, 2009.
- [133] A. M. O. Haruni, "A Stand-Alone Hybrid Power System with Energy Storage," Ph.D. dissertation, Centre of Renewable Energy and Power Systems (CREPS), School of Engineering, University of Tasmania, 2013.
- [134] N. Mendis, K. M. Muttaqi, and S. Perera, "Management of battery-supercapacitor hybrid energy storage and synchronous condenser for isolated operation of PMSG based variable-speed wind turbine generating systems," *IEEE Trans. Smart Grid*, vol. 5, no. 2, pp. 944-953, Mar. 2014.
- [135] J. Philip *et al.*, "Control and implementation of a standalone solar photovoltaic hybrid system," *IEEE Trans. Indus. Appl.*, vol. 52, no. 4, pp. 3472-3479, July-Aug. 2016.
- [136] S. K. Tiwari, B. Singh, and P. K. Goel, "Design and control of autonomous wind-solar system with DFIG feeding 3-phase 4-wire loads," *IEEE Trans. Indus. Appl.*, vol. 54, no. 2, pp. 1119-1127, Apr. 2018.
- [137] T. Kamal, S. Z. Hassan, M. J. Espinosa-Trujillo, H. Li, and M. Flota, "An optimal power sharing and power control strategy of photovoltaic/fuel cell/ultracapacitor hybrid power system," *J. Renew. Sustain. Energy*, vol. 8, May 2016.
- [138] A. M. O. Haruni, M. Negnevitsky, M. E. Haque, and A. Gargoom, "A novel operation and control strategy for a standalone hybrid renewable power system," *IEEE Trans. Sustain. Energy*, vol. 4, no. 2, pp. 402-413, Apr. 2013.
- [139] T. Vigneysh and N. Kumarappan, "Autonomous operation and control of photovoltaic/solid oxide fuel cell/battery energy storage based microgrid using fuzzy logic controller," *Int. J. Hydrogen Energy*, vol. 41, no. 3, pp. 1877-1891, Jan. 2016.
- [140] E. M. Natsheh, A. R. Natsheh, and A. Albarbar, "Intelligent controller for managing power flow within standalone hybrid power systems," *IET Science Meas. Tech.*, vol. 7, no. 4, pp. 191-200, Jul. 2013.
- [141] S. Saravanan and S. Thangavel, "Fuzzy logic controller-based power management for a standalone solar/wind/fuel cell fed hybrid system," *J. Renew. Sustain. Energy*, vol. 5, pp. 053147, Oct. 2013.
- [142] A. Bag, B. Subudhi, and P. K. Ray, "An adaptive variable leaky least mean square control scheme for grid integration of a PV system," *IEEE Trans. Sustain. Energy*, vol. 11, no. 3, pp. 1508-1515, Jul. 2020.
- [143] P. Shanthi, G. Uma, and M. S. Keerthana, "Effective power transfer scheme for a grid connected hybrid wind/photovoltaic system," *IET Renew. Power Gener.*, vol. 11, no. 7, pp. 1005-1017, Jun. 2017.
- [144] A. Guichi, A. Talha, E.M. Berkouk, and S. Mekhilef, "Energy management and performance evaluation of grid connected PV-battery hybrid system with inherent control scheme," *Sustain. Cities and Society*, vol. 41, pp. 490-504, Aug. 2018.

- [145] P. García, C. A. García, L. M. Fernández, F. Llorens and F. Jurado, "ANFIS-based control of a grid-connected hybrid system integrating renewable energies, hydrogen and batteries," *IEEE Trans. Indus. Inform.*, vol. 10, no. 2, pp. 1107-1117, May 2014.
- [146] R. Sedaghati and M. R. Shakarami, "A novel control strategy and power management of hybrid PV/FC/SC/battery renewable power system-based grid-connected microgrid," *Sustain. Cities Society*, vol. 44, pp. 830-843, Jan. 2019.
- [147] A. Choudar, D. Boukhetala, S. Barkat, and J. Brucker, "A local energy management of a hybrid PV-storage based distributed generation for microgrids," *Energy Conver. Manag.*, vol. 90, pp. 21-33, Jan. 2015.
- [148] S. Kim, J. Jeon, C. Cho, J. Ahn, and S. Kwon, "Dynamic modeling and control of a grid-connected hybrid generation system with versatile power transfer," *IEEE Trans. Indus. Electron.*, vol. 55, no. 4, pp. 1677-1688, Apr. 2008.
- [149] J. Jia, G. Yang and A. H. Nielsen, "A review on grid-connected converter control for short-circuit power provision under grid unbalanced faults," *IEEE Trans. Power Del.*, vol. 33, no. 2, pp. 649-661, Apr. 2018.
- [150] A. Hajizadeh, M. A. Golkar, and A. Feliachi, "Voltage control and active power management of hybrid fuel-cell/energy-storage power conversion system under unbalanced voltage sag conditions," *IEEE Trans. Energy Convers.*, vol. 25, no. 4, pp. 1195-1208, Dec. 2010.
- [151] S. M. Tripathi, A. N. Tiwari and D. Singh, "Low-voltage ride-through enhancement with the ω and T controls of PMSG in a grid-integrated wind generation system," *IET Gener. Trans. Distrib.*, vol. 13, no. 10, pp. 1979-1988, May 2019.
- [152] M. V. Gururaj and N. P. Padhy, "A cost-effective single architecture to operate DC microgrid interfaced DFIG wind system during grid-connected, fault, and isolated conditions," *IEEE Trans. Indus. Inform.*, vol. 16, no. 2, pp. 922-934, Feb. 2020.
- [153] S. K. Tiwari, B. Singh, and P. K. Goel, "Design and control of microgrid fed by renewable energy generating sources," *IEEE Trans. Indus. Appl.*, vol. 54, no. 3, pp. 2041-2050, Jun. 2018.
- [154] C. Abbey and G. Joos, "Supercapacitor energy storage for wind energy applications," *IEEE Trans. Indus. Appl.*, vol. 43, no. 3, pp. 769-776, Jun. 2007.
- [155] W.C. Carvalho, R.P. Bataglioli, R.A.S. Fernandes, and D.V. Coury, "Fuzzy-based approach for power smoothing of a full-converter wind turbine generator using a supercapacitor energy storage," *Electric Power. Sys. Res.*, vol. 184, Jul. 2020.
- [156] M. Y. Worku and M. A. Abido, "Fault ride-through and power smoothing control of PMSG-based wind generation using supercapacitor energy storage system," *Arab J. Sci Eng.*, vol. 44, pp. 2067–2078, Apr. 2019.
- [157] K. E. Okedu, "Enhancing the performance of DFIG variable speed wind turbine using a parallel integrated capacitor and modified modulated braking resistor," *IET Gener., Trans. & Dist.*, vol. 13, no. 15, pp. 3378-3387, Aug. 2019.
- [158] V. R. R. Rudraraju, C. Nagamani, and S. I. Ganesan, "A control strategy for reliable power output from a stand-alone wrig with battery-supported dc Link," *IEEE Trans. Power Electron.*, vol. 32, no. 6, pp. 4334-4343, Jun. 2017.
- [159] N. K. S. Naidu and B. Singh, "Grid-interfaced DFIG-based variable speed wind energy conversion system with power smoothing," *IEEE Trans. Sustain. Energy*, vol. 8, no. 1, pp. 51-58, Jan. 2017.
- [160] A. K. Singh and A. Saxena, "A novel neuro-fuzzy control scheme for wind-driven DFIG with ANN-controlled solar PV array," *Environ. Dev. Sustain.*, vol. 22, pp. 6605–6626, Oct. 2020.
- [161] R. S. Mena, L. M. F. Ramírez, C. A. G. Vázquez, and F. Jurado, "Fuzzy logic-based power management strategy of a multi-MW doubly-fed induction generator wind turbine with battery and ultracapacitor," *Energy*, vol. 70, pp. 561-576, Jun. 2014.

- [162] K. V. Shihabudheen, S. K. Raju, and G. N. Pillai, "Control for grid-connected DFIG-based wind energy system using adaptive neuro-fuzzy technique," *Int. Trans. Electr. Energ. Syst.*, vol. 28, Jan. 2018.
- [163] U. Sowmmiya and G. Uma, "ANFIS-based sensor fault-tolerant control for hybrid grid," *IET Gener., Trans. & Distr.*, vol. 12, no. 1, pp. 31-41, Jan. 2018.
- [164] M. Singh and A. Chandra, "Real-time implementation of ANFIS control for renewable interfacing inverter in 3P4W distribution network," *IEEE Trans. Indus. Electron.*, vol. 60, no. 1, pp. 121-128, Jan. 2013.
- [165] T. H. Nguyen and D. Lee, "Advanced fault ride-through technique for PMSG wind turbine systems using line-side converter as STATCOM," *IEEE Trans. Indus. Electron.*, vol. 60, no. 7, pp. 2842-2850, Jul. 2013.
- [166] J. Mohammadi, S. Afsharnia, S. Vaez-Zadeh and S. Farhangi, "Improved fault ride through strategy for doubly fed induction generator-based wind turbines under both symmetrical and asymmetrical grid faults," *IET Renew. Power Gener.*, vol. 10, no. 8, pp. 1114-1122, Sept. 2016.
- [167] W. Guo, L. Xiao, and S. Dai, "Fault current limiter-battery energy storage system for the doubly-fed induction generator: analysis and experimental verification," *IET Gener. Trans. Distr.*, vol. 10, no. 3, pp. 653-660, Feb. 2016.
- [168] W. Guo et al., "LVRT capability enhancement of DFIG with switch-type fault current limiter," *IEEE Trans. Indus. Electron.*, vol. 62, no. 1, pp. 332-342, Jan. 2015.
- [169] N. Jabbour, E. Tsioumas, C. Mademlis and E. Solomin, "A highly effective fault-ride-through strategy for a wind energy conversion system with a doubly fed induction generator," *IEEE Trans. Power Electron.*, vol. 35, no. 8, pp. 8154-8164, Aug. 2020.

List of Publications from Research Work

Science Citation Index (SCI) Publications:

- [1] Amit Kumar Roy, Prasenjit Basak, and Gyan Ranjan Biswal, “Low voltage ride through capability enhancement in a grid-connected wind/fuel cell hybrid system via combined feed-forward and fuzzy logic control,” *IET Generation, Transmission & Distribution* (Publisher: IET, UK), vol.13, Issue 13, pp. 2866-2876, July 2019. DOI: [10.1049/iet-gtd.2019.0021](https://doi.org/10.1049/iet-gtd.2019.0021) (Impact Factor: 2.862).
- [2] Amit Kumar Roy, Gyan Ranjan Biswal, and Prasenjit Basak, “An integrated rule-based power management and dynamic feed-forward low voltage ride through scheme for a grid connected hybrid energy system,” *Journal of Renewable and Sustainable Energy* (Publisher: AIP, USA), vol. 12, Issue 5, pp. 056303: 1-19, Oct. 2020. DOI: <https://doi.org/10.1063/5.0019254> (Impact Factor: 1.575).

Conference Publications:

- [1] Amit Kumar Roy and Gyan Ranjan Biswal, “Effect of Unbalance Fault and Load transients on a Standalone Fuel Cell System,” in *Proc. National Conference on Emerging Trends in Electrical and Electronics Engineering (ETEEE-2015)*, Jamia Millia Islamia, New Delhi, pp. 292- 300, 2nd & 3rd- Feb. 2015.
- [2] Amit Kumar Roy and Gyan Ranjan Biswal, “Investigation of a fuel cell system operating in standalone and grid connected mode,” *2015 Annual IEEE India Conference (INDICON)*, New Delhi, 2015, pp. 1-6.
- [3] Amit Kumar Roy, Gyan Ranjan Biswal and Narayana Prasad Padhy, “An improvized fuel cell system for stand-alone mode application,” *2016 IEEE Power and Energy Society General Meeting (PESGM)*, Boston, MA, 2016, pp. 1-5.
- [4] Amit Kumar Roy, Prasenjit Basak, and Gyan Ranjan Biswal, “Characterization Study of a Grid Connected DFIG Based WECS Under Variable Wind Speed and Loading Conditions,” *2018 2nd IEEE International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES)*, Delhi, India, 2018, pp. 449-454.