

DESIGN AND CONTROL OF MICROGRID SYSTEM FOR OPTIMUM OPERATION

A Thesis

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Doctor of Philosophy

in Engineering

Submitted by

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Dedicated

To

My Parents

Mr. Dev Karan Kaushal & Mrs. Beena Kaushal

My Parents-in-law

Mr. Hari Dass Garg & Mrs. Prem Lata Garg

My Wife

Mrs. Nancy Garg Kaushal

And

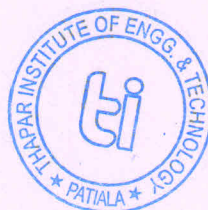
My Daughter

Ms. Dakshyani Kaushal

CERTIFICATE

This is to certify that the thesis entitled “**Design and control of microgrid system for optimum operation**” being submitted by Mr. Jitender 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 my guidance and supervision and has fulfilled the requirements for the submission of this thesis, which to my 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

A microgrid is equipped with variants of distributed energy resources offering a challenging situation to power engineers to maintain the power quality during its operation. So, monitoring and maintaining power quality is a critical issue for healthy operation of microgrid system up to consumer satisfaction. From the outcome of comprehensive literature review, it has been found that a decision-making methodology is required to assess the power quality of an AC microgrid through assessment of power quality-related electrical parameters such as voltage, frequency, power factor, total harmonic distortion (THD) etc. Hence, a decision making methodology is proposed to quantify the fuzziness in random variation of power quality. In this context, one of the major contributions of this research work is introduction of a power quality monitoring index (PQMI) which has been proposed using 256 rule-based fuzzy inference system (FIS) tested single-phase, as well as three-phase AC microgrid model. The results show the effectiveness of the proposed methodology to assess the status of PQMI, depending upon the acceptable limits of above mentioned electrical parameters, operating in grid-connected or islanded mode. The proposed methodology is verified through Mamdani and Sugeno type FIS using MATLAB-Simulink software. It is also found that the proposed PQMI is significant to define the status of microgrid even during transition from grid-connected to islanded mode and vice-versa.

In this research work, it has been found that the battery energy storage (BES), intelligent protection and power quality are considered as independent issues, but these three factors can be interlinked effectively for control of microgrid through automated demand side management (ADSM). In this context, the proposed approach may change the conventional way for microgrid operation and control giving priority to the power quality issues considering protection and BES systems. The control algorithm is implemented through FIS based PQMI and ADSM. As a part of intelligent protection, the logic table for circuit breaker coordination has been developed without/with backup for relay devices to provide proper demand side management. The proposed scheme has been simulated using MATLAB-software and validated through experimental setup using OPAL-RT OP4510 real-time simulator for the assessment of power quality related parameters such as voltage, frequency, THD and power factor.

In the present scenario of microgrid system, conversion of electrical energy has initiated a challenge to maintain the power quality within its satisfactory range which can be influenced by the voltage deviation, sag/swell, unbalancing, frequency, THD and power factor as per nature and location of loads and distributed energy resources (DERs). The existing literature show that the above mentioned parameters are not considered simultaneously for the assessment and controlling of power quality in PV based AC microgrid. To minimize the effect of these variables, a novel artificial neural network (ANN) based control approach has been proposed which can control the power quality as per IEEE/IEC standards. The proposed method has shown fast, smooth and stable operation while the performance of the same is verified with that of the proportional-integral (PI) and fuzzy-PI controllers in three-phase AC microgrid using MATLAB-Simulink software.

Moreover, a small size microgrid model is tested for the assessment of power quality parameters considering the effect of line impedance and communication delay. Also, this model has been extended to a large size realistic microgrid structure for the feasibility study of proposed control methodology based on power quality related parameters. Simulation results of the realistic microgrid structure are found satisfactory considering the effects of line impedance, communication delay, demand response and off-nominal conditions during on-grid and off-grid operations.

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LIST OF ACRONYMS

AC	Alternating current
DC	Direct current
ADSM	Automated demand side management
AGC	Automatic generation control
AHP	Analytic hierarchy process
ANFIS-UPQC	Adaptive neuro fuzzy inference system-unified power quality conditioner
ANN	Artificial neural network
APC	Active power conditioner
AVC	Active voltage conditioner
BES	Battery energy storage
BMS	Battery management system
CB	Circuit breaker
CL	Critical load
CPD	Custom power device
CPU	Central processing unit
DEO-ANN	Differential evolution optimization and artificial neural network
DER	Distributed energy resource
DFIG	Doubly fed-induction generator
DG	Distributed generation
DPG	Distributed power generation
DSO	Digital storage oscilloscope
DSTATCOM	Distribution static synchronous compensator
DVR	Dynamic voltage restorer
ESS	Energy storage system
F	Frequency
FIS	Fuzzy inference system
FLC	Fuzzy logic controller
FPGA	Field programmable gate array
GRC	Generation rate constraint
HIL	Hardware-in-the-loop
IBS	Intelligent bypass switch

IEC	International electrotechnical commission
IED	Intelligent electronic device
IEEE	Institute of electrical and electronics engineers
IGBT	Insulated-gate bipolar transistor
LBC	Low-bandwidth communication
LV	Low voltage
MAN	Metropolitan area network
MAS	Multiagent system
MCDM	Multi-criteria decision making
MG	Microgrid
MGCC	Microgrid central controller
MLMS	Momentum-based least mean square
MMC	Microgrid master controller
MMS	Microgrid management system
MPC	Model predictive control
MPP	Maximum power point
MPPT	Maximum power point tracking
MSE	Mean square error
MV	Medium voltage
NCL	Non-critical load
NSIC	Negative-sequence impedance controller
OPNET	Optimized network engineering tools
PCC	Point-of-common coupling
PCS	Power conditioning system
PF	Power factor
PI	Proportional-integral
PID	Proportional-integral-differential
PLL	Phase locked loop
PQ	Power quality
PQMI	Power quality monitoring index
PV	Photovoltaic
PWM	Pulse width modulation
qZSI	Quasi-Z source inverter

RBFNN	Radial basis function neural network
RCP	Rapid control prototyping
RES	Renewable energy source
RMS	Root mean square
RTDS	Real-time digital simulator
SAIFI	System average interruption frequency index
SARFI	System average RMS frequency index
SD	Standard deviation
SMES	Superconducting magnetic-energy storage
SSD	Sparse signal decomposition
SVC	Static var compensation
SWG	System wellbeing
THD	Total harmonic distortion
UPQI	Unified power quality index
UPS	Uninterruptible power supply
VD	Voltage deviation
VSC	Voltage source converter
WPT	Wavelet packet transform

CHAPTER 1

INTRODUCTION

Microgrid is an emerging power system which consists of different types of interconnected DERs such as photovoltaic (PV), wind, fuel cell, battery energy storage (BES) systems etc. It has shown a paradigm shift from conventional power system to this emerging technology with less pollution or carbon footprints reducing the consumption of fossil fuels which will be exhausted in near future. In the evolution of this technology, it has been observed that maintenance of power quality is a fundamental challenge to microgrid systems. The alternating current (AC) microgrid system is proficient to integrate with conventional utility grid in combination with different types of DERs in fulfilment of most preferable AC loads. AC microgrid system has implicated its role in the existing AC power system to redesign the overall AC network as per international standards for voltage, harmonics, frequency, unbalancing, power factor etc. Several DERs generate direct current (DC) power while few of them generate AC power which creates major challenges for their integration, synchronisation and power quality. To overcome these challenges, effective operation and control topologies should be implemented in order to overcome these challenges through microgrid central controller (MGCC).

In this context, the effective design of a microgrid system including its central controller should be taken care of optimum operation during on-grid and off-grid conditions. It has been found through comprehensive literature survey that many conventional methods have been proposed based on voltage, droop control (P-f, Q-V), active-reactive power exchange etc. If power quality control is considered as a major issue then it needs to be quantified, may be in the form of an index for effective control of the same using controller in microgrid systems. Hence, a microgrid system including controller can be designed to maintain satisfactory operation of microgrid system considering the power quality related parameters in the control topology. This kind of controller can take corrective action based on the status of power quality in the microgrid. If power quality based control is required then the power quality monitoring index can help in effective control of microgrid considering simultaneous effect of large number of variable such as voltage deviation, frequency, THD, power factor, unbalancing, interruption etc.

The major contribution of the thesis is that a power quality monitoring index (PQMI) has been proposed to display the status of power quality during grid-connected (on-grid) and/or islanding (off-grid). Another major contribution of this research can be considered as a proposed controller to control PQ of microgrid based on the value of PQMI under linear, non-linear, rotational and dynamic loads. As a part of microgrid operation and control, it can be realized that there are huge amount of non-linearity in the system with the combination of different DERs. To make stable and reliable operation of microgrid, the power quality should be maintained to the best satisfaction of consumers with lesser burden on power supplier entities or distributed generators (DGs).

In recent published literature on microgrid systems, the requirement of any backup for MGCC is not discussed adequately. It is also found in many literature that the microgrid is equipped with energy storage backup for critical loads but need of a power backup for MGCC itself has been less explored. The BES framework is required to ensure reliability and security which can be provided through automated demand side management (ADSM) considering power quality as a principal issue for the sensitive or critical loads including the backup for MGCC.

1.1 MOTIVATION OF RESEARCH

The microgrid system comprises of different types of energy sources which are interconnected in the form of distributed network as per their geographical location. It becomes difficult to integrate the distributed energy resources (DERs) as low voltage (LV) network due to the different nature of the resources (PV, wind etc.) present in the microgrid system. Since, power outputs of DERs are mostly dependent upon the climate conditions and various surrounding factors. For example, wind speed is viewed as a common central consideration of wind power, while the power of a photovoltaic cell relies upon sun oriented radiation and surrounding temperature. These lead to errors in forecasting of power generation by the DERs. The combined operation of DERs has problems with unbalanced and bidirectional power flow, variability of network configuration, coordination of DERs. Also, maintaining power quality becomes a challenge in this scenario. Hence, all these issues motivate the author to explore the uncertainty and variability of DER outputs in the study of microgrid systems. In addition, the power quality monitoring, detection and mitigation are also considered as motivation in the present research.

So, it is realized that the integration of resources is an important issue to explore its features to cater the load demand by supplying power from the integrated DERs during on-grid and off-grid conditions. It is also observed that the integration of DERs in the field of microgrid including its necessary operation and control issues are required to be analyzed for optimum operation of microgrid system.

The operation and control issues should be explored based on the design of microgrid including controller, power sharing characteristics and power quality control. The power quality can validate the operational health status of integrated microgrid model during its operation under grid-connected mode, islanded mode and during the transition period from one mode to other mode. The nature of loads also directly affects the power quality of microgrid. If the power quality of a microgrid is controlled properly, it can ensure satisfactory operation of the same to cater the load demand. For reliable operation and control of microgrid, a communication infrastructure has an important role while applying control topology in the microgrid system. All the above mentioned observations are considered as the motivating factors for present research. The overview on integration of DERs in microgrid systems is discussed in next Sub-sections 1.1.1. The active-reactive power sharing and power quality control related parameters are elaborated in next Sub-sections 1.1.2 and 1.1.3 respectively.

1.1.1 Integration of distributed energy resources (DERs) in microgrid system

The concept of microgrid suggests the integration of distributed generating units such as micro-turbines, wind turbines, PV panels, fuel cells etc. within their geographical peripheral. It can be understood that a typical microgrid setting, control, management and coordination need to be configured at different levels of DERs and network [1]. The traditional approaches of DER are mentioned in draft P1547 standard referred by the Institute of Electrical and Electronics Engineers (IEEE) which presents impact of DERs on grid performance and issues related to integration of DERs [2]. Both IEEE 1547.4-2011 and International Electrotechnical Commission (IEC) 62109 standards suggest guidelines for operation of grid connected DERs while IEEE 1547.4-2011 standard presents aspects of design and integration of DERs [3]. The utility-interconnected PV inverters can be prevented from false islanding condition followed by IEC/TR 61850-90-7 standard [4] and as per IEC 62477 standard, the proper communication networks can be implemented for automated integration of utility with DERs

[5]. The paradigm shift of traditional generation into the small generators can be connected with distribution system utilizing renewable sources. Due to this, the electricity can be stored for later use with affordable energy storage devices, surplus of solar and/or wind power enables microgrids to dispatch power [6] and new trends are observed to use them as regular source of power during grid connected and islanded modes of operation [7]. The active and reactive power of DGs can be controlled for frequency and voltage limits during grid connected and islanded operations [8]. Like in [9] with the integration of DERs, the existing protection coordination could be updated with considerable investment which encouraged users to consume energy optimally. AC microgrid also supports utility grid if there is a deficit in power generation, so under this condition, the power can be taken from microgrid itself to fulfil the load demand during on-grid operation.

1.1.2 Active-reactive power sharing for voltage, frequency and harmonics control

The active-reactive power exchange maintains power system parameters within the line and on the distribution side as well. The control techniques can be optimized in order to improve the grid operation and adjust power factor at point-of-common coupling (PCC) by injecting or absorbing the active power from the grid or DER to deliver constant load [15]. Like, intelligent bypass switch (IBS) maintains the active power flow during grid-connected operation at different state of battery level [16]. The voltage and frequency can be maintained using active power versus frequency (P-f) control and reactive power versus voltage (Q-V) droop control approaches respectively connected in microgrid system [17–18]. Similarly, hierarchical approach suggested that the frequency can be controlled through active power generation while connected to several DERs in case of islanded microgrid [19]. As per [20], the power quality issues can be mitigated using energy storage system (ESS) and the optimal choice, placement, sizing, charging/discharging of ESS improve performance of the distribution network. Power quality problems such as voltage variation, harmonics etc. can be controlled by exchanging active and reactive power using BES system in the distribution network [21] and wind energy system [22].

1.1.3 Power quality control in microgrid

In the present scenario of power generation by microgrid system, conversion of electrical energy from different kinds of renewable energy systems has initiated a challenge to maintain the power quality within a satisfactory range. It can be influenced by the voltage deviation,

voltage sag/swell, unbalancing, frequency, THD and power factor as per the nature of local loads and the condition of DERs. The relationship between the power quality and the set of these variables are non-linear in nature. The existing literature show that the above mentioned parameters are not considered simultaneously for assessment and controlling the power quality in PV based AC microgrid. In addition, an adaptive neuro fuzzy inference system-unified power quality conditioner (ANFIS-UPQC) device is investigated to enhance the power quality of microgrid with the consideration of grid and DER side's disturbances [23]. As compared to power quality disturbances, the voltage drop and harmonic distortions are severe in the utility and customer side respectively. The proposed ANFIS based UPQC is explored for compensation of PQ distortions originated in utility associated microgrid. The voltage and frequency of islanded microgrid are maintained to their nominal values by implementing online tuning of control parameters using ANN approach, subjected to sudden change in load [24]. The proposed approach is predicated on renovating the voltage and frequency by utilizing online tuning of the control parameters by denotes of a keenly intellectual self-optimizing based MGCC.

The power balancing and quality could be maintained and secured by providing the standardized communication network under IEC 61850 [25]. The testbeds contain different DERs, for example, photovoltaics, energy management systems, and electric vehicles. The methodology of coordinating the IEC 61850 standard incorporates the framework engineering setup, informational collection configuration, test record write-up, and arrangement for communication. The active and reactive power flow, grid-side power factor and THD could be controlled using double-band hysteresis controller [26]. This controller is implemented to ensure the real and reactive power flow from renewable energy system (RES) to the utility grid through inverter. The coordination among active power sharing and voltage regulation is controlled using droop control within the interconnected AC and DC microgrids [27]. The power quality could be monitored for optimal operation of microgrid with minimum use of carbon emissions and production cost [28]. The planning and execution approach have been proposed for long-term energy management in microgrids. It is the most difficult job during transitions to maintain the sound health of power quality and hence, estimated based on unbalanced voltages, THD and frequency under islanded condition [29]. The island-detection methods, black-start operation, fault management and protection systems, along with a comprehensive review of power quality have been addressed.

The microgrid is equipped with variants of DERs offering a challenging situation to power engineers to maintain the power quality during its operation. So, monitoring and maintaining the power quality is a critical issue for healthy operation of microgrid system up to the consumers' satisfaction. Hence, the techniques, previously applied for power quality monitoring, detection and mitigation are critically reviewed in the literature. Now, the literature review is focussed comprehensively on the power quality control as described in the next Chapter 2.

1.2 ORGANISATION OF THESIS

To describe the entire research work for achieving the objectives as mentioned in Sub-section 2.6, the thesis has been organized into seven chapters and a brief outline is appended below.

CHAPTER 1: This chapter introduces the motivation of research and integration of the distributed energy resources in microgrid system.

CHAPTER 2: This chapter presents a comprehensive literature survey in the area of microgrid operation and control. The operation and control of microgrid system have been analyzed as major issues considering basic design of microgrid system, controller and importance of the power quality parameters. The prominent research gaps and outcomes have been identified. Further, objectives of research work are defined for design and optimum performance of microgrid used in this study.

CHAPTER 3: The design and modelling of single-phase and three-phase AC microgrid systems have been presented in this chapter in perspective of power quality monitoring parameters during grid-connected and islanded conditions. The PQMI has been proposed in this chapter including discussion on concept and design based on FIS predicated set of rules.

CHAPTER 4: In this chapter, the proposed methodology for PQMI has been applied in both single-phase and three-phase AC microgrid systems under different types of loads. This novel PQMI has been compared with significant developed methods [49–50] for its validation and feasibility in the area of microgrid topologies. A decision making methodology has been applied in three-phase AC microgrid system to assess PQMI for resistive, inductive, rotational, non-linear and dynamic loads.

CHAPTER 5: The power quality control in microgrid through ADSM is discussed in this chapter with the application of BES system for protection. The control algorithm is

implemented through FIS based PQMI and ADSM for three-phase AC microgrid system. The relation among microgrid power quality, protection coordination and BES has been framed in this chapter to reflect the effective interlink between them. The proposed control scheme has been validated through experimental setup using a basic level OPAL-RT simulator OP4510 RT-LAB-RCP/HIL system.

CHAPTER 6: This chapter describes power quality control based on voltage sag/swell, unbalancing, frequency, THD and power factor using ANN in PV integrated AC microgrid. A simple microgrid model has been extended to a realistic structure/architecture of microgrid considering the effect of line impedance as a part of distribution network. The effect of line impedance on power quality parameters have been analyzed during on-grid and off-grid operation of microgrid. The power sharing and reactive power circulation have been assessed with and without availability of PV system. The power losses in sources and distribution wires have been measured to maintain balance between demand and supply.

CHAPTER 7: This chapter presents brief summary, contribution and conclusions of the thesis and the recommendation for future proposition of the current research.

The power quality of a power system from generation to the load needs to be monitored for balancing demand and supply [30]. Nowadays, the power quality is a prominent concern for utility operators as well as consumers [31]. Even power quality indices could be used to determine the capacity of the utility side generators [32]. To reduce the distortion in output power, fuzzy logic controllers could be useful to enhance the power quality [33]. In off-grid condition, THD is a major concern to the power quality issues for the end user appliances [34]. To enhance the economic and social development [35], the intelligent control system could be implemented to utilize full use of renewable energy. The term ‘power quality’ is defined as the electromagnetic phenomena variation due to voltage and current at a given time corresponding to the location in a power system as mentioned in [36], the electromagnetic disturbances are classified as harmonics, voltage fluctuations, dips, interruptions and imbalance, power-frequency variations, induced low-frequency voltages, DC components in AC networks, induced continuous wave voltages or currents and transients. Apart from sparse signal decomposition (SSD) [37], the wavelet, Hilbert transform, Gabor-Wigner transform, S transform and Hilbert–Haung transform methods are used to detect and rectify the power quality disturbances. To enhance the power quality indices the voltages at different buses are to be monitored [38]. As per this reference, the locations of energy storage elements can be investigated to inspect the system performance in accordance to the power quality.

The work presented in [33],[36],[38] have illustrated the power quality assessment and issues based on individual parameter while designing a LV microgrid system. Sometimes the simultaneous effects of one or two variables at a time (say voltage and THD) are considered for power quality issues. It is realized that there are difficulties to maintain discretely categorical ideal magnitude of parameters such as voltage, frequency, harmonic distortion etc. With this consideration, fuzzy logic concept can be used to propose a power quality index for AC microgrid. The power quality of a microgrid could additionally be affected by the generation forecasts, any failure and fault in a DER or PV module [39]. The power quality might be affected during grid-synchronization between single-phase and three-phase system with the consideration of fundamental and harmonic frequencies [40]. The grid-

connected inverters [41] without any control loop are highly responsible for harmonics (say, THD) in the system so the impact of switching and over modulation indexing could contravene the quality of power. It has been observed through literature survey that the power quality monitoring index is not explored with the consideration of four paramount parameters such as voltage deviation, frequency, power factor and THD at same instant; applied to the microgrid system. Like in [30–32], the authors have investigated power quality issues by considering only one, two or infrequently three variable parameters. Hence, it is encouraged as that to contribute in the field of power quality enhancement by considering arbitrary changes in system variables during grid-connected and islanded modes of operation in AC microgrid system.

ESS can enhance the microgrid reliability and stability by reducing the power quality challenges and problems [42]. Also, the system frequency can be controlled using a BES system to enhance the control features of microgrid such as power quality, stability and security [43]. The battery management system (BMS) maintained the power quality and grid stability with proper utilization of batteries [44–45]. The LV microgrid is affected by the weather conditions either connected to UG or not. An ANN based MGCC can be implemented to enhance the power quality of microgrid subjected to the set of large non-linear equations and variables.

The custom power devices (CPDs) such as active power conditioner (APC), active voltage conditioner (AVC), dynamic voltage restorer (DVR) and distribution static synchronous compensator (DSTATCOM) are beneficial to improve the power quality due to the disturbances like voltage sag/swell, interruptions and harmonics [46]. The applications of CPDs are presented in [47] which showed the wide range survey in power quality control in favour of customers' satisfaction. The three-phase current and power factor could be maintained using static var compensation (SVC) and active filters with the application of reactive power compensation to improve the power quality [48]. In connection to the power quality improvement, a corrective action can be taken by implementing the unified power quality conditioner (UPQC) which compensates the voltage and current harmonics [49]. The power quality disturbances could be detected and classified using sparse signal decomposition on hybrid dictionaries considering different noise levels [37]. In addition, some other methods/controllers that are used for improving the power quality are summarized herewith. An inductively active filtering method, a PV fed UPQC, advanced reactive power

compensation and an advanced fuzzy power extraction control methods are discussed in [48], [50–52] which have shown importance of the power quality control at high as well as low level of power systems to the satisfaction of power suppliers and customers.

It is realized that a typical microgrid setting, control, management and coordination need to be configured at different levels of DERs and networks [1]. The overall system functionalities of a microgrid could be framed with the hierarchy of network interface, microgrid control, protection and management [53]. The microgrid control strategy could be characterized as local, secondary, global and central or emergency controls. The droop control strategies could be implemented in three ways such as P/f and Q/V droop control for automatic power sharing, adjustment of power sharing capacity of the inverter and DC-DC converter interfacing for power sharing between the energy sources and load bus [54]. A generalized droop control scheme can be extended based on adaptive neuro-fuzzy inference system (ANFIS) for wide range of load change scenarios [55]. A distributed proportional integral method could be used for the restoration of microgrid frequency while balancing active power sharing with the combination of a finite-time observer [56]. The voltage and frequency deviations could be restored using secondary control strategy for the power electronic based AC microgrid based on inner and outer level of high bandwidth control [57]. The generalized droop characteristic could be applied to control the system voltage and frequency based on demand response (DR) in an isolated microgrid [58]. In addition, there are some optimization tools for power quality improvement such as photovoltaic fed DSTATCOM based on JAYA optimization, forecasting model for off-grid system based on multi-objective optimization, optimization of power factor using predictive data etc. [59–61].

The power quality and power energy management reliability of a standalone microgrid could be enhanced through optimization in terms of active damping technique, reduction in the size of LC filter and implementing a strong fuzzy logic supervisor [62]. The power quality could be ensured at common bus of loads by implementing a novel cost-function-based decentralized control of unbalance and harmonics for simultaneous compensation of voltage and current as compared to existing virtual-impedance-based method due to nonlinearities of inverters [63]. The power quality could also be improved using adaptive filtering technique including momentum-based least mean square (MLMS) control for nonlinear loads integrated with wind, solar and utility grid along with the battery energy storage (BES) system [64]. By the optimal utilization of BES, the microgrid voltage and

frequency could be restored based on hybrid differential evolution optimization and artificial neural network (DEO-ANN) controller considering wide range of disturbances [65]. The optimal dispatch of power sources could be levelized based on the optimum combination of energy from grid, solar and energy storage system (ESS) [66]. Further, the combination of optimal energy and power flow could provide feasible and optimized operating point for both unbalanced and balanced loads in islanded microgrid [67]. The optimum reconfiguration of islanded microgrid could optimize the usage of resources, possibility of maximum demand and minimizing the switching costs among DERs as a multi-objective optimization problem [68] and also, the optimum power quality service could regulate the power quality as an individual standard in different areas as a part of multi-bus microgrid systems [69]. Like master-slave control method, it has the benefits of simple, better voltage and frequency regulation characteristics and dynamic response in microgrid applications. The improved V/f control strategy, frequency-based control, power quality enhancement modelling and control with communication delay, modified droop control for load sharing and peer to peer integration of microgrids based on master-slave control are discussed in [70–75].

These control strategies deal with the control of DGs, improvement in power quality and performance, power transfer between main grid and microgrid using microgrid central controller (MGCC) and international standards (IEEE/IEC) of microgrid interfacing with utility grid [76]. The radial basis function neural network (RBFNN) is implemented for better power sharing in microgrid system under the operation of non-linear and unbalanced loads. The power quality could be improved by compensating the harmonics and unbalance in voltage and frequency under the governance of RBFNN model [77]. The maximum power point of renewable energy resources is tracked using adaptive neural network (NN). The adaptive NN controls the power exchange between DGs and utility grid (UG); extracting minimum power from the UG to satisfy the load requirement under different operating conditions [78]. The series active power filter is introduced to compensate the voltage and current harmonics and interruptions [79]. A fuzzy logic controller is used to improve the power quality of PV based three-phase three-wire DSTATCOM by maintaining DC link voltage of voltage source converter (VSC) [80].

The RBFNN is also proposed to track the maximum power point (MPP) in PV system to improve the dynamic response of microgrid under different modes of operation [81]. The fuzzy droop control strategy could also be implemented to design storage system of DC

microgrid [82]. The different storage devices could coordinate to each other with the optimal design of model predictive control (MPC) for load frequency control [83].

As a part of the power quality assessment in robust microgrid operation and control, it is realized that there is a huge amount of non-linearity in the system with the combination of different DERs. The microgrid comprises the interconnection of DERs as per their geographical locations which increase the number of variables and equations like solar irradiance level, temperature, humidity, weather condition, wind speed, seasons etc. To make stable and reliable operation of microgrid, the power quality should be maintained to the best satisfaction of consumers with lesser burden on power supplier entities or DGs.

The term ‘microgrid’ is introduced to utilize the distributed generation from renewable energy, energy storage and combined heat plants with reduced transmission and distribution losses. This improves the grid resiliency, power quality and the amount of electricity. The microgrid operation can be made secure and reliable with the help of advanced technologies like power electronics, communication protocols, control and efficient use of energy storage devices under grid-connected and islanded conditions.

In addition, the microgrid central control (MGCC) plays very important role in microgrid control framework. It manages DERs, BESs, loads profile, monitoring and controlling the entire microgrid operation. It also ensures the smooth transition between the utility grid and DERs. In grid-connected mode, the MGCC regulates the microgrid for best operational performance and also adjusts the DER output and load consumption to ensure stable and safe operation of the microgrid during islanded condition. The literature on operation and control of microgrid system are discussed in case of grid-connected mode, during transition period and islanded mode of operation in the next Sub-sections 2.1, 2.2 and 2.3 respectively. The role of communication infrastructure in microgrid control and the outcome of literature survey are discussed in the Sub-sections 2.4 and 2.5 respectively. The objectives of research work are summarised in Sub-section 2.6.

2.1 OPERATION AND CONTROL OF MICROGRID IN GRID-CONNECTED MODE

The authors have implemented a laboratory protocol for multibus microgrid under grid-connected mode using unified controller to regulate the power within the microgrid and on grid side [10]. The microgrid is composed of main grid and different types of renewable

energy sources (RES). The control techniques could be optimized in order to improve the grid operation. Hence, it could be more beneficial to adjust power factor at PCC in different time periods and generator operates under constant power by filtering the active power [15]. The proposed control scheme is capable to maintain the voltage and frequency within the standard permissible levels during grid-connected mode of operation. To study the frequency and angle reference of the PCC voltage, a phase locked loop (PLL) method is being used [84].

The three control modes could be implemented like fixed-power or PQ, droop and voltage/frequency control. The voltage and frequency could be maintained by means of active power versus frequency (P-f) control and reactive power versus voltage (Q-V) droop control. A voltage versus frequency (V-f) control scheme could be developed by simulation software under which voltage and frequency regulations were adjusted. A control scheme was implemented to test a medium voltage (MV) distribution network connected with microgrid during the transition from a grid-connected to an islanded mode as well as during autonomous operation [17].

A fuzzy control scheme could maintain PV system healthy under variable solar radiation profile on its maximum power condition. The self-tuned proportional-integral-differential (PID) control method might be adopted to achieve maximum power point tracking (MPPT) control of PV system. This could also help to improve the stability of whole microgrid and achieved high power factor under grid-connected mode with the elimination of harmonics using PWM control of inverter [85].

The microgrid could be utilized effectively to reduce the consequences of natural disaster, so a proposed control scheme could maintain a coordinated operation between interconnected units in microgrid and main grid which satisfied the emergency situations and disaster relief requirements [86]. The combination of superconducting magnetic-energy storage (SMES) with DSTATCOM could control the tie-line power flow effectively including wind generation. This is capable of supplying the active and reactive powers simultaneously in the power system which enhanced the dynamic security [87].

From the above study it is observed that it is much essential to maintain voltage stability, active-reactive power, power quality and balanced sharing of powers under grid-connected mode. The system should be controlled under any operating condition by continuous

monitoring of live data so that emergency loads will not suffer from any unavoidable situation.

2.2 MICROGRID CONTROL DURING TRANSITION FROM GRID-CONNECTED TO ISLANDED MODE AND VICE-VERSA

The multiagent system (MAS) could be implemented to control the microgrid operation under grid-connected and islanded modes. The MAS has provided the integrated control mechanism for deciding the proposer use of each DER and critical loads. This approach could be useful to make a comparison between decentralized and centralized control for a microgrid [88]. By comparing the main grid voltage characteristics with pre-established threshold value for a short (tolerable) period of time, it could be decided to transfer the load from main grid to the islanded microgrid. This comparison also helped in removal of unwanted islanding of the microgrid. Before reconnecting the microgrid DERs from islanded to grid-connected mode, the microgrid has to be synchronized with grid voltage within the tolerable time limit [15].

An IBS has ability to detect the fault in main grid and microgrid during transition from grid-connected to islanded operation. During this transition, power reference, frequency and amplitude of the voltage inside the microgrid could be adjusted but after clearing the fault, it is found that the transition from islanded to grid-connected operation is more complicated. After recovering the fault, all major parameters could be detected by IBS which has decided the final condition of resynchronization [16]. An adaptive control system could be proposed for a DC microgrid in relevance to the data centres which worked on the eight different modes under 23 possible transitional states with planned or unplanned events. The adaptive control system could be able to monitor the conditions like outage, re-stabilization of utility grid and all the DERs connected within microgrid. The proposed model also resulted about the transition affects on current, operational, emergency and standby modes [19].

To access the economical benefits for industrial and commercial customers, a microgrid could be controlled with a central controller using neural network to optimize the proper scheduling of generators and sensitive loads. It could be implemented that the learning and prediction time must match with the real situation of the system [89]. With the combination of various power sources, it could affect the quality of power supply and created problems with control system. The researchers had proposed control technique to maintain the

operational stability with the combination of various DERs by solving the power quality issues such as frequency fluctuation, real power balancing and maintaining tie-line power flow fluctuation within the microgrid system [90].

In paralleled inverter-based distributed generator units, there is a problem of low-frequency relative stability. So, the adaptive decentralized droop control methodology could be introduced by proper sharing of power to maintain the overall stability. This controller ensured the robust performance of paralleled inverter system that the active damping of power oscillations at any operating condition could be achieved [91]. By introducing a central controller for microgrids, it could be possible to maximize the optimal production of local DGs and power sharing with the main grid which is being developed for low-voltage microgrid in all modes of operation [92]. To compensate the fluctuation of active power in microgrid, a power system stabilizer could be proposed which makes an efficient operation of DGs and maintain stable power supply to the loads during transition of DERs [93].

The hardware-in-the-loop (HIL) simulation system could be proposed to develop and test control algorithms and operation strategies in the application of microgrid. The system is composed of a real-time digital simulator (RTDS) for real-time world and a prototype microgrid management system (MMS) for testing. The MMS could be designed to operate and control the power flow at the PCC in grid-connected mode; and voltage and frequency control in the islanded mode [94]. The power sharing by droop controller could be decentralized with the presence of converter interface and inertial sources. It is observed that the real power sharing depends on frequency, angle droop control and output voltage angle [18].

A hybrid AC/DC microgrid could be implemented to reduce the processes of multiple DC-AC-DC or AC-DC-AC conversions in a single AC or DC microgrid. Both AC and DC networks are connected together by multi-bidirectional converters. The control algorithm could be proposed for smooth power transfer between AC and DC links and stable system operation under different generation and load conditions. It is found that the system could maintain stable operation while there is a change in transition state [95]. A novel control system could be proposed for the operation and protection of a microgrid with following functionalities such as static switch control system, power line signal processing system, magnetic contactor control system and dynamic load shedding system to ensure the fast faults

detection [96]. The combination of SMES controller and power conditioning system (PCS) could be used for the stabilization and power flow control of wind hybrid microgrids during transition periods [97]. The balance between distributed resources could be controlled by implementing the generation rate constraint (GRC) and P-f droop characteristics for the parallel operation of generating sources incorporated with automatic generation control (AGC) [98].

With the previous discussion, it is revealed that the overall performance of microgrid could be improved by the use of system wellbeing (SWB) index which has shown the reliability and supply-adequacy improvement from 86% to 93% by optimal installation of distributed reactive sources and distributed energy storage resources [99]. The bidirectional quasi-Z source inverter (qZSI) control strategy could be used as the interlink converter in hybrid AC/DC microgrids. It provided the maximum constant boost for the qZSI in grid-connected and islanded modes of operation without regulating the voltage of the capacitor at the DC side of the qZSI interlink [100].

In order to improve the performance of a microgrid, a low-bandwidth communication (LBC) based decentralized droop control method could be implemented to enhance the current sharing accuracy and restoration of the bus voltage during transition period [101]. The market policies of the microgrid could be introduced into the commercial power system using the Power World Simulator. A suitable mechanism could be developed including inverter-interfaced DERs for power-flow studies [102].

It is concluded from above discussion that the transitional state for emergency loads are much crucial because it is compulsory for whole system to be synchronized during switching from grid connected to islanded or isolated condition and vice-versa. A typical microgrid must withstand under any operating conditions to maintain the voltage profile, frequency and power sharing within the allowable limits among the selected DERs.

2.3 OPERATION AND CONTROL TECHNIQUES IN ISLANDED MODE

The islanding of microgrid could be scheduled or forced while maintaining the system health, the single and/or multi-master control strategies are effective, efficient and fast under the same operation using more storage devices [103]. In case of islanded low voltage (LV) microgrid, the operation of parallel inverters in AC distributed system could be controlled using novel wireless load-sharing controller. It is found that the proposed resistive output

impedance method is reliable, flexible and convenient as compared to conventional droop control method [104].

The control strategies for islanded microgrid operation could be maintained stable and efficient using the multi-master controller under power importing and exporting conditions. It is recommended to have more storage devices for stable, better and fast control strategies under islanded mode [105]. Under autonomous operation when microgrid is taking all the responsibilities, the droop method could balance the power sharing between all the connected uninterruptible power supplies (UPSs) with respect to charged batteries of each module [16].

The hierarchical approach suggested that how the problem of controlling frequency and active power generation of a MV network could be sought out under islanded mode of operation with respect to several DERs. The same approach provided a flexible and cost effective method to control the whole network with multiple numbers of microgrids [19]. A control strategy could be implemented to keep constant voltage to the local loads when microgrid put intentionally under islanded mode. The proposed control scheme is also capable to maintain the voltage and frequency within the standard permissible levels during islanding condition [84]. The high performance of power and voltage regulation could be achieved with the help of proposed active power-voltage control scheme. A new active power and voltage control schemes could be implemented for inverters and droop control method for power sharing under parallel inverters interfaced with DERs [106].

For a stable operation, a BES system could be interfaced with a bi-directional inverter because during transition from grid-connected to island mode, the inverter could set the voltage and frequency by means of absorbing or releasing energy and this could increase the reliability of energy supply in microgrid operation [107]. In islanded mode, it is observed that the power management scheme might be beneficial for power electronics based LV microgrid. The proposed real and reactive power control could be used to improve the system transient and stability performance based on the virtual frequency and voltage [108].

A control strategy was proposed in islanded mode based on the line frequency control between the distributed power generation (DPG) modules. The algorithm of DPG voltage module could control the battery charge with a frequency generator function and DPG current module could control its output current through the frequency detection function [100]. The proposed hybrid control architecture could balance the power sharing among the multiple

interfaced inverters and optimize the system efficiency to sustain with the loads variations under islanded condition [109].

Under islanded mode of operation, the conventional droop P/f control strategy could be used for active power control which is called as the voltage-droop controller. The active load control could be triggered by the microgrid voltage and hence the voltage-droop control strategy allows reliable power supply without inter-unit communication with efficient use of DERs [110]. The RS-485 based master-slave interface could be developed for the operational control of microgrid. The solar PV source could be controlled by microgrid master controller (MMC) to cater the critical and non-critical loads [111]. A model could be implemented for the control of reactive power in islanded mode of operation. The dynamics of voltage and reactive power of doubly fed-induction generator (DFIG) and synchronous generator are designed through this model. The control strategy could be used to compensate the reactive power during islanded condition [112].

The proposed control strategy could be comprised by a proportional resonance controller with an adjustable resonance frequency, droop control and a negative-sequence impedance controller (NSIC) to regulate the load voltage and power sharing components. The NSIC is used to compensate the negative-sequence currents of the unbalanced loads and improved the power quality of the microgrid [113]. On the basis of two-loop current-mode, the variable frequency and output power feed-forward controls could be applied for stable and better operation of the converter during fault conditions [114]. Under islanded mode of operation, the proper control strategies could be analyzed at the PCC for islanding detection techniques and black box arc model of circuit breaker [115].

It is revealed from the above literature survey that the microgrid must have capability of operation under isolated or islanded condition to fulfil the demand for critical loads like hospitals, shopping malls, offices etc. By applying useful and reliable techniques, microgrid could work smoothly under islanded condition with more energy storage devices and balanced power sharing to the main utility and emergency loads.

2.4 ROLE OF COMMUNICATION INFRASTRUCTURE FOR MICROGRID CONTROL AND PROTECTION

With the existence of generators connected to distribution system, a new protection system could be developed which monitors the microgrid and keeps updating relay fault currents

according to the variations in the system. The proposed model of protection could be implemented with the help of IEC61850 and IEC61850-7-420 communication standards. The proposed system could be designed in such a way to give fast response with respect to connection/disconnection of DGs under dynamic changes [116]. A digital protection system could be executed in microgrid based on the wavelet packet transform (WPT) to extract high-frequency contents present in the d-q axis current components. The d-q WPT based digital protection system has given fast, reliable, accurate classification and response to different transient disturbances and this protection system is able to generate a trip signal within quarter cycle based on respective system frequency [117].

The feasibility of wireless fidelity (Wi-Fi) for a metropolitan area network (MAN) of intelligent electronic devices (IEDs) could be investigated in a meshed network of a microgrid. A wireless network such as Wi-Fi could allow fault location identification by the use of triangulation method however the wireless network has some security and interference issues [118]. For large microgrids in power distribution system, a dedicated communication network is required to control the actions under various operating conditions. It is suggested that the communication system might be implemented for wireless transmission and accommodates the traffic patterns generated by the control action within the microgrid. The communication model could be implemented based on the optimized network engineering tools (OPNETTM) simulation tool for investigating the impacts of latency and losses in the microgrids [119].

It is revealed that the best control and protection systems are more essential including communication system for a reliable and stable operation of a microgrid. The advance protection schemes are administrated by the communication systems to monitor the live status of grid-connected and islanded microgrids. The communication system would also help to make protection system more reliable and fast switching between these two operating modes without disturbing the supply to the emergency (critical) loads. As a whole, the operation and control of microgrid have direct relationship with the power quality, stability, security and reliability.

2.5 OUTCOMES OF LITERATURE SURVEY: GAPS IN RESEARCH

It has been realized that in most of the research articles the combination of voltage, frequency, THD and power factor as estimating variables have not been considered

simultaneously in microgrid application. In addition, the thrust research areas, such as, power quality control, communication protocol based control ensuring higher level of protection and reliability are found as the emerging fields where some new features can add value in microgrid research. During the literature review, it is realized that the present work can be extended in the area of controller design for AC microgrid. It is also found that the power quality should be ensured for satisfactory operation and control of microgrid system. The microgrid controller may facilitate ADSM to cater the critical and non-critical loads connected with the microgrid. It is also revealed that microgrid controller can work based on voltage and frequency of the system ensuring stability. So, the design and modelling of controller is a challenging issue in the microgrid research to extract the optimum performance of overall system. The microgrid system can be investigated under various loading conditions since its performance may vary depending upon the types of loads.

2.6 OBJECTIVES OF RESEARCH WORK

The power quality control, modes of operation and communication infrastructure are the major issues to make optimum operation of microgrid. The power quality related control parameters, modes of operation (grid-connected and islanded) and role of communication infrastructure have been considered for microgrid design to focus on the importance of power quality including the microgrid central controller. This accomplishes the first two objectives of the thesis in designing and modelling of microgrid and controller topologies. To propose a microgrid controller, proper designing of microgrid system is very much essential to validate the effectiveness of proposed controller through modelling and simulation. The main objective of this research is to quantify the power quality considering the fuzziness in variation of voltage, frequency, power factor and THD due to the occurrence of voltage sag, swell, interruption and unbalancing in three-phase AC microgrid feeding linear/non-linear, balanced/unbalanced, dynamic and rotational loads. Therefore, a novel FIS based PQMI is proposed to determine the status of power quality. The present work sets to exhibit the combined effect of voltage deviation, frequency, power factor, THD, voltage sag, swell, interruption and unbalance on the PQMI. This may vary individually or simultaneously as per the transition between DERs and nature of loads depending upon the site conditions. The power quality is monitored with the help of number of variables such as voltage deviation, voltage sag/swell, unbalancing, frequency, THD and power factor which have not been explored simultaneously in previous literature.

An ANN-based MGCC has been proposed to enhance the overall performance with fast, smooth and stable operation of microgrid due to large number of variables with non-linear equations. It is not possible completely to eliminate the cause of power quality disturbances but the quality of power can be improved or maintained by the use of mitigation techniques like custom power devices and power conditioning equipment. Hence, the microgrid model has been proposed and simulated successfully by maintaining voltage dips, THD, power factor, frequency and unbalancing of the three-phase AC microgrid. So, considering all these issues the following objectives are set for the present research work.

1. Design and model of microgrid system.
2. Design of controllers for microgrid system.
3. Optimum performance of microgrid system.
4. Performance of microgrid under linear/non-linear, balanced/unbalanced and dynamic loads.

DESIGN AND MODELLING OF MICROGRID SYSTEM IN PERSPECTIVE OF POWER QUALITY MONITORING PARAMETERS

If the modelling and simulation are done properly then the system performance can be validated before on-site installation which can reduce the research and development costs for planning and design of the microgrid system. Hence, the proposed microgrid has been modeled using MATLAB-Simulink software which is discussed in the next sub-sections presented in this chapter. The microgrid system has been modeled and simulated as single-phase and three-phase AC systems. The work is started with a small single-phase AC microgrid model and then extended to medium size three-phase AC system considering the parameters related to power quality.

3.1 OPERATION AND CONTROL AS MAJOR ISSUES IN MICROGRID SYSTEM

Microgrid is a self-sustaining energy model to enhance a futuristic smart grid with almost negligible carbon emissions and environmental hazards. This would suggest generation and distribution of power within its small boundary of operation in a coordinated way with focus on integration of non-conventional sources. During grid-connected and islanded conditions, the microgrid has following issues for its satisfactory operation and control.

- The active and reactive power balance while maintaining power quality within the microgrid.
- The conventional protection and controlling devices are not feasible or valid due to bidirectional power flow between the DERs and utility grid.
- Coordination issues of intermittent sources like PV or wind as they dependent upon availability of sources.
- Protection issues of microgrid during grid-connected and islanded modes of operation.

The above mentioned issues and problems highlight the background for the satisfactory operation and control of a microgrid system. So, the design aspects of microgrid and controller are reviewed in next Sub-section 3.1.1.

3.1.1 Design of microgrid system and controller

The proper design of microgrid system can help engineers to design the controller effectively for its successful operation as the system and controller, both are equally important and have close relation to each other. The unified controller could be designed and analyzed to initiate switching between grid connected and islanded modes for multibus microgrid system [10]. An inverter based microgrid could be modeled, analyzed and tested for autonomous operation to improve the system stability in low and high frequency ranges [11]. It is reviewed that the efficient design, control, operation, protection and economic issues are the major challenges of microgrid integration in power systems for the engineers [12]. The design of DERs and loads could be interfaced based on frequency analysis during islanded mode when main grid is disconnected [13]. The fault could be isolated rapidly with proper design and coordination of circuit breakers to restore the overall performance of distributed system [14]. The design approaches, schematic diagrams of single-phase and three-phase AC microgrid systems are discussed in next Sub-sections 3.2, 3.3 and 3.4 respectively.

3.2 DESIGN APPROACH FOR MICROGRID SYSTEM

The planning and design of a microgrid system should follow the IEEE Recommended Practice Std. 2030.9-2019 [120]. In the proposed microgrid model, the following parameters have been considered accordingly. In addition, the necessary components have been added in the design of the proposed microgrid as per specific features related to the power quality control issues. The microgrid planning consists load analysis, system configuration, power generation capacity etc. The microgrid design comprises of the voltage level selection, location of PCC, selection of electrical equipment etc. The power quality indices such as voltage sag/swell, fluctuations, flickers, interruption, frequency, THD, power factor etc. are the requirements which have been considered for power quality monitoring and control in the proposed system.

Selection of operating voltage: The primary microgrid system design requires proper selection of voltage level and installed capacity as per IEEE Std. 2030.9-2019. In the proposed single-phase and three-phase AC microgrid systems, the operating voltage levels are chosen as 0.23 kV (230 V) and 0.4 kV (400 V) respectively connected to the 10 kW load which is less than 2 MW.

Selection of PCC for grid connection: In the present research mainly three numbers microgrid models are considered. In the proposed model presented in this chapter, two DERs, one utility grid and two critical and non-critical loads (consumers) are considered. Hence, PCC is selected as shown in Figure 3.1 and Figure 3.2 of the proposed microgrid. It has a main feature of connection and disconnection of microgrid with utility grid with provision of protection comprising a power electronic based static switch.

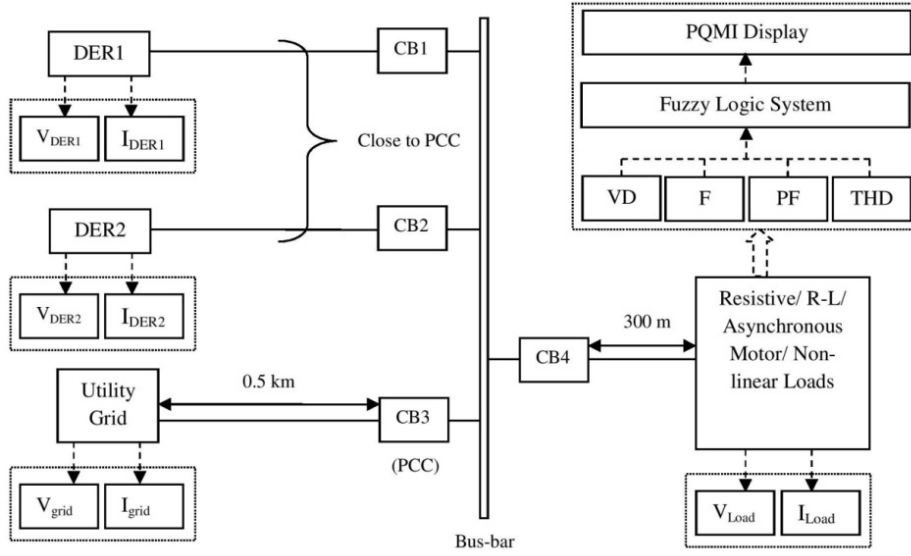
Electrical grid structure: For small size microgrid system, two DERs, one utility grid and two buses of 4 kW critical and 6 kW non-critical loads have been considered within the LV distribution network. The placement of DERs, utility grid and loads including their line distance are presented in Figure 3.1 and Figure 3.2.

Monitoring and control: For data acquisition, the FIS based PQMI has been proposed which assesses the microgrid parameters such as voltage, current, active/reactive power, power factor, frequency, THD etc.

3.3 A SINGLE-PHASE AC MICROGRID SYSTEM CONFIGURATION AND MODELLING

A 10 kW, 230 V, 50 Hz, single-phase microgrid model is proposed with the combination of two DERs and one utility grid. In this model, one DER is postulated as a fine-tuned PV generator and other one is postulated as a fine-tuned source of fuel cell. In this study, the output voltage of both DERs is postulated to be constant. The DER1 and DER2 are designed with same power rating of single-phase bridge inverter. Here, the main objective is to analyze the parameters of a microgrid during different transition periods in favour of power quality indices under different loading conditions. The microgrid is operated through transitions from grid connected to islanded mode and vice-versa. The utility grid is located at a line distance of half kilometre (0.5 km) from the PCC close to common bus as shown in Figure 3.1.

Further, from PCC, the distance of load in terms of line length is considered as 300 metres. In the low voltage (LV) line, the resistance (R) is 0.642ohm/km and reactance (X) is 0.083ohm/km so accordingly the R/X ratio is 7.7 [121] where in case of medium and high voltage lines this ratio is less than one. Consequently, the impedances of 0.5km and 300m lines have been calculated considering LV resistive network as per reference [121] to replicate a practical microgrid system.



Legends:

DER	: Distributed energy resource	CB	: Circuit breaker
PCC	: Point-of-common coupling	VD	: Voltage deviation
F	: Frequency	THD	: Total harmonic distortion
V	: Voltage	I	: Current
PQMI	: Power quality monitoring index	PF	: Power factor

Figure 3.1. A proposed single-phase AC microgrid system for power quality monitoring

The transition between DER1, DER2 and utility grid is initiated through the operation of three circuit breakers (CBs). The Figure 3.1 shows the proposed microgrid model in which DER1, DER2, utility grid and load are connected through CB1, CB2, CB3 and CB4 respectively. The circuit breaker CB1, CB2 and CB4 are connected with the bus-bar adjacent to the PCC (CB3) as shown in Figure 3.1. In this study the transition between all three sources take place with the operation of CB1, CB2 and CB3 keeping CB4 closed for entire simulation time.

A 10kW single-phase AC microgrid is modelled in MATLAB-Simulink in accordance with the system model configuration parameters as mentioned in Table 3.1. A Simulink block diagram represents a set of simultaneous equations that relate a system or subsystem's inputs to its outputs as a function of time. Each block in the simulink diagram represents an equation of the form $y = f(t, x, u)$ where t is the current time, u is a block input, y is a block output, and x is a system state function represented by the sundry types of blocks that make up the diagram. Lines connecting the blocks represent dependencies among the blocks, i.e. inputs whose current values are the outputs of other blocks.

Table 3.1. System simulink model configuration parameters

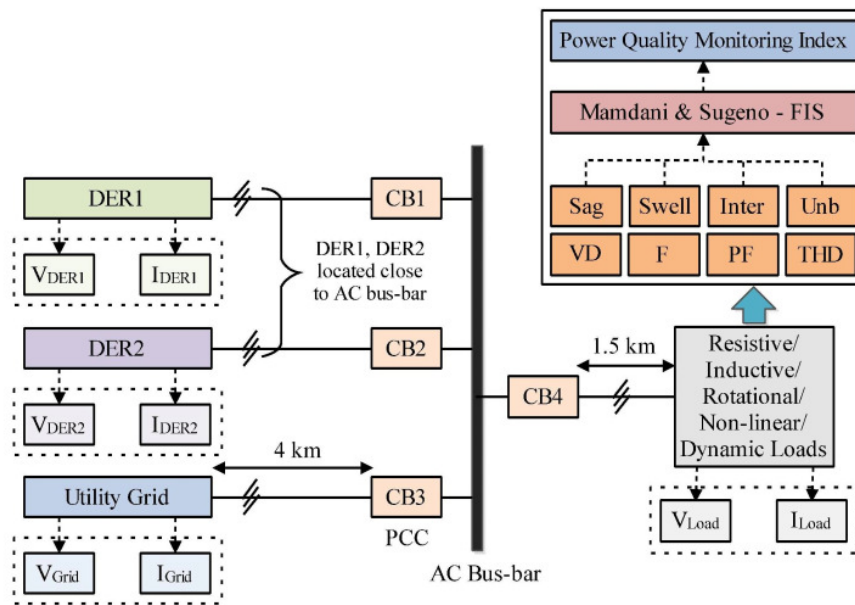
Property	Value
Simulation Mode	normal
Components	523
Start Time	0.0
Stop Time	6
AbsTol	auto
Fixed Step	1e-6
Initial Step	auto
Max Num Min Steps	-1
Max Order	5
Zc Threshold	auto
Consecutive ZCs Step Rel Tol	10*128*eps
Max Consecutive ZCs	1000
Extrapolation Order	4
Number Newton Iterations	1
Max Step	auto
Min Step	auto
Max Consecutive Min Step	1
Rel Tol	1e-3
Solver Mode	Auto
Solver	ode23tb
Solver Type	Variable-step
Solver Jacobian Method Control	auto
Zero Cross Algorithm	Adaptive
Solver Reset Method	Fast
Sample Time Constraint	Unconstrained

An implementation of a design described in this model computes a root system's outputs at each time by computing the outputs of the blocks in an order determined by block input/output dependencies. A subsystem is treated as a unit by an implementation of the design documented in this model. The implementation computes the outputs of all the blocks in the root subsystem by computing the next block in the parent system's block execution order.

3.4 A THREE-PHASE AC MICROGRID SYSTEM CONFIGURATION AND MODELLING

A three-phase AC microgrid model has been proposed with the combination of two DERs and one utility grid. In this model, DER1 and DER2 are considered as fine tuned PV

generators. The microgrid model is tested under different loading conditions to analyze the PQMI during transition periods. The three-phase AC microgrid is operated during transitions from grid-connected to islanded mode and vice-versa. It is assumed that the utility grid and load centre are located at a line length of 4 km and 1.5 km respectively from the PCC as shown in Figure 3.2. The transition modes are initiated through the operation of three units of three-phase circuit breakers (CB1, CB2 and CB3) between DER1, DER2 and utility grid as presented in Figure 3.2.



Legends:

DER	: Distributed energy resource	CB	: Circuit breaker
PCC	: Point-of-common coupling	VD	: Voltage deviation
F	: Frequency	THD	: Total harmonic distortion
V	: Voltage	I	: Current
PF	: Power factor	FIS	: Fuzzy inference system
Inter	: 3-phase interruption	Unb	: 3-phase unbalance

Figure 3.2. Proposed scheme for three-phase AC microgrid to assess PQMI using fuzzy inference system

Modelling approach using MATLAB-Simulink software

A 10 kW, 400 V, 50 Hz, three-phase AC microgrid system is modelled in MATLAB-Simulink software to evaluate the status of PQMI under different loading conditions during grid-connected and islanded modes of operation. The root system of three-phase AC microgrid is shown in Figure 3.3 including two DERs, one utility grid and load connected

through PCC. Both DERs are rated with same power rating and supplying constant power without considering climatic changes. In this chapter, the DER1/DER2 are selected as a fixed supply of DC source but the effect of actual model of the PV source considering the variation in irradiance is analyzed in Chapter 6 while maintaining the power quality for optimum operation of microgrid. The inverter model based on ANN control is explained in detail in Chapter 5 because this chapter presents only the monitoring parameters without analyzing the power quality control aspects. The gate pulses of IGBT based three-phase inverter are supplied by the simple PWM pulse generator with carrier frequency 4000 Hz and modulation index 0.85.

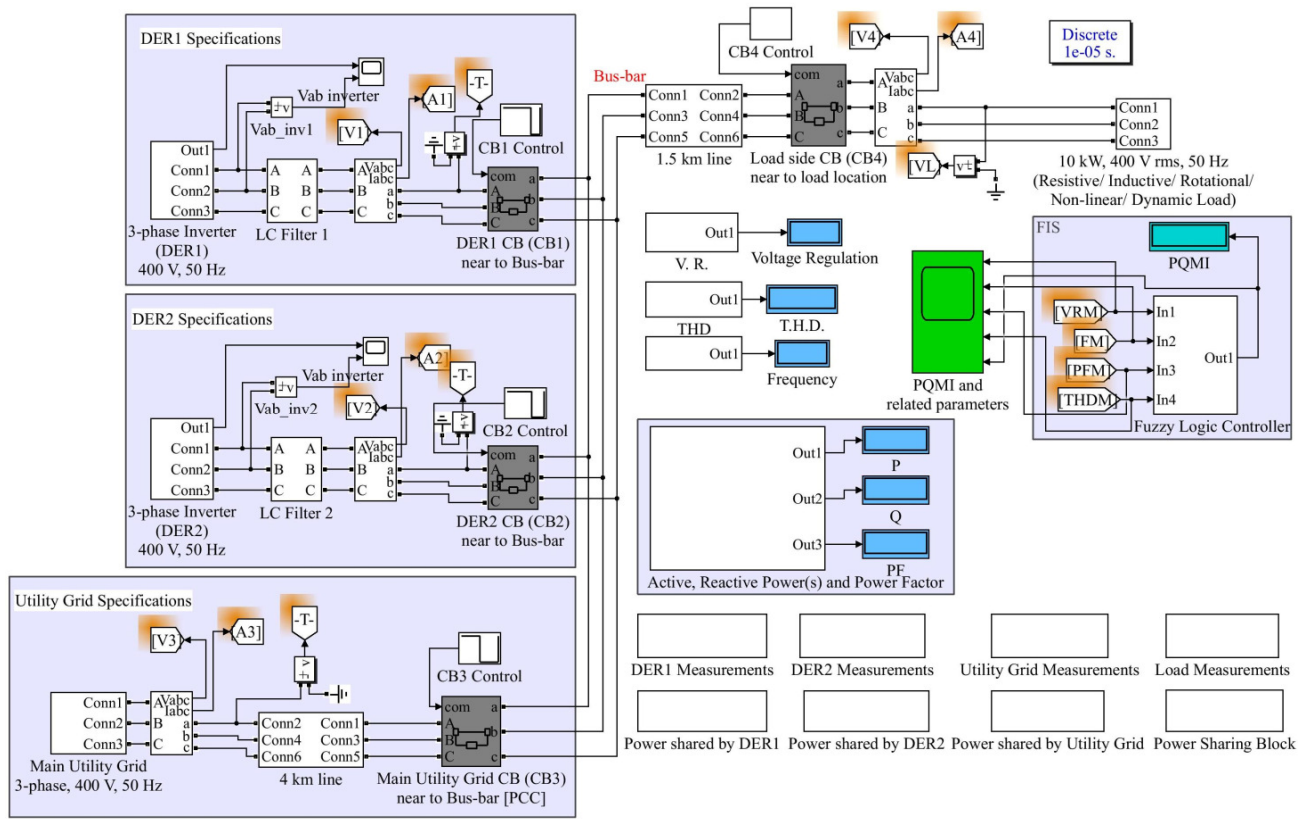


Figure 3.3. Simulink model of proposed three-phase AC microgrid root system using FIS to assess the status of PQMI

The major transitions such as grid-connected and islanded modes are initiated by operating the breaker CB3 (or PCC). The measured parameters from DER1, DER2, utility grid and load measurement windows are fed to FIS block which displays the PQMI using fuzzy logic controller as shown in Figure 3.3. The detailed modelling of fuzzy inference system (FIS) is discussed in next Sub-sections 3.5 and 3.6 to avoid repetition. The three-phase AC microgrid is tested for resistive, inductive, rotational, non-linear and dynamic load

to enhance the power quality during grid-connected and islanded modes of operation. The three-phase load is located at a line distance of 1.5 km from PCC connected near to AC bus-bar and 5.5 km (4 km + 1.5 km) from utility grid through PCC as shown in Figure 3.3. The impedances of 4 km and 1.5 km lines are calculated as per [121] to replicate a practical three-phase AC microgrid model. The PQMI is assessed as per status of the VD, F, PF, THD, sag, swell, interruptions and unbalance during microgrid operation in the next Chapter 4.

3.5 IMPORTANCE OF FIS SYSTEM FOR POWER QUALITY MONITORING

The fuzzy logic system is utilized to formalize reasoning and decision making predicated on system output replication. In this paper, the methodology is proposed to take a decision to exhibit the PQMI predicated on status of four input variables such as voltage deviation, frequency, power factor and THD during transition periods. The 256 number of rules are pre-defined/designed in FIS window for taking decision to exhibit the PQMI predicated on rule-based fuzzy system as per the arbitrary/simultaneous status of four input variables. Here, fuzzy rule-predicated system is subsidiary to pick any rule out of 256 numbers of rules predicated on the hypothetical combination of four input variables during grid-connected and islanded modes of operation. The fuzzy logic controller (FLC) is flexible, intuitive cognizance base design control, convenient, utilizer amicable, more facile computation; and validation and consistency of the system can be checked utilizing rule-predicated approach. It is apposite with the combination of reasoning and function approximation for the concerned system quandary. Many advantages and circumscriptions of FLC have been concluded in [122]. Since, microgrid model deals with non-linearity due to converter topologies and nature of loads, the FIS shows the practical applicability to monitor the power quality during grid-connected and islanded modes of operation.

The FIS system can be designed for assessment of PQMI corresponding to n number of rules as per m numbers of input variables. The input variables would be listed as per the following variables represented by equation (3.1).

$$\mu(x_m) = f(x_1, x_2, x_3, \dots, x_m) \quad (3.1)$$

where x_1 is voltage deviation, x_2 is frequency, x_3 is power factor, x_4 is THD, x_5 is long interruptions, x_6 is short interruptions, x_7 is voltage sag, x_8 is voltage swell, x_9 is flickering, and up to x_m for m number of input variables. The output variable y can be generated as per

the total number of rules associated with the actual number of input variables. The rules are framed as per the combination of input variables for assessment of PQMI; the number of rules can be calculated using equation (3.2).

$$\text{Number of rules, } n = MF^a \quad (3.2)$$

where MF represents total number of membership functions for each input variable and a is the total number of considered input variables.

The proposed FIS presented in Figure 3.4 can be implemented for any combination of DERs along with different nature of loads (linear/non-linear). The same FIS has been incorporated in case of three-phase AC microgrid system to check the health of power quality at load end. It is observed that the FIS presented in Figure 3.4 will work smoothly for three-phase AC microgrid topology. Four input variables have been considered to assess the PQMI for two types of topologies of microgrid system i.e. single-phase and three-phase AC system. So, based on number of input variables, power quality can be quantified in reference to the maximum number of rules given by equation (3.2).

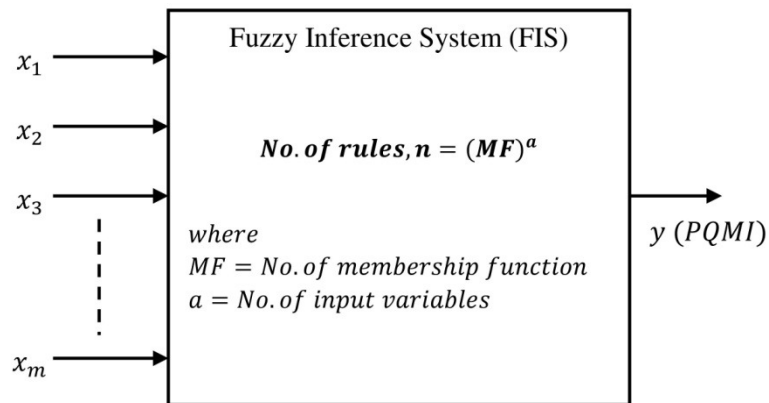


Figure 3.4. A general FIS approach for assessment of PQMI

3.6 ASSESSMENT OF POWER QUALITY MONITORING INDEX (PQMI)

The proposed PQMI can be considered as the major contribution of this thesis. It can quantify the quality of power through a single index. This novel PQMI can guide a power manager for decision making action in monitoring, controlling and maintaining reliability of the microgrid system. This proposed PQMI can be used as a decision variable to highlight the health status of microgrid by sensing the system parameters continuously such as voltage deviation, sag,

swell, interruption, unbalance, frequency variation, power factor and THD during grid-connected and islanded modes of operation.

The PQMI can be monitored during grid connected and islanded modes by operating CB1, CB2 and CB3 while CB4 remains closed throughout the simulation operation. The resistive, inductive, rotational, non-linear and dynamic loads have been considered for the assessment of PQMI. The PQMI has been displayed based on the following input parameters such as voltage deviation, frequency, power factor, THD, voltage sag, swell, interruption and unbalancing in three-phase system. The status of these parameters avails to exhibit the FIS-based PQMI. The Mamdani and Sugeno type FISs are discussed in Sub-section 3.6.1 and 3.6.2 respectively to assess the PQMI for proposed microgrid system. As per present power market scenario, it is desired for three-phase AC microgrid to feed loads efficiently with appreciable quality of power. The smooth power supply is to be maintained to accommodate best to the consumer under grid-connected and islanded modes of operation. The Figure 3.5 shows the interfacing of rules including four inputs and one output variable predicated on Mamdani-FIS in MATLAB fuzzy implement box. The status of power quality can be defined by a predefined index number with the application of FIS. The pre-set values of PQMI (best, good, average and poor) are presented in Table 3.2 including four input membership functions with their respective ranges as per IEEE/IEC standards which are analysed and explained in later sections. Further, VD is characterized by sag, swell, interruption and unbalancing which are considered one-by-one within the FIS model to assess the PQMI during microgrid operation as shown in Figure 3.5.

Table 3.2. Membership functions range(s) for three-phase AC microgrid parameters as per IEEE 1547

MFs	Range(s)			
	Best	Good	Poor	V. Poor
VD (-10 to 25)%	[-10,0,10]	[7,10,14]	[12.5,16.5,20]	[18,22.5,25]
F (47 to 52)Hz	More Poor [47,48,48.5]	N. Poor [48,48.5,49.6]	Best [49.5,50,50.5]	P. Poor [50.4,51,52]
PF (0.4 to 1.0)	Poor [0.4,0.55,0.7]	Good [0.6,0.7,0.8]	V. Good [0.78,0.85,0.92]	Best [0.9,0.95,1.0]
THD (0 to 20)%	Best [0,2.5,5.5]	Average [5,7.5,10]	Poor [9.5,12.5,15.5]	V. Poor [14.5,17.5,20]
PQMI (0 to 8)	Best [0,1,2.2]	Good [1.8,3,4.2]	Average [3.8,5,6.2]	Poor [5.8,7,8]

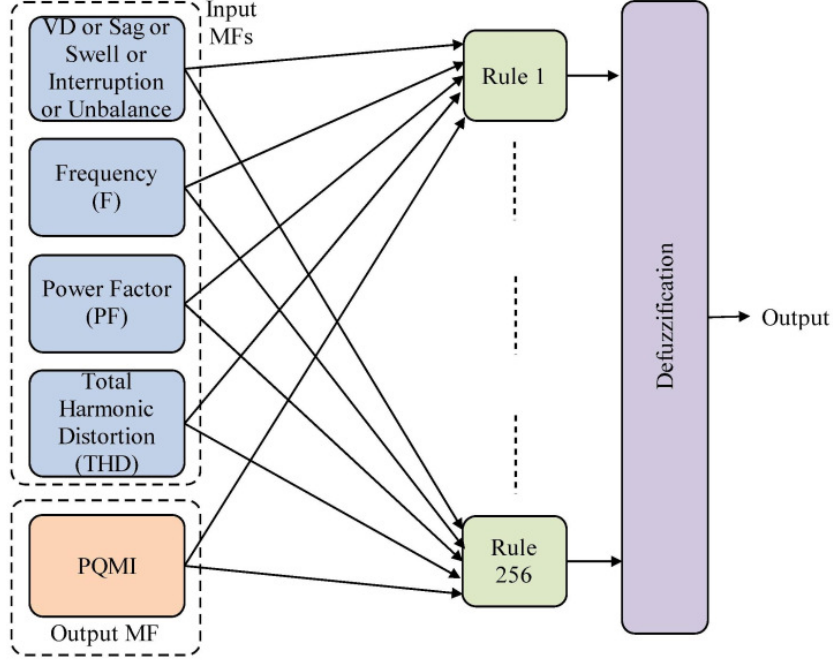


Figure 3.5. Fuzzy inference system for a proposed three-phase AC microgrid model

3.6.1 Formation of Mamdani-FIS for power quality monitoring

The PQMI is exhibited during grid-connected and islanded conditions as per the variations in four input variables. The PQMI is represented by output triangular membership function while voltage deviation, frequency, power factor and THD are represented by the group of input triangular membership functions. The ranges of all four input variables are set as per adequate limits presented in IEEE 1547 standard in favour of power quality as shown in Table 3.2. The Mamdani-FIS is appropriate to human input, instinctive and having wide area of acceptance cognate to system parameters. The Mamdani-FIS can be introduced to display the status of PQMI as per Table 3.2 during grid-connected and islanded conditions. The value of PQMI is decided by Mamdani-FIS predicated rules running from Rule 1 to Rule 256.

3.6.1.1 Design approach for membership functions

The input and output membership functions can be drawn utilizing triangular membership functions and shown in Figure 3.6(a)–3.6(e) with their respective ranges as per IEEE and IEC standards. The PQMI is decided by the Mamdani-FIS predicated rules which are framed as per the following rules like from Rule 1 to Rule 256. For the sake of better understanding, few rules are presented below out of 256 rules. The complete list of 256 numbers of rules based on four input variables and one output variable are shown in Table A as presented in

the Appendix. The single proposed PQMI would be used for further corrective action using MGCC based on the status of four input variables.

Rule 1: If V.D. is Best and Frequency is More Poor and P.F. is Poor and THD is Best Then PQMI is Poor.

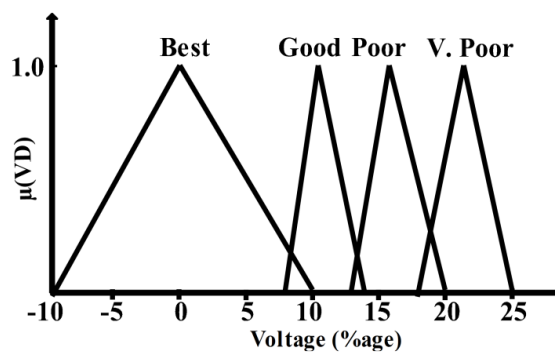
Rule 2: If V.D. is Best and Frequency is More Poor and P.F. is Poor and THD is Average Then PQMI is Poor.

Rule 105: If V.D. is Good and Frequency is Best and P.F. is V. Good and THD is Best Then PQMI is Good.

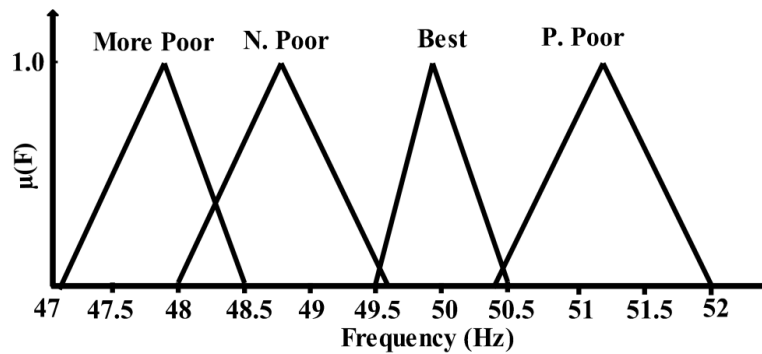
Rule 256: If V.D. is V. Poor and Frequency is P. Poor and P.F. is Best and THD is V. Poor Then PQMI is Poor.

In Figure 3.6(a)–3.6(e), four input variables have been considered such as voltage deviation (VD), frequency (F), power factor (PF) and THD for the assessment of PQMI. The triangular membership functions have been used for both input and out variables in FIS system. The allowable limit or best value of voltage deviation in case LV power system must lie within 10% of the nominal value as per IEEE Std. 1250-2011. So, the first membership function of VD as best has been formulated as (-10, 0, 10); the rest three membership functions such as Good, Poor and V. Poor were selected as per the variation observed in different nature of loads. The range for frequency variable has been settled as per IEC 61000-3-2. The variation of 0.5 Hz is designated as the best value of frequency while the remaining three membership functions are modified as per the minimum/maximum possible frequency abnormality due to non-linear loads connected in microgrid system. The authors have selected a major component which is having more concern at load side and that component is power factor. It is found from literatures that power factor has not been considered very frequently for the assessment of power quality. The range of PF has been decided by incorporating the IEC 60831-1/2 standard which suggests that the PF must be equal or greater than 0.9 otherwise low PF may damage the equipment or device due to excessive flow of current and heat. Therefore, the range of PF from 0.9 to 1.0 has been selected as best and others are represented accordingly by V. Good, Good and Poor as they are below 0.9. The non-linear loads are highly source of harmonics injection in power system so it becomes essential to maintain THD at a particular level as per IEEE Std. 519-2014 which recommends that the THD should be 5% for LV power system. Hence, the first membership function is

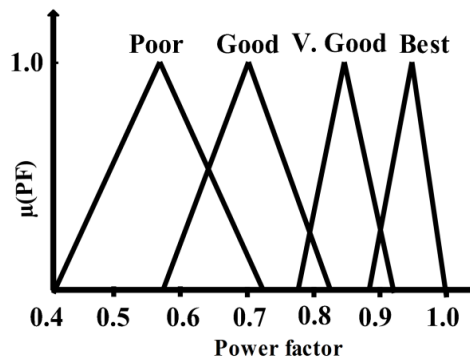
chosen as Best because of the range (0, 2.5, 5.5) while for other functions, this will be selected beyond the permissible limit. The THD level is found very high especially under islanded condition because the load is driven by the inverter supplied through PV module as in case of non-linear load. The fourth membership function is selected corresponding to the worst level of THD i.e. (14.5, 17.5, 20) which shows V. Poor THD level. Thus, the output variable (PQMI) will be displayed as per status of four input variables framed through different combination of rules. The minimum value of membership function of PQMI will reflect best quality of power and higher value of PQMI will lead to the poor power quality as listed in Table 3.2.



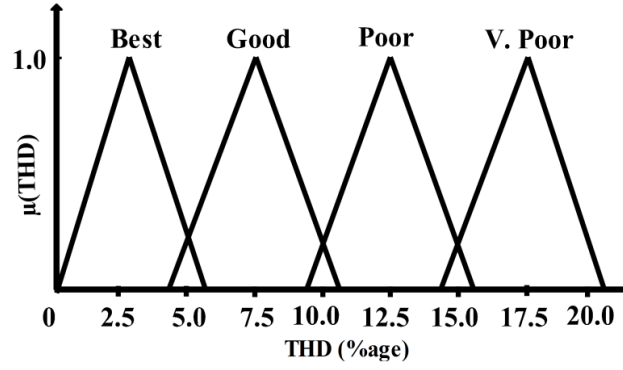
(a)



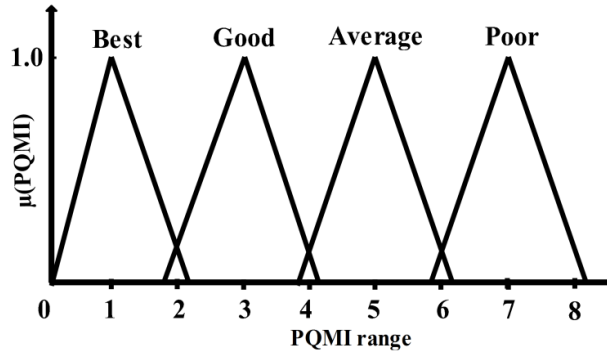
(b)



(c)



(d)



(e)

Figure 3.6. Membership functions for (a) Voltage Deviation (VD), (b) Frequency, (c) Power Factor (PF), (d) Total Harmonic Distortion (THD) and (e) Power Quality Monitoring Index (PQMI)

3.6.2 Formation of Sugeno-FIS for power quality monitoring

It may possible that the Mamdani-FIS is efficient in many cases by utilizing single spike as output membership function rather than a distributed fuzzy set. It improves the efficiency of defuzzification process due to general approach which discovers the centroid of two-dimensional function. In case of Sugeno-FIS, it utilizes the weighted average of few data points in support of the type of system. The Sugeno-FIS can be modelled for any system in which the output membership function is either linear or constant and this makes Sugeno different from Mamdani-FIS. The output function of each rule is defined as constant parameter that is singleton spike utilizing Sugeno-type inference system. The implicative suggestion and aggregation of the output is simply multiplication of all the singletons. The weighted average output is then defuzzified to the crisp value. This defuzzified output is exhibited as the status of PQMI predicated on four input variables during grid-connected and islanded operations.

$$z(PQMI) = a(VD) + b(F) + c(PF) + d(THD) + e \quad (3.3)$$

$$\text{Final or weighted output} = \frac{\sum_{i=1}^N w_i z_i}{\sum_{i=1}^N w_i}; \quad (3.4)$$

where $i = 1, 2, \dots, 256$ ($N = 256$; number of rules).

If input1 = VD, input2 = F, input3 = PF and input4 = THD then output (PQMI) is represented by equation (3.3). For a zero-order Sugeno model, the output level is constant, that is $a = b = c = d = 0$. The output level z_i of each rule is weighted by the firing strength or weight w_i of the rule; $w_i = \text{AndMethod}(VD, F, PF, THD)$. The final output of the system is a weighted average which is given by equation (3.4). The Sugeno-model is implicated using four input variables comprising 256 rules with weighted values (w_i). The final output can be calculated by substituting the values of w_i and z_i in equation (3.4) running from Rule 1 to Rule 256. As per Rule 1, if VD is 5% (Best), F is 48.5 Hz (More Poor), PF is 0.7 (Poor), THD is 2.5% (Best) then truth or weighted value (w_i) will be $\text{Min}(VD, F, PF, THD)$ that is 0.7. Therefore, equation (3.4) can be solved for all 256 rules considering the values of FIS variables as shown in equation (3.5).

$$= \frac{(0.7 \times 7)|_{Rule1} + (0.7 \times 7)|_{Rule2} + \dots + (1.0 \times 7)|_{Rule255} + (1.0 \times 7)|_{Rule256}}{(0.70)|_{Rule1} + (0.70)|_{Rule2} + \dots + (1.0)|_{Rule255} + (1.0)|_{Rule256}} \quad (3.5)$$

The constants have been placed as per the combination of rules defined in FIS, considering four membership functions for input and output variables such as VD, F, THD, PF and PQMI. In this model, the defined 256 rules are not executed simultaneously as shown in equation (3.5) rather the FIS searches autonomously the status of four input variables under grid-connected and islanded conditions. Hence, the PQMI is displayed according to the existence of one of the rules out of total 256 rules at a time. The equation (3.4) can be tested for the existence of one of the rules out of 256. Suppose, if VD is 27% (V. Poor), F is 53Hz (P. Poor), PF is 0.9 (V. Good) and THD is 15% (Poor) then PQMI should be 7.0 (Poor), which means rule no. 251 could exist as per FIS variables presented in Table 3.2.

$$\text{From equation (3.4), the final or weighted output for 251st rule} = \frac{\sum_{i=251}^{256} w_i z_i}{\sum_{i=251}^{256} w_i}$$

$\therefore$ PQMI corresponding to 251st rule is

$$= \frac{(0.9 \times 7) + (0.9 \times 7) + (1 \times 7) + (1 \times 7) + (1 \times 7) + (1 \times 7)}{0.9 + 0.9 + 1 + 1 + 1 + 1} = 7.0 \text{ (Poor)}$$

From above solution, it is concluded that the Sugeno-FIS has worked effectively by satisfying the equation (3.4) with respect to rule no. 251 as per ranges of FIS variables presented in Table 3.2.

In this chapter, the design and modelling of single-phase, three-phase AC microgrid systems and FIS-based PQMI have been presented in perspective of power quality monitoring parameters during grid-connected and islanded conditions. This novel PQMI will be compared in next Chapter 4 with significant developed methods [124–126] for its validation and feasibility in the area of microgrid topologies. The modelling approach based on MATLAB-Simulink for the proposed three-phase AC microgrid root system is

RESEARCH METHODS FOR DETERMINATION OF PQMI AND ITS APPLICATION IN MICROGRID

The PQMI-based methodology is implemented in single-phase and three-phase AC microgrid models to assess the status of power quality related parameters such as voltage deviation, sag/swell, frequency, THD, power factor etc. during grid-connected and islanded modes of operation. The proposed PQMI is assessed for these models while supplying power to linear/non-linear, static/rotational and dynamic loads. The performance of single-phase AC microgrid system has been analyzed during grid connected and islanded modes of operation as presented in the next Sub-section 4.1. This proposed PQMI approach is compared with the existing methodologies in Sub-section 4.2. The PQMI of a three-phase AC microgrid system has been assessed under different loading conditions and its performance is analyzed in the Sub-section 4.3.

4.1 SINGLE-PHASE AC MICROGRID MODEL FOR THE ASSESSMENT OF PQMI

A single-phase AC microgrid system proposed in Section 3.3 has now been monitored under grid-connected and islanded modes of operation to investigate the power quality issues. These issues have been studied for resistive, inductive (R-L), rotational and non-linear loads. The load is located at 300 m from the microgrid and 0.8 km from utility grid source through PCC as shown in Figure 3.1. The behaviours of microgrid system parameters under grid-connected and islanded conditions are plotted utilizing MATLAB Simulink Data Inspector which avails the facility to highlight the individual or group of waveform(s). The microgrid operation is monitored under grid connected and islanded modes to investigate the status of power quality for resistive load, inductive load, rotational load and non-linear load as described in the following Sub-sections 4.1.1, 4.1.2, 4.1.3 and 4.1.4 respectively. In addition to this, the combination of linear, non-linear and rotational loads connected to common load bus is also studied in Sub-section 4.1.5 to assess the quality of power (PQMI).

4.1.1 Resistive load

As per the 10 kW capacity of load, a resistance of 5.29 has been considered for pure resistive load. The PQMI is examined for the total simulation time of 6 seconds as shown in the Figure 4.1(b). The status of PQMI is monitored under different transition intervals/periods such as

grid-connected and islanded modes. The grid-connected condition is initiated from 0 second to 4 seconds. Both DERs and utility grid are connected from 1 second to 2 seconds to test the grid-connected condition. Further, during grid-connected condition, DER1 is disconnected while DER2 is connected (from 2 seconds to 3 seconds); and DER1 is connected while DER2 is disconnected (from 3 seconds to 4 seconds). If one of the DERs get opened or not available in that case how PQMI would be affected; so this situation is tested intentionally from 2 seconds to 4 seconds by operating CB1 and CB2 alternatively. The isolated/islanded condition is initiated from 4 seconds to 5 seconds by disconnecting utility grid through CB3. After 5 seconds the utility grid is recuperated up to final time window of 6 seconds. The status of PQMI is exhibited utilizing FIS methodology for above mentioned loads. In case of resistive load, it is found that the frequency waveform remain proximate to 50Hz as shown in Figure 4.1(a) under grid-connected and islanded modes of operation. The output nature of PQMI is shown in Figure 4.1(b) predicated on four input variables such as voltage deviation, power factor, THD and frequency.

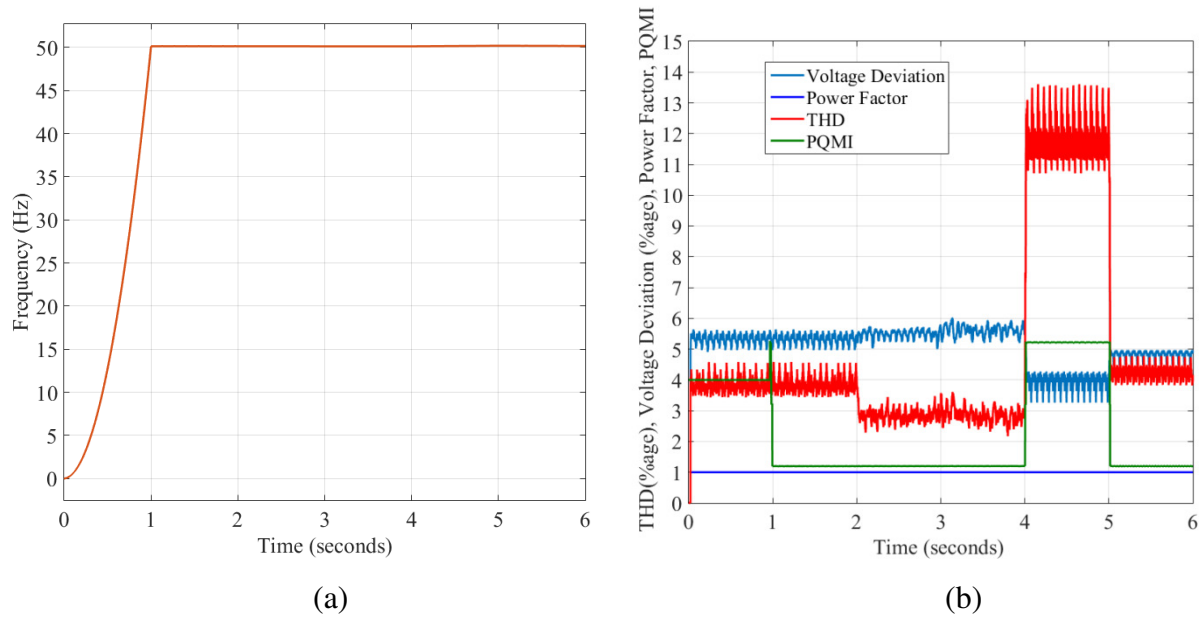
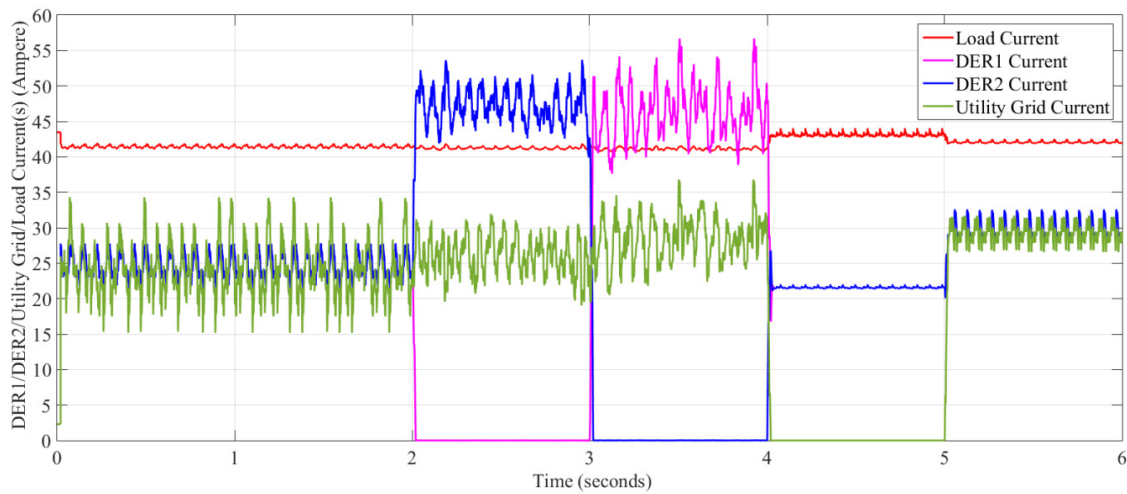


Figure 4.1. Microgrid performance (a) frequency and (b) related parameters for resistive load

Table 4.1 Single-phase AC microgrid system parameters for resistive load

Mode(s) of operation	Transition interval (seconds)	Parameters				
		V.D. (%age)	Frequency (Hz.)	P.F. (cos θ)	THD (%age)	PQMI (Scale)
Grid-connected	1 to 2	5.41	50.15	1.00	3.55	1.20
DER1 (open), DER2 (connected)	2 to 3	5.57	50.14	1.00	3.00	1.20
DER1 (connected), DER2 (open)	3 to 4	5.33	50.14	1.00	2.76	1.20
Islanded	4 to 5	3.95	50.17	1.00	13.35	5.21

It is evident that the value of PQMI is 1.20 (best) as per Table 3.2 during grid-connected mode since all four input variables are within the range as listed in Table 4.1. During islanded condition, the PQMI is observed as 5.21 (average) which is shown in Figure 4.1(b) and its magnitude is listed in Table 4.1. The reason for PQMI to be in the range of average value (5.21) is that the load is being supplied by the DERs through two parallel inverters which have inherent property of harmonics at their outputs. So due to switching in the inverter circuits the THD level is found 13.35% which is beyond the nominal range of 5% as recommended in IEEE Standard 519 [40] and [123]. Although, under islanded condition, the voltage deviation is found 3.95% which is less as compared to grid-connected condition and the reason is that the line of 0.5 km is thoroughly disconnected by opening of CB3. Consequently overall voltage drop from source to the load is reduced to 3.95% as shown in Table 4.1. The load current and current shared by DER1, DER2 and utility grid are shown in Figure 4.2 which shows clearly the contribution of DERs and utility grid.

**Figure 4.2.** Current(s) sharing during grid-connected and islanded conditions – resistive load

4.1.2 Inductive load

The load impedance (R-L) of 10 kW and 7.5 kVar are set to monitor the power quality index for a single-phase AC microgrid model during grid-connected and islanded modes of operation. The Figure 4.3 represents the grid-connected condition from 0 to 4 seconds in which DER1 is disconnected from 2 seconds to 3 seconds while DER2 supplied the load. From 3 seconds to 4 seconds, the DER1 is reconnected while DER2 is disconnected. The utility grid is shut down after 4 seconds to investigate the islanded condition while DER1 and DER2 are simultaneously connected with the microgrid system. After 5 seconds the utility grid is recuperated till the terminus of simulation time with reverence to already connected DER1 and DER2. The system parameters during grid-connected and islanded modes of operation are rolled in Table 4.2 and the observation of this table is graphically represented in Figure 4.3(a) and 4.3(b).

It is visually perceived that the PQMI is exhibited as 3.20 to 3.25 (good) during grid-connected condition due to the range of power factor (0.89, lagging) and frequency (49.53Hz to 50.17Hz) input membership functions as shown in Table 4.2. During islanded condition, the PQMI is obtained as 5.22 (average) due to the reduction in frequency (49.26Hz) and power factor (0.89, lagging) as shown in Table 4.2 which is ruled out predicated on Table 3.2. In addition, this average value of power quality index occurs due to the reason that the two parallel connected inverters supply power with innate property of harmonics in the output. So, due to switching circuit in the inverters the THD level is observed as 8.52% which is outside the recommended range of 5% as illustrated in IEEE Standard 519. During islanded condition, the voltage deviation is amended by one percent as shown in Figure 4.3(b) and Table 4.2 because utility grid is disconnected thus eliminating the power loss due to 0.5 km line which is the distance between utility grid source and PCC. The variation in voltage deviation, THD, frequency and power factor are shown in Figure 4.3(a) and 4.3(b). The load current and current shared by DER1, DER2 and utility grid are shown in Figure 4.4 which expresses the virtually constant pattern of load current during all transitions from 0 second to 6 seconds.

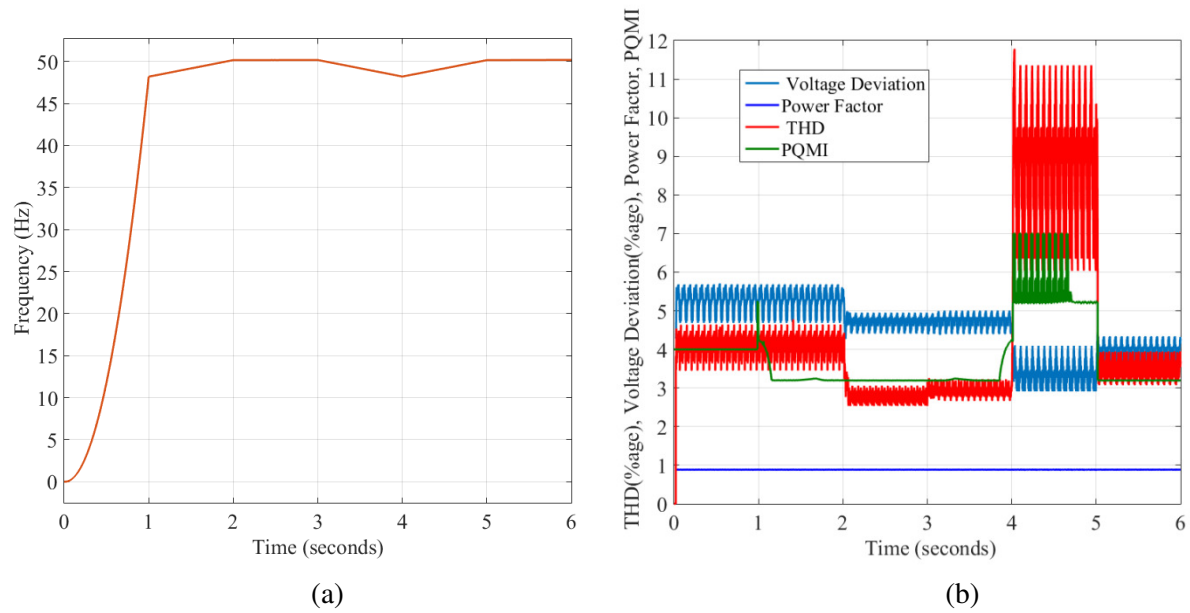


Figure 4.3. Microgrid performance (a) frequency and (b) related parameters for inductive load

Table 4.2. Single-phase AC microgrid system parameters for inductive load

Mode(s) of operation	Transition interval (seconds)	Parameters				
		V.D. (%age)	Frequency (Hz.)	P.F. (cos θ)	THD (%age)	PQMI (Scale)
Grid-connected	1 to 2	4.81	49.53	0.89	3.46	3.25
DER1 (open), DER2 (connected)	2 to 3	4.83	50.17	0.89	2.92	3.20
DER1 (connected), DER2 (open)	3 to 4	4.83	50.17	0.89	2.92	3.20
Islanded	4 to 5	3.85	49.26	0.89	8.52	5.22

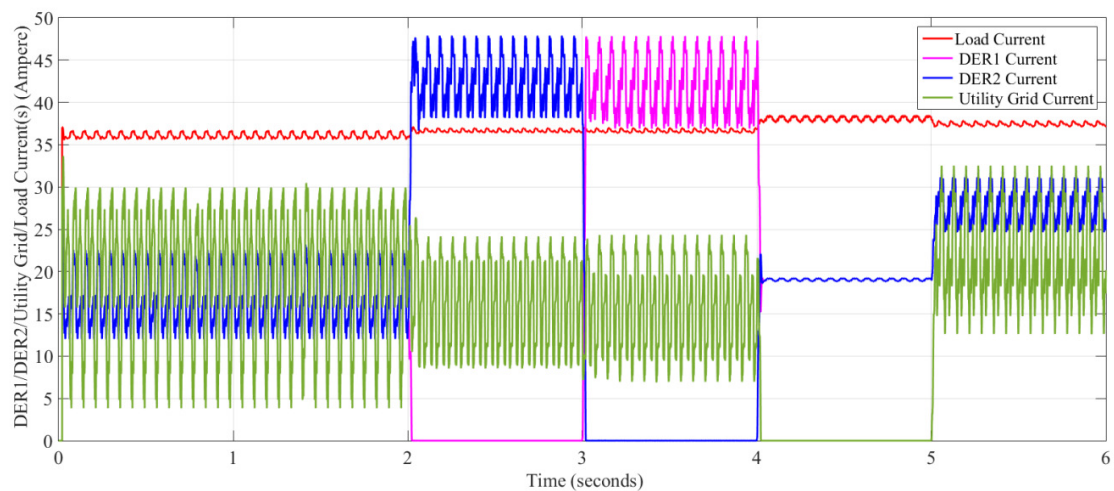


Figure 4.4. Current(s) sharing during grid-connected and islanded conditions – inductive load

4.1.3 Rotational load

In authentic power system, the asynchronous or induction motors are more dominating load at residential, commercial and industrial level. The authors monitor the same microgrid model for its performance with the application of one 7 kW, 230 V, 50 Hz, 1450 rpm split-phase asynchronous motor as rotational load connected to the microgrid under grid-connected and islanded conditions. The frequency of the system is found as 49.20 Hz, 49.30 Hz, 49.30 Hz and 49.23 Hz operating under grid-connected mode with both DERs, grid-connected mode with DER1 opened, grid-connected mode with DER2 opened and islanded mode respectively. These magnitudes of frequency are listed in Table 4.3 those are beyond acceptable range of best as recommended in Table 3.2.

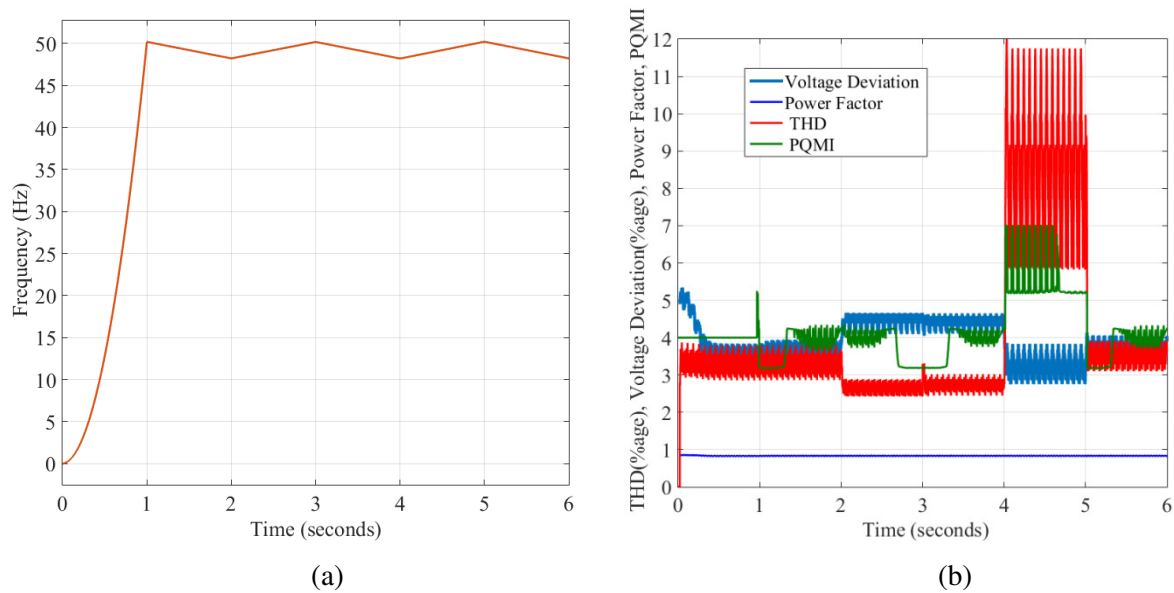


Figure 4.5. Microgrid performance (a) frequency and (b) related parameters for rotational load

Table 4.3. Single-phase AC microgrid system parameters for rotational load

Mode(s) of operation	Transition interval (seconds)	Parameters				
		V.D. (%age)	Frequency (Hz.)	P.F. (cos θ)	THD (%age)	PQMI (Scale)
Grid-connected	1 to 2	3.83	49.20	0.83	3.20	4.07
DER1 (open), DER2 (connected)	2 to 3	4.64	49.30	0.83	2.83	4.22
DER1 (connected), DER2 (open)	3 to 4	4.19	49.30	0.83	2.63	4.21
Islanded	4 to 5	3.03	49.23	0.83	9.13	5.26

In addition, the power factor is found as 0.83 lagging for all the above mentioned modes of operation and it is not in the category of best as listed in Table 3.2. Due to these variations, the magnitude of PQMI is exhibited as 4.07, 4.22, 4.21 and 5.26 under grid-connected, grid-connected with DER1 opened, grid-connected with DER2 opened and islanded mode respectively as shown in the Figure 4.5 and listed in Table 4.3. The pattern of load current and current shared by DER1, DER2 and utility grid are shown in Figure 4.6 which shows the virtually constant load current profile during grid-connected and islanded conditions. The remarkable observation is found that the PQMI is incremented to 5.26 (average) due to THD of 9.13%, frequency of 49.23 Hz and power factor of 0.83 lagging during islanded condition as shown in Table 4.3 and plotted in Figure 4.5(a) and 4.5(b). It is again found that the harmonic content of the inverter output is responsible factor for incremented value of the THD similar to the precedent cases. After 5 seconds utility grid is restored and grid-connected condition of a single-phase AC microgrid is established.

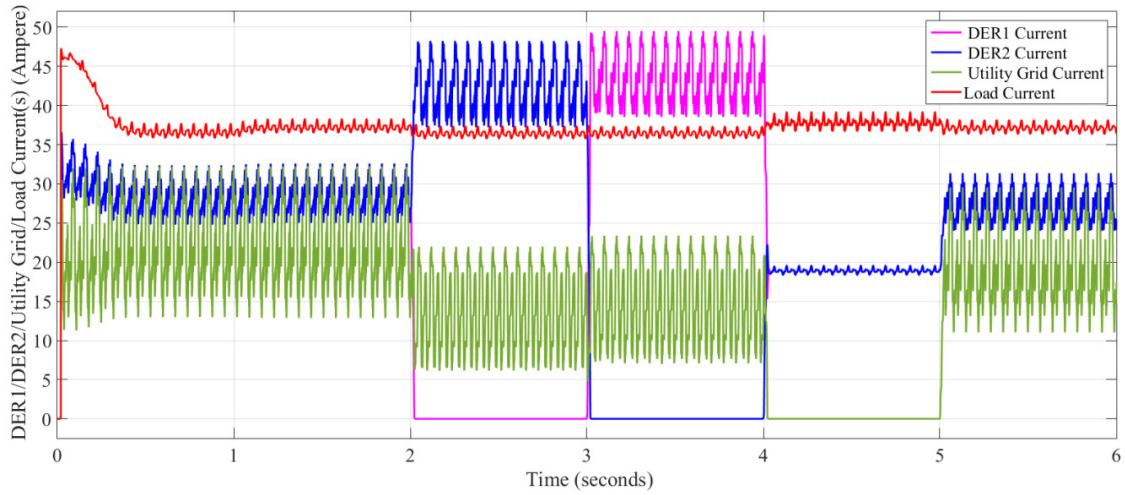


Figure 4.6. Current(s) sharing during grid-connected and islanded conditions – rotational load

4.1.4 Non-linear load

Always linear system may not be available in practical situation, so non-linearity is to be studied for microgrid power quality monitoring issues. To simulate a non-linear load, a rectifier circuit with resistance of 10 kW at its output is connected as a load to monitor the status of microgrid during grid-connected and islanded modes of operation. In this case, the THD level is observed about 110% which is very high as compared to tolerable range of 5%. The reason of high THD is due to the converter topologies which are connected at DERs and load sides. The switching operations in converters are responsible for the event of THD.

The nature of THD is plotted in Figure 4.7(a) which shows the variation of THD and frequency during grid-connected and islanded modes of operation. The voltage deviation is additionally found high in the category of poor as defined in Table 3.2. The Figure 4.7(b) shows the variation of voltage deviation, PQMI (7.00, poor) with unity power factor for consummate transition periods (0 second to 6 seconds). The magnitudes of all parameters cognate to non-linear load are listed in Table 4.4. Hence, the PQMI is obtained as 7.00 (poor) during grid-connected and islanded modes of operation due to the contravention mainly in voltage deviation and THD. In case of non-linear load, load current shared by both DERs and utility grid are shown in Figure 4.8 during grid-connected and islanded modes of operation.

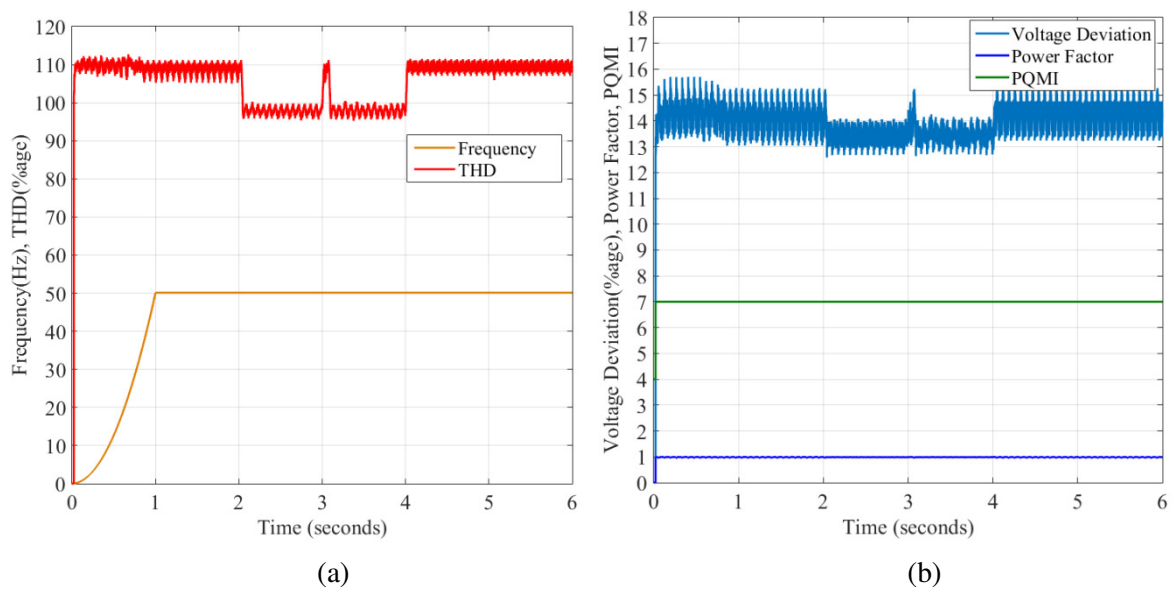


Figure. 4.7. Microgrid performance (a) frequency, THD and (b) related parameters for non-linear load

Table 4.4. Single-phase AC microgrid system parameters for non-linear load

Mode(s) of operation	Transition interval (seconds)	Parameters				
		V.D. (%age)	Frequency (Hz.)	P.F. (cos θ)	THD (%age)	PQMI (Scale)
Grid-connected	1 to 2	14.70	50.12	1.00	108.20	7.00
DER1 (open), DER2 (connected)	2 to 3	13.50	50.13	1.00	97.50	7.00
DER1 (connected), DER2 (open)	3 to 4	13.50	50.13	1.00	97.50	7.00
Islanded	4 to 5	14.00	50.14	1.00	110.10	7.00

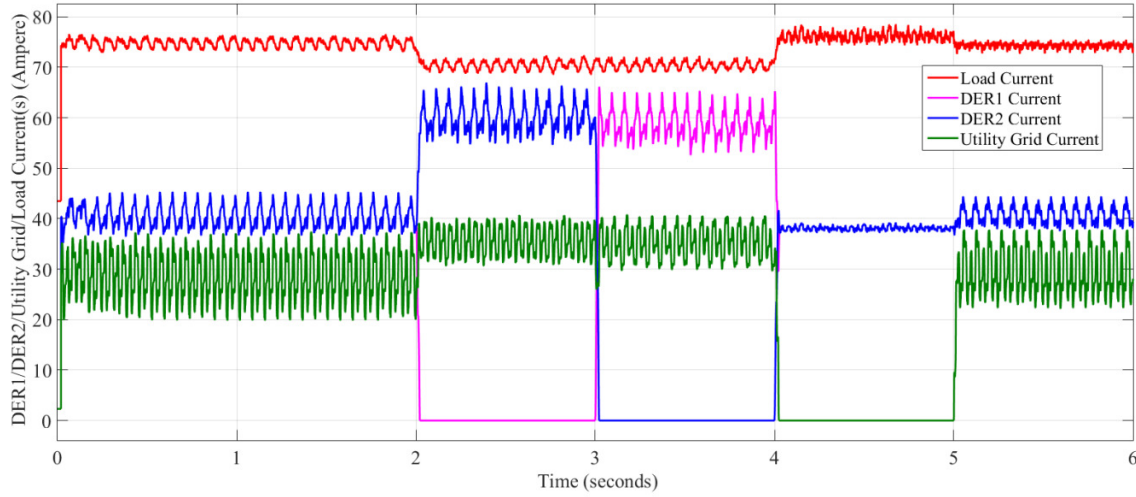


Figure 4.8. Current(s) sharing during grid-connected and islanded conditions – non-linear load

4.1.5 Combination of linear, non-linear and rotational loads on a common load bus

The proposed FIS system could be tested for the combination of linear, non-linear and rotational loads connected on common load bus after CB4 as shown in Figure 4.9. All three loads are fed by both DERs (DER1 and DER2) and utility grid subjected to grid-connected or islanded modes of operation. The single-phase AC microgrid system is simulated for time period of 5 seconds in MATLAB-Simulink environment. The grid-connected mode is initiated from 0 to 3 seconds (from 1 to 2 seconds, DER1 is off and DER2 is on; and from 2 to 3 seconds, DER1 is on and DER2 is off) and from 3 to 4 seconds, islanded condition is executed for testing the performance of AC microgrid.

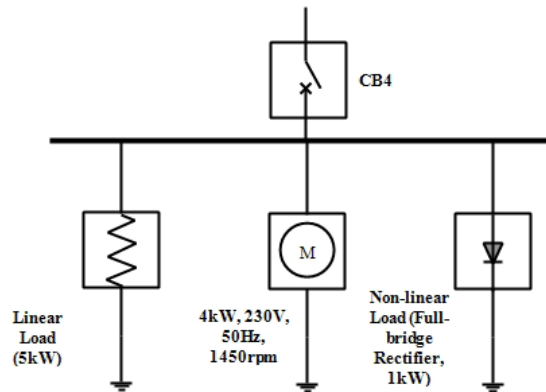


Figure 4.9. Linear, non-linear and rotational loads connected on common bus load

After completion of 4 seconds utility grid is again charged and connected back to the DERs which establishes grid-connected mode again. Figure 4.10(a) and 4.10(b) represent the variation in four considered input variables and one output variable as a PQMI. Under the

combination of loads, it is found that the PQMI is 7.00 (poor) throughout the operation under grid-connected and islanded modes. The possibility of poor PQMI is due to the parallel connection of full-bridge rectifier and asynchronous motor, which cause the variation in voltage and THD as shown in Figure 4.10(b). As per the combination made for input fuzzy variables listed in Table 3.2, the voltage and THD are violated drastically beyond the nominal limits; therefore, PQMI is out to be poor. Hence, the proposed FIS system is working satisfactorily even under the different combination of loads connected to microgrid.

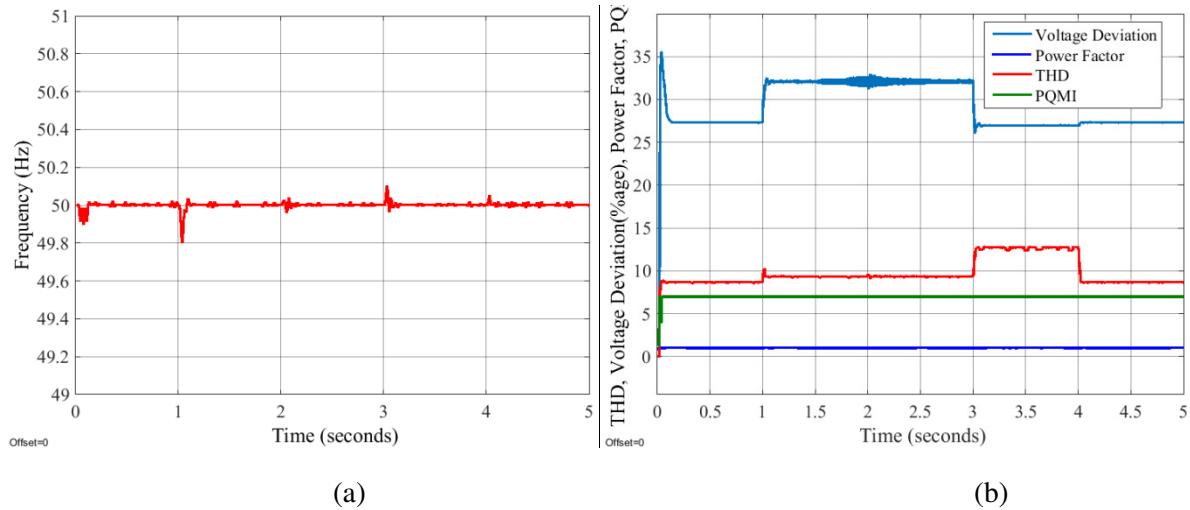


Figure 4.10. Microgrid performance (a) frequency and (b) power quality related parameters for the combination of loads

4.2 COMPARISON OF PROPOSED METHOD FOR PQMI ASSESSMENT WITH SIGNIFICANT DEVELOPED METHODS

The feasibility of proposed FIS system is compared with [124–126] for enhancing the performance of microgrid system during grid-connected and islanded modes of operation.

4.2.1 Multi-criteria decision methodology (MCDM)

The fuzzy input variables are represented by the mathematical equations considering their respective membership functions. The expression for voltage deviation as per IEEE Std. 1250-2011 is expressed in equation (4.1). The IEC 61000-2-2:2002 declares that the nominal voltage tolerance must be 10%.

$$\mu(VD) = \begin{cases} 0; & v \leq 80\% \\ \frac{1}{0.05}(v - 0.8); & 80\% \leq v \leq 85\% \\ 1; & 85\% \leq v \leq 100\% \end{cases} \quad (4.1)$$

The power factor is expressed in equation (4.2) and the corresponding limits are framed as per power factor correction techniques listed in IEC 60831-1/2.

$$\mu(PF) = \begin{cases} 0; & PF \leq 40\% \\ \frac{1}{0.5}(PF - 0.40); & 40\% \leq PF \leq 90\% \\ 1; & 90\% \leq PF \leq 100\% \end{cases} \quad (4.2)$$

The frequency limitation is presented in equation (4.3) under as recommended in IEC 61000-3-2 standard operating at 50 Hz.

$$\mu(F) = \begin{cases} 0; & f \leq 94\% \\ \frac{1}{0.055}(f - 0.94); & 94\% \leq f \leq 99.5\% \\ 1; & 99.5\% \leq f \leq 100\% \end{cases} \quad (4.3)$$

The total harmonic distortion (THD) fuzzy variable is expressed through mathematical equation as shown in equation (4.4) as per IEEE standard 519-2014.

$$\mu(THD) = \begin{cases} 0; & THD \leq 95\% \\ \frac{1}{0.04}(THD - 0.95); & 95\% \leq THD \leq 99\% \\ 1; & 99\% \leq THD \leq 100\% \end{cases} \quad (4.4)$$

The ranges of all above mentioned four input fuzzy variables have been settled as per their respective international standards and the most possible disturbance initiated in microgrid system due to different natures of loads. It is observed that during the transition of DERs there are violations in input variables like voltage deviation, frequency and THD; so accordingly the range of individual variable will be adjusted to project power quality index as an average or poor depending on the rules framework. The PQMI will be displayed using multi-criteria decision making (MCDM) methodology and compared with proposed FIS system. The feasibility of novel decision making FIS system has been identified and validated in comparison with MCDM methodology [124]. The weights for the assessment of PQMI have been calculated using Saaty's matrix in reference to VD, PF, F and THD as shown in Table 4.5. Now, the weights or eigenvector (w) from Table 4.5 have been evaluated and shown by equation (4.5). The PQMI can be identified using equation (4.6) under grid-connected and islanded modes of operation subjected to different natures of loads.

$$w = \begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ w_4 \end{bmatrix} = \begin{bmatrix} 7.4912 \\ 3.3688 \\ 1.7584 \\ 1 \end{bmatrix} \quad (4.5)$$

$$PQMI = \min[\mu(VD)^{w_1}, \mu(PF)^{w_2}, \mu(F)^{w_3}, \mu(THD)^{w_4}] \quad (4.6)$$

Table 4.5. Saaty's matrix of fuzzy variables for the assessment of PQMI

Variable	VD	PF	F	THD
VD	1	3	5	5
PF	1/3	1	3	3
F	1/5	1/3	1	3
THD	1/5	1/3	1/3	1

From equations (4.1) to (4.4), $\mu(VD) = 0.8$ at $v = 84\%$ (193.2 V w.r.t. nominal voltage of 230V), $\mu(PF) = 0.96$ at $PF = 88\%$ (i.e. PF is 0.88) $\mu(F) = 0.727$ at $F = 98\%$ (49.0 Hz w.r.t. nominal frequency of 50 Hz), $\mu(THD) = 0.5$ at $THD = 97\%$ (w.r.t. fundamental component) Therefore, the final PQMI as per values obtained from equations (4.1) to (4.4) can be calculated using equation (4.6), $PQMI = \min(0.1879, 0.8715, 0.5708, 0.5) = 0.1879$. Now, if this PQMI value (0.1879) is compared with the actual output variable framed in Table 3.2. It is evident that 0.1879 falls under third membership function (*Average*) which reflects PQMI as 4.2 as per the status of four input variable calculated from equations (4.1) to (4.4). Hence, it is concluded that due to the variation in voltage (84%), power factor (88%), frequency (98%) and THD (97%), the overall PQMI will be average (considering one case) even not good in compliance with ranges framed in Table 3.2.

4.2.2 Ideal analytic hierarchy process to assess PQMI

By referring Figure 3.1, the load bus after CB4 can be explored into critical and non-critical loads as shown in Figure 4.11(a). The load bus has been represented as a distribution network with five load points such as L1, L2, L3, L4 and L5. The Figure 4.11(b) represents the distribution of non-critical load (6kW) with total 15 consumers and critical load (4kW) with total 10 consumers. The power quality index (PQI) could be assessed using ideal analytic hierarchy process (AHP) utilizing reliability indices (like SAIFI), voltage sag (SARFI) and harmonics (THD) for a distribution system model [125]. The unified PQI is obtained using ideal AHP after rescaling of reliability indices, SARFI and THD. The proposed FIS system

would be tested for identification of PQMI of AC microgrid system based on SAIFI, SARFI and THD as framed in Figure 4.12 with their respective range in reference to [125]. As per three input fuzzy variables such as SAIFI, SARFI and THD, the output variable PQMI will be decided based on 27 numbers of rules (3^3) due to three membership functions in each input variable. Three cases have been made by setting up the values of SAIFI, SARFI and THD to display PQMI as per the framed membership functions in Figure 4.12 and listed in Table 4.6. Case 1 represents the complete distribution network as presented in Figure 4.11(a), Case 2 shows the distribution of loads in the form of loop system as shown in Figure 4.11(b) while Case 3 replicates a radial distribution system as mentioned in Figure 4.11(c). From Table 4.6, it is evident that the optimal PQMI has found in Case 2 as compared to Case 1 and Case 3.

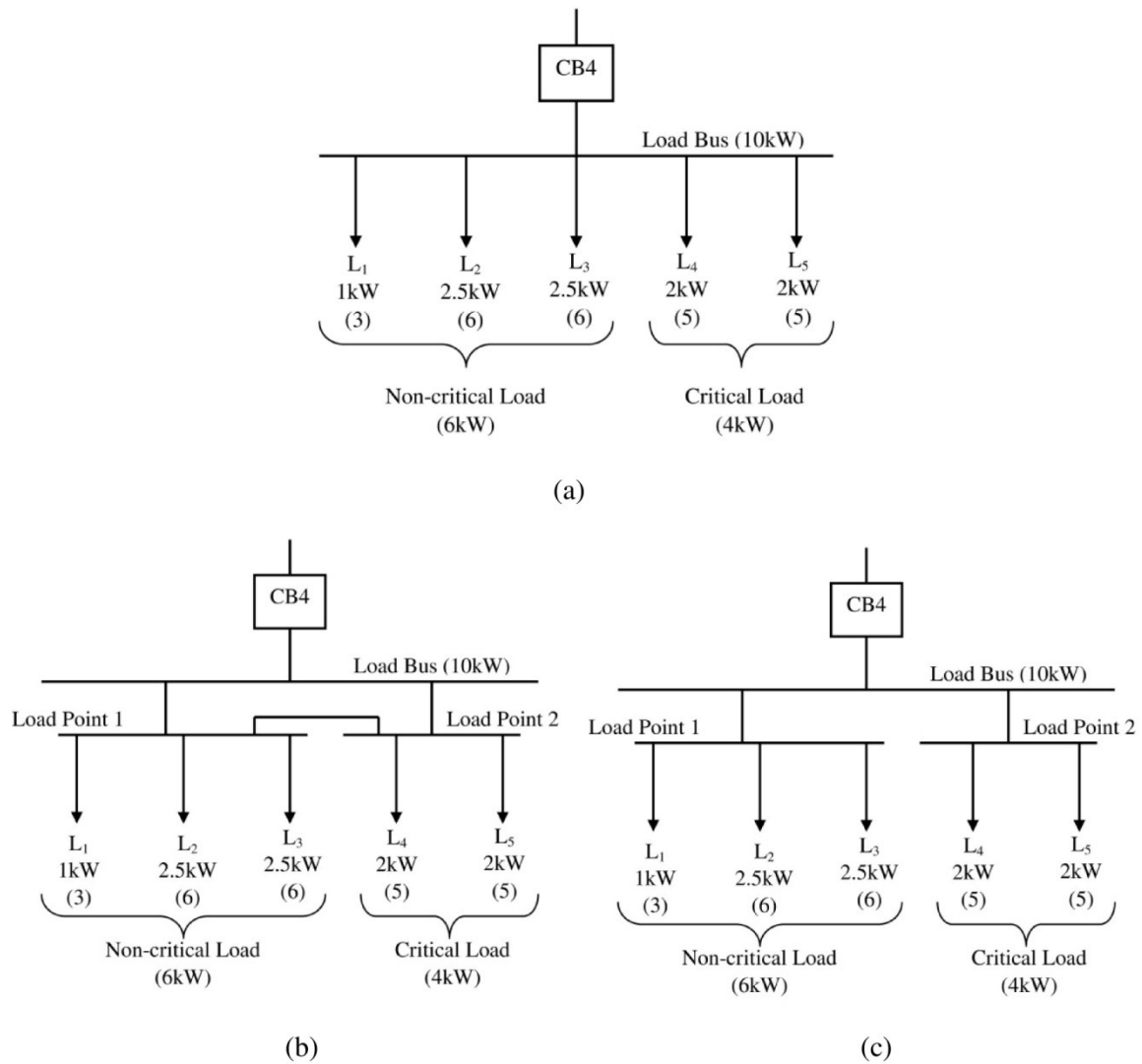


Figure 4.11. Distribution of critical and non-critical loads at common load bus with the configuration of (a) simple system, (b) loop system and (c) radial system

Hence, in case of loop system, the PQMI is minimum (i.e. 1.96) which makes optimal operation of microgrid system subject to violation in reliability index SAIFI, SARFI (voltage sag) and THD, while the UPQI was optimal in case 2 in reference to [125]. The PQMI has been framed in the range of 0 to 6.5 which is already listed in Table 3.2 just to maintain the similarity in Best, Good and Average membership functions as shown in Figure 4.12(d) as compared to the optimal value of UPQI in [125]. So, the value 1.96 means PQMI is best that is quality of power is healthy in case 2 as similar in case of ideal AHP presented in [125]. Finally, it can be concluded that the proposed FIS system has been validated with ideal AHP and satisfies the optimal parameters for displaying PQMI. The three-dimensional (3D) interpretation of SAIFI–SARFI and SARFI–THD mapping with PQMI is presented in Figure 4.13(a) and 4.13(b) respectively. The surface view shows the output surface (PQMI) for any two inputs of the FIS system to make decision on health status of power quality under grid-connected and islanded conditions.

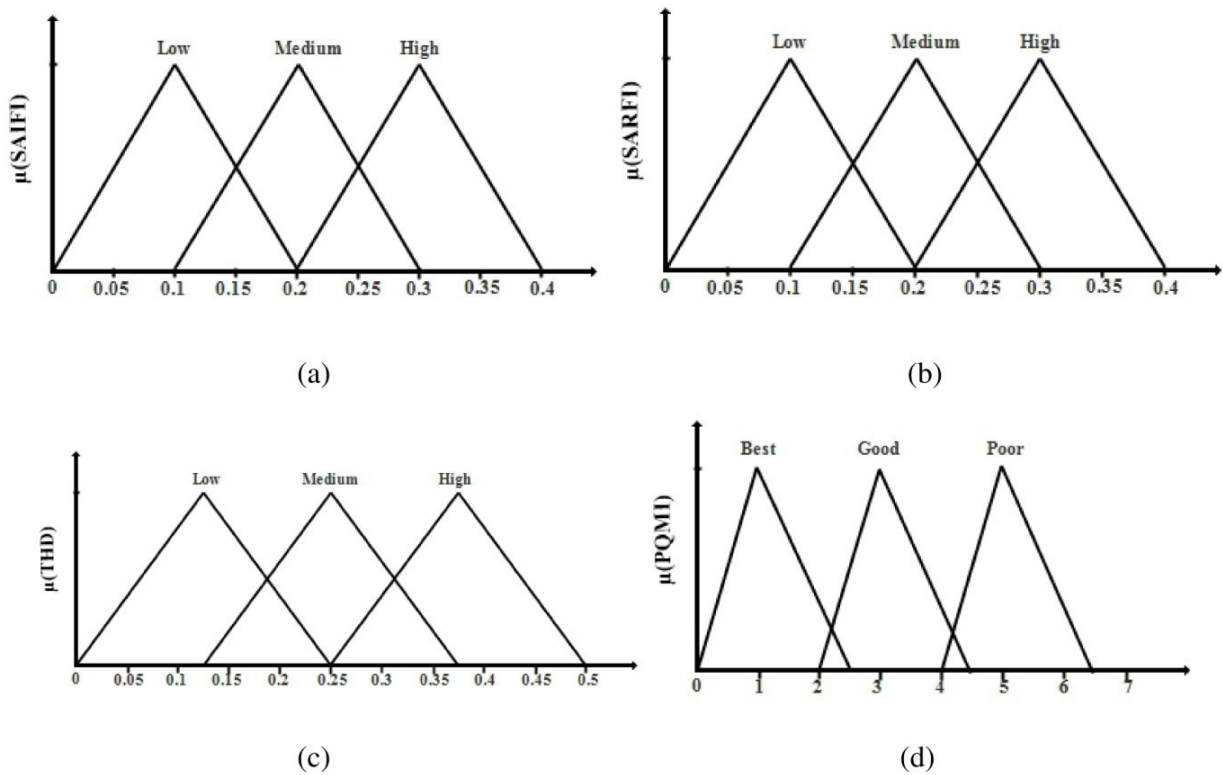


Figure 4.12. Membership functions for (a) SAIFI, (b) SARFI, (c) THD and (d) PQMI

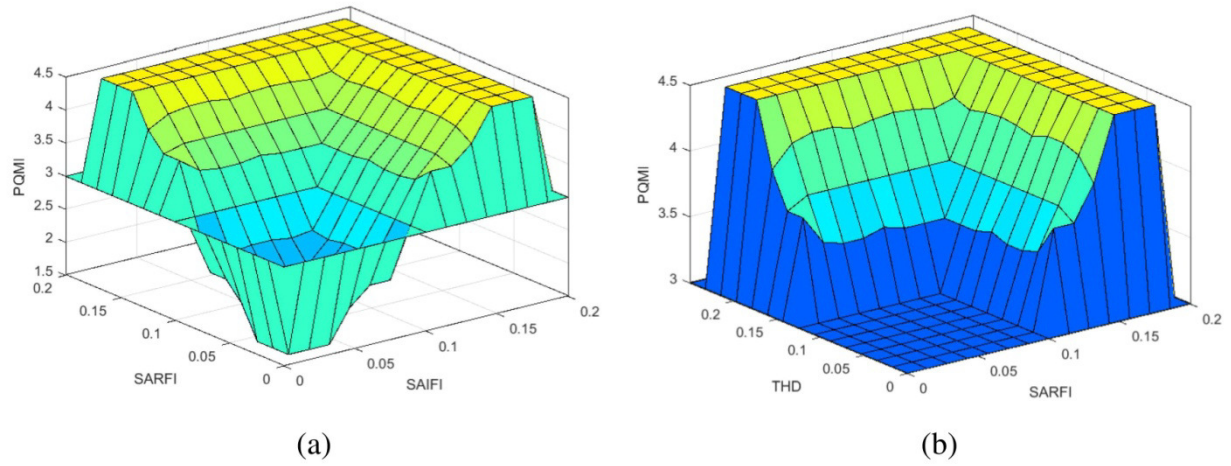


Figure 4.13. Surface view of PQMI as a combination of (a) SAIFI–SARFI and (b) SARFI–THD

Table 4.6. Calculation of indices using proposed FIS system

Indices	Case 1	Case 2	Case 3
SAIFI	0.134	0.113	0.167
SARFI (Voltage sag)	0.133	0.133	0.133
THD	0.165	0.182	0.176
Proposed PQMI	2.02	1.96	2.4

4.2.3 Power quality evaluation using optimal combination of weights method

By An optimal combination weights method considering both subjective and objective weight information in power quality evaluation is proposed in [126]. To evaluate and quantify power quality, a hierarchy model is proposed based on subjective and objective weighting method. In the process of fuzzy evaluation, the judgement matrix method of analytic hierarchy process is used in the referred paper [126]. The objective weighting method is implemented based on the actual data through numerical method to obtain the index weight. The combination of subjective and objective weighting methods is tested as an application in detailed assessment of power quality at PCC of a distribution network. Though, in the present paper, a Mamdani-FIS system is formulated to propose the PQMI for a single-phase AC microgrid in a simple and compact manner.

In the competitive electricity market, the application in comprehensive evaluation of the power quality only at a specific point such as PCC may not be adequate for an islanded or grid-connected AC microgrid, rather the power quality assessment preferably to be done at various load points aiming consumers satisfaction. In the proposed method of power quality assessment, the power factor is considered as one of the important parameters of microgrid.

This parameter is not considered in [126], though the other parameters such as voltage, frequency, voltage and current distortion etc. have been considered in hierarchy model for power quality assessment. In the present paper, the power quality is assessed considering power factor as an important parameter including the other parameters such as voltage deviation, frequency and total harmonic distortion.

4.2.4 Advantages and limitations of proposed PQMI

The power quality for a microgrid system can be quantified based on the magnitude of several parameters such as voltage deviation, frequency, power factor, THD etc. The main flexibility of the proposed method is that any combination of the parameters in a particular microgrid may be considered for determination of power quality monitoring index. It is not a good practice to consider only one parameter at a time for monitoring the power quality of a system. So, the proposed methodology is advantageous to consider the fuzziness in variation of different parameters using Mamdani-FIS. The proposed PQMI is displayed based on the rules considering the recommended standards and practical observations of electrical parameters in a microgrid system using FIS, which is simple and effective for power quality assessment.

The proposed methodology is simple compared to MCDM referred in [124], as explained in Sub-section 4.2.1 due to the use of FIS in MATLAB-Simulink environment. While comparing with the index proposed in [125] and [126] in Sub-sections 4.2.2 and 4.3.3 respectively, it is observed that the application in comprehensive evaluation of the power quality at a specific point may not be sufficient for an islanded or grid-connected AC microgrid, rather the power quality monitoring preferably to be done at various load points aiming consumers satisfaction which can be achieved using proposed PQMI.

The one limitation of this proposed methodology is that the number of rules for FIS will be large if number of linguistic variable is more in a microgrid system. It will be relevant to mention that the 256 number of rules are framed based on four input variables with four membership functions in the present research. It is also observed that more number of rules can monitor power quality satisfactorily considering the fuzziness in variation of large number of electrical parameters.

The present challenge of the proposed methodology is to initiate the operation and control measures through hardware implementation and to improve the power quality of microgrid system based on the status of a particular electrical parameter. For an example, if a system is observed with poor power factor while the voltage and frequency deviation is less; the corrective control action can be initiated for power factor improvement which will improve the power quality minimizing the real power loss in the system. This feature is considered as the future scope of research.

4.3 THREE-PHASE AC MICROGRID MODEL FOR THE ASSESSMENT OF PROPOSED PQMI

The root system of a three-phase AC microgrid model referred in Figure 3.3 as presented in previous Chapter 3 is monitored under different loading conditions during grid-connected and islanded modes to investigate the power quality issues. The microgrid system performance is monitored under grid-connected mode from 0 to 3 seconds in which DER1 is disconnected (CB1) from 1 second to 2 seconds while DER2 (CB2) is connected with the system. In the rest part of grid-connected mode, the DER1 (CB1) is reconnected and DER2 (CB2) is disconnected from 2 seconds to 3 seconds. During islanded condition, the utility grid is disconnected (CB3, disconnected) in the interval of 3 seconds to 4 seconds of total simulation time. The grid-connected condition is created again by closing CB3 after 4 seconds up to final simulation period of 5 seconds.

The results are discussed in the following Sub-sections 4.3.1, 4.3.2, 4.3.3, 4.3.4 and 4.3.5 under different transitions to display the status of PQMI based on VD, F, PF and THD. In Sub-section 4.3.6, the PQMI is presented with the effect of voltage sag, swell, three-phase interruption and unbalance during islanded condition. The comparison between Mamdani and Sugeno-FIS is discussed in Sub-section 4.3.7.

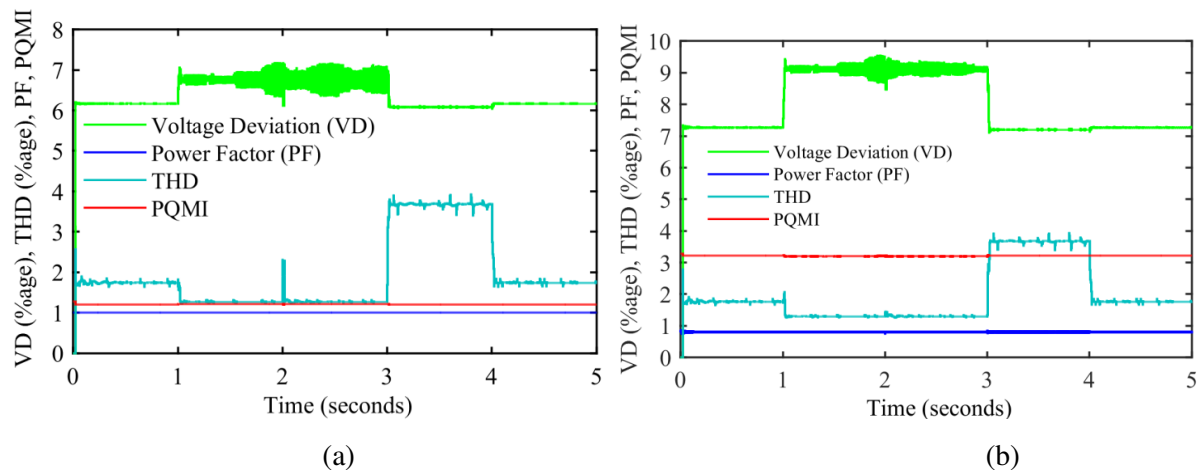
4.3.1 Resistive load

A three-phase microgrid system is modelled for 10 kW capacity of three-phase star-grounded resistive load. The PQMI is monitored during grid-connected and islanded conditions for the total simulation time of 5 seconds as shown in Figure 4.14(a) and listed in Table 4.7. The PQMI is observed as 1.21 (best) for complete 5 seconds as shown in Table 4.7 because all four input variables are falling in the range of best as defined in Table 3.2 as per IEEE 1547.

The PQMI is found same as 1.21 (best) with slight increment of 3.68% in THD under islanded condition as shown in Figure 4.14(a) due to parallel connection of inverters, which are having inherent property of harmonics in the circuit. The DER1 and DER2 are simultaneously connected with microgrid to supply the load under islanded condition and after 4 seconds the utility grid is restored till the end of simulation time. The Table 4.8 shows the active power sharing by DERs and utility grid under grid-connected and islanded modes of operation. The difference between Mamdani and Sugeno-FIS has been observed under all modes of operation, which is presented in bar form in Figure 4.17(a)-4.17(d). So, it is suggested that Mamdani-FIS can be used for precise values and Sugeno-FIS can be utilized for round-off values of PQMI.

4.3.2 Inductive load

The proposed three-phase AC microgrid is tested for a three-phase 10 kW, 7.5 kVar, star-grounded inductive load. During grid-connected condition, the PQMI is found as 3.22 (good) while DER1 and DER2 are operating alternatively as shown in Table 4.7 and Figure 4.15(b). This PQMI value is obtained due to the low PF of 0.8 (good) while other parameters are within the acceptable limits. The voltage deviation is increased up to 9.12% as shown in Figure 4.14(b) where in case of resistive load it was found as 6.78%. As per IEC 60038, the maximum allowable voltage variation is $\pm 10\%$ up to nominal voltage of 1000 V with fundamental frequency of 50Hz. The THD level is found as 3.67% which is less than the maximum allowable THD level of 5% as recommended in IEEE Standard 519. The active power delivered to inductive load under all modes of operation is listed in Table 4.8. The Table 4.7 also shows the deviation between Mamdani and Sugeno-FIS in accordance with PQMI with respect to inductive load and also shown in Figure 4.17.



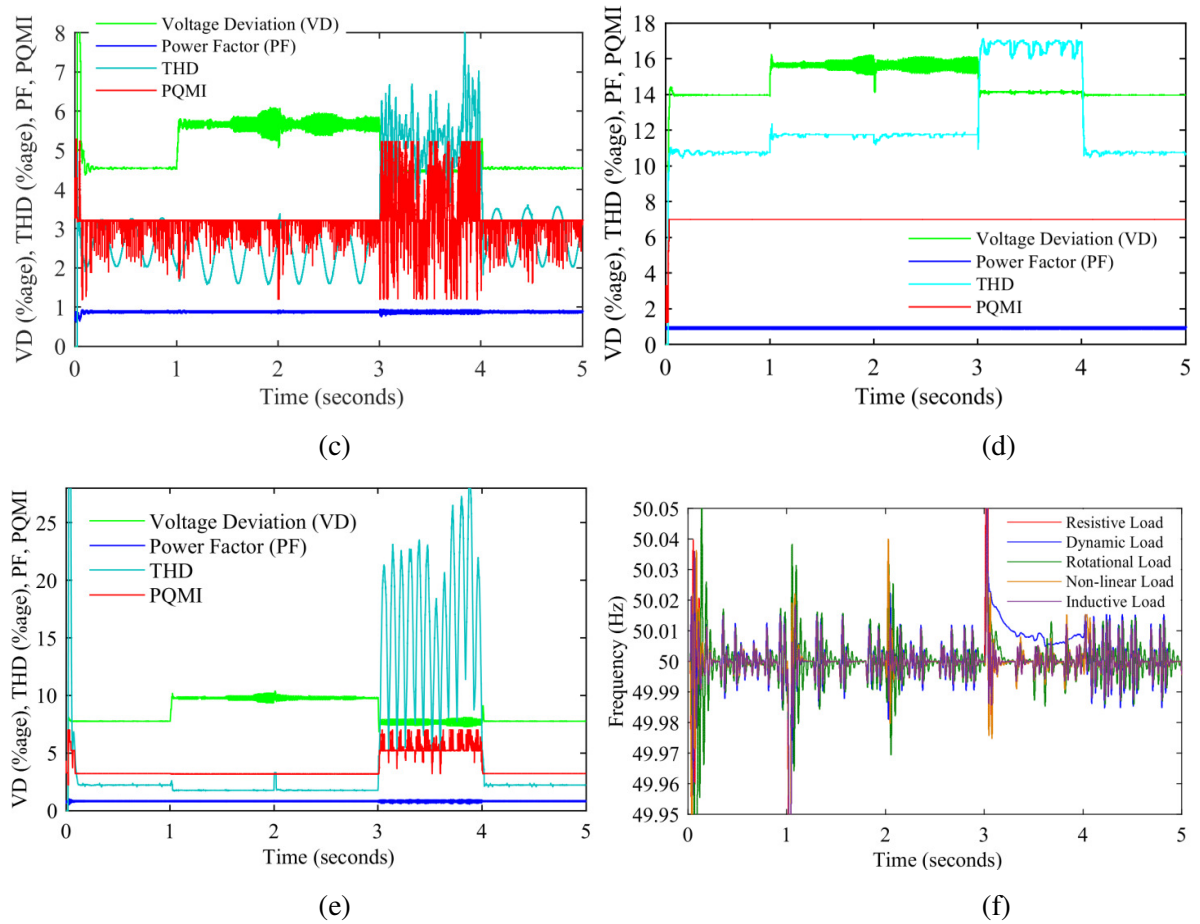


Figure 4.14. Microgrid performance showing PQMI for (a) resistive, (b) inductive, (c) rotational, (d) non-linear, (e) dynamic loads, and (f) fundamental frequency response for all five loads

Table 4.7. Three-phase microgrid system PQMI for resistive/inductive/rotational/non-linear/dynamic load

Mode(s) of operation	Transition interval (seconds)	Power Quality Monitoring Index (PQMI)									
		Resistive Load		Inductive Load		Rotational Load		Non-linear Load		Dynamic Load	
		Mamdani	Sugeno	Mamdani	Sugeno	Mamdani	Sugeno	Mamdani	Sugeno	Mamdani	Sugeno
Grid-connected	0 to 1	1.21	1.00	3.22	3.00	3.20	3.00	7.00	7.00	3.21	3.00
DER1 (open), DER2 (connected)	1 to 2	1.21	1.00	3.19	3.00	3.20	3.00	7.00	7.00	3.18	3.00
DER1 (connected), DER2 (open)	2 to 3	1.21	1.00	3.19	3.00	3.20	3.00	7.00	7.00	3.18	3.00
Islanded	3 to 4	1.21	1.00	3.22	3.00	5.20	5.00	7.00	7.00	5.22	5.00
Grid-connected	4 to 5	1.21	1.00	3.22	3.00	3.20	3.00	7.00	7.00	3.21	3.00

Table 4.8. Power delivered/shared by DER1, DER2 and utility grid to the load

Mode(s) of operation	Transition interval (seconds)	Resistive Load		Inductive Load		Rotational Load		Non-linear Load		Dynamic Load	
		Power Delivered (Watt)	Power Loss (%age)	Power Delivered (Watt)	Power Loss (%age)	Power Delivered (Watt)	Power Loss (%age)	Power Delivered (Watt)	Power Loss (%age)	Power Delivered (Watt)	Power Loss (%age)
Grid-connected	0 to 1	8850	5.69	8507	8.78	6153	2.55	18000	13.04	9200	8.00
DER1 (open), DER2 (connected)	1 to 2	8760	6.51	8292	9.89	6045	4.85	18000	10.00	8900	11.00
DER1 (connected), DER2 (open)	2 to 3	8760	6.51	8292	9.89	6045	4.85	18000	10.00	8900	11.00
Islanded	3 to 4	8832	6.12	8580	8.62	6105	2.82	18000	14.28	9000	8.16
Grid-connected	4 to 5	8850	5.69	8507	8.78	6153	2.55	18000	13.04	9200	8.00

4.3.3 Rotational load - Asynchronous motor

In microgrid operation, always to deal with the static load is practically not possible, so it is also necessary to study the effect of rotational loads on the power quality. A 4 kW, 400 V, 50 Hz, 1450 rpm, squirrel-cage asynchronous motor is used to quantify its effect on the power quality under grid-connected and islanded conditions. The PQMI is observed as 3.20 (good) as shown in Table 4.7 and Figure 4.14(c) during grid-connected condition with acceptable limits. During islanded condition, the PQMI is found as 5.20 (average) due to little violation in THD level (5.54%) as shown in Figure 4.14(c) which is higher than the allowable limit of 5%. The active powers shared by DER1, DER2 and utility grid are shown in Table 4.8. It is observed that the active power consumed by the rotational load is almost constant during grid-connected because motor is running under no-load condition. Under islanded condition, the power loss is found minimum (2.82%) as compared to others because it is totally fed by the two parallel connected inverters subjected to the fixed input DC source and there is no introduction of line losses. Under grid-connected and islanded conditions, the deviations between Mamdani and Sugeno type FIS in term of PQMI is shown through bars in Figure 4.17.

4.3.4 Non-linear load

Nowadays, the electronics equipment, variable frequency drives, and rectifier-based circuits are mostly being in used, which are having non-linear characteristics. A three-phase bridge

rectifier is considered as a non-linear load to supply a 10 kW of resistive load. The PQMI is observed as 7.00 (poor) due to large voltage deviation and THD level as shown in Figure 4.14(d) and listed in Table 4.7, which are higher than the acceptable limits. During islanded condition, the THD level is found 17.02% which is much higher than the acceptable limit of 5% as shown in Figure 4.14(d). It is investigated that during islanded condition the active power loss is 14.28% as listed in Table 4.8 and this is happened due to the higher switching loss in three-phase bridge rectifier topology. Further, it is observed that there is no deviation in PQMI when it is displayed using Mamdani and Sugeno-FIS for three-phase non-linear load as mentioned in Table 4.7 and Figure 4.17(a)-4.17(d).

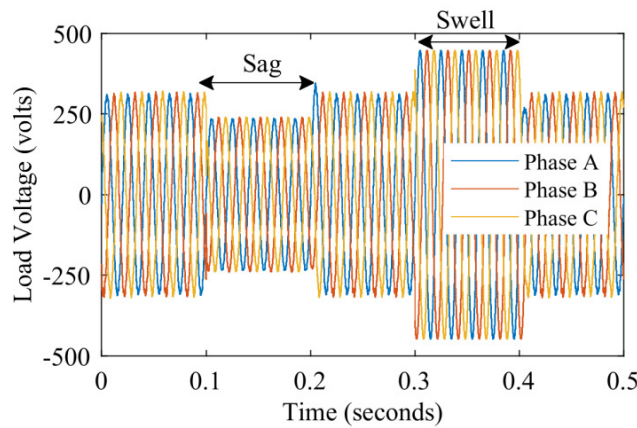
4.3.5 Dynamic load

The three-phase microgrid system is modelled for three-phase, three-wire 10 kW, 7.5 kVar, 400 V, 50 Hz dynamic load. During grid connected condition, PQMI is found as 3.21 (good) based on four input variables such as VD (7.76% to 9.78%), F (50 Hz), PF (0.81) and THD (2.22%) as shown in Figure 4.14(e). Since, the utility grid source is located at a line length of 4 km from PCC which incorporates the line loss; hence, VD is increased to 9.78%. During islanded condition, the THD level is found very high on average of 22.7% which is shown in Figure 4.14(e). This is occurred due to the switching in both three-phase inverters which are highly influenced by the harmonics at their outputs. The PQMI is found on an average of 5.22 due to low PF and high THD level as shown in Figure 4.14(e) and listed in Table 3.7. The active powers shared by the DER1, DER2 and utility grid are presented in Table 4.8. Hence, it is revealed that the power quality is a challenging issue when a three-phase AC microgrid is subjected to the dynamic load. The deviations between Mamdani and Sugeno-FIS have been observed and listed in Table 4.7. The frequency responses for all above loads are found almost near to 50 Hz (49.95 Hz to 50.05 Hz) as shown in Figure 4.14(f). Hence, the PQMI is not affected so much by the system frequency during grid-connected and islanded modes of operation in reference to the proposed three-phase AC microgrid system.

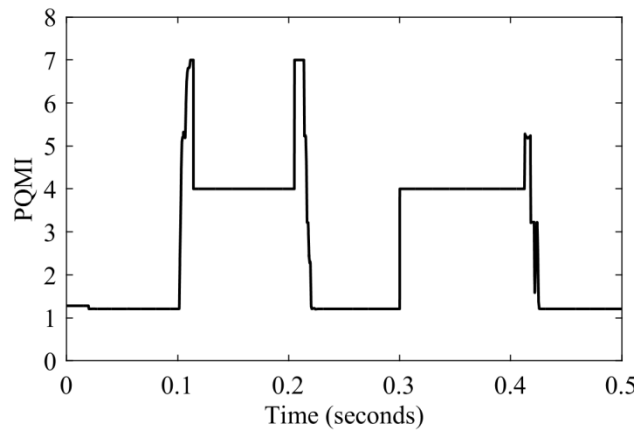
4.3.6 Microgrid operation considering the effect of voltage sag, swell, interruption and unbalance in three-phase system

The proposed AC microgrid is also investigated to assess the PQMI by considering the effect of voltage sag, swell, interruption and unbalance in three-phase system. Under islanded condition, due to the sudden high increase in the load (from 0.1 to 0.2 second), a fall or sag in

the voltage has been experienced at load end as shown in Figure 4.15(a). The non-critical loads have been curtailed immediately after 0.2 second and the system voltage reached to its nominal value again. Further, there is an abrupt reduction in load which causes voltage swell after 0.3 second as shown in Figure 4.15(a) and recovered just after 0.4 second by maintaining required level of system voltage at the load bus. Due to the impact of voltage sag and swell, the PQMI is assessed and it is found ‘average’ during voltage sag and swell time periods 0.1 to 0.2 second and 0.3 to 0.4 second respectively as shown in Figure 4.15(b). The three-phase AC supply is interrupted to the load for a short duration (0.2 to 0.25 second) due to the momentary loss of voltage just at the PCC as shown in Figure 4.16(a). Under the interruption period, the PQMI is observed as ‘poor’ and tried to recover after 0.25 second as shown in Figure 4.16(b). On the other side, after 0.35 second, microgrid has experienced the three-phase unbalance in one of the phases due to unequal or unbalanced load which makes PQMI noisier as shown in Figure 4.16(b), as compared to interruption period.



(a)



(b)

Figure 4.15. Microgrid operation for sag and swell (a) load voltage, and (b) PQMI assessment under islanded mode

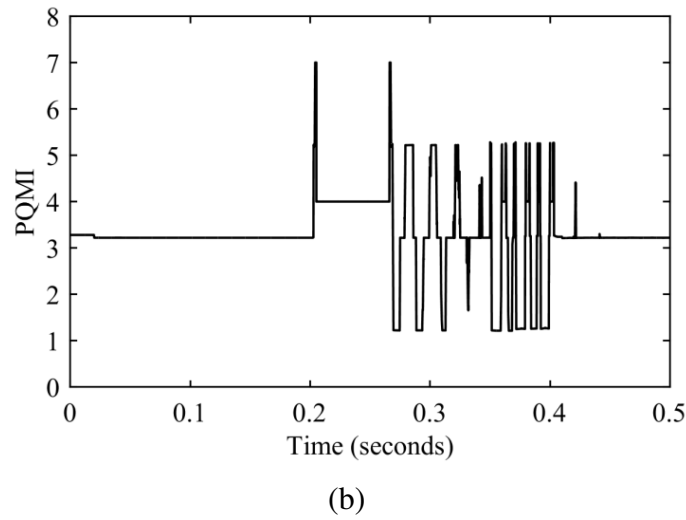
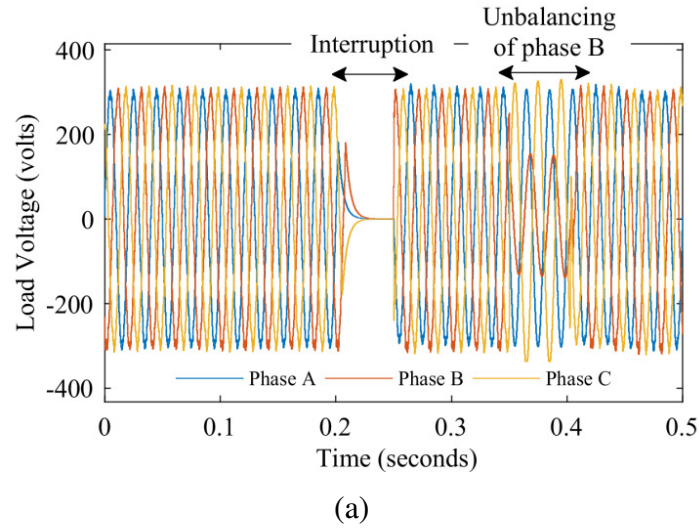


Figure 4.16. Microgrid operation for interruption and unbalance (a) load voltage, and (b) PQMI assessment under islanded mode

The phase B (Red in colour) is went out of the phase as compared to the other two phases A and C and after recovering of phase A, the system becomes balanced immediately at 0.4 second as shown in Figure 4.16(a) and 4.16(b). The ANSI C84.1 suggests that the maximum allowable voltage unbalance should not be more than 3% while in this case, the voltage unbalance is coming out 17.4% ($[(230 - 190)/230] \times 100$). In case of unbalanced condition, the PQMI is found 'poor' (crossing the scale value above 5) as shown in Figure 4.16(b).

4.3.7 Comparison between Mamdani and Sugeno type FIS for PQMI

A simple standard deviation (SD) is calculated to scrutinize the role of Mamdani and Sugeno-FIS for the assessment of PQMI under different loading conditions. The Figure 4.17(b) and

4.17(c) are identical because both DERs are rated with same three-phase inverter module. It is observed that magnitudes of PQMI obtained using Mamdani and Sugeno type FISs are almost close to each other under grid-connected and islanded conditions as shown in Figure 4.17(a)-4.17(d).

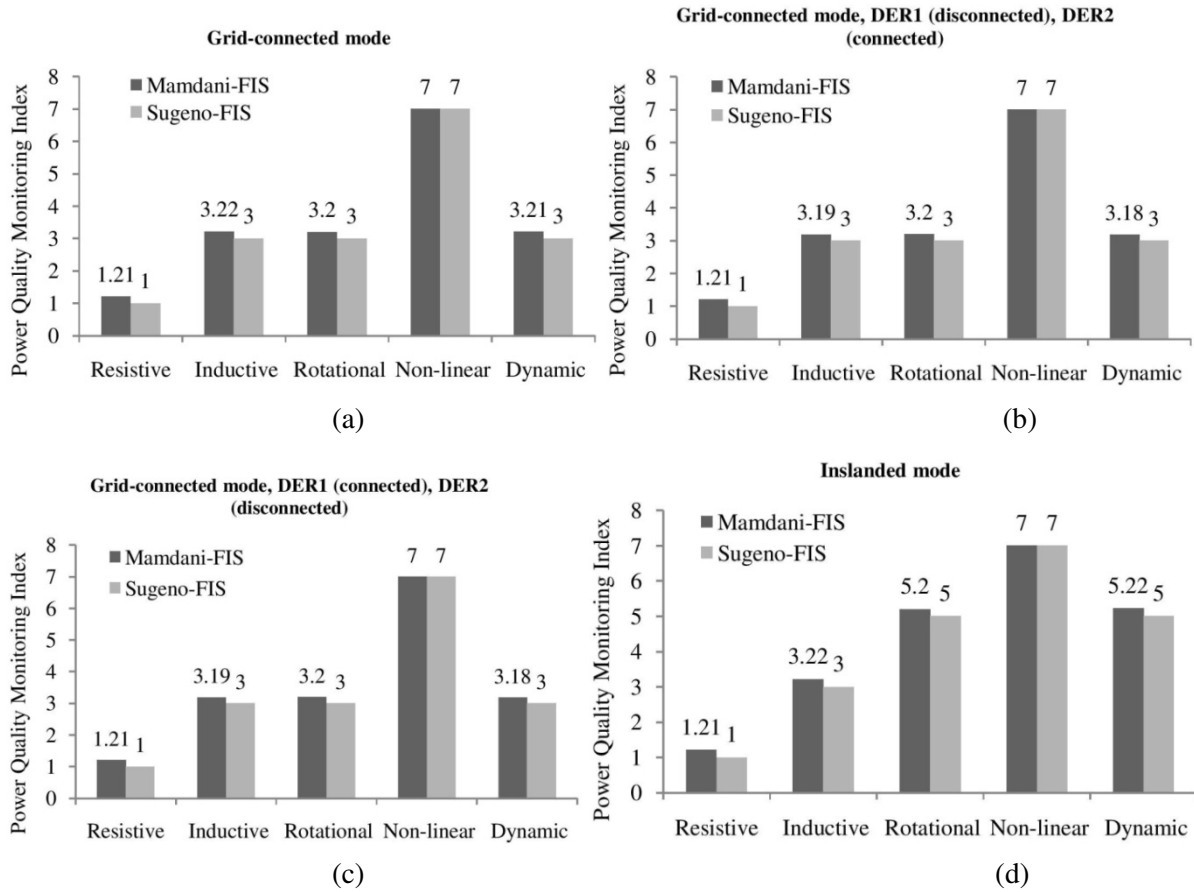


Figure 4.17. PQMIs comparison under different loading conditions using Mamdani and Sugeno-FIS for (a) grid-connected, (b) grid-connected, DER1 (disconnected), DER2 (connected) (c) grid-connected, DER1 (connected), DER2 (disconnected), and (d) islanded modes

The Mamdani-FIS is compared with Sugeno-FIS to verify the correctness of the results using expression of sample SD [127] as given in the following equation (4.7). During grid-connected and islanded modes, the minimum and maximum range of SD reveals that any one of the two FISs can be used to determine the PQMI. Further, it actually supports the accuracy of proposed method through the above analysis.

$$S = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N=2} (x_i - \bar{x})^2} \quad (4.7)$$

where $i = 1, 2, \dots, N$;

N = number of fuzzy inference systems i.e. $N = 2$.

x_i = sample value of PQMI; $i = 1, 2$.

x_1 = PQMI obtained using Mamdani – FIS

x_2 = PQMI obtained using Sugeno – FIS and $\bar{x}$ = mean of x_1 and x_2 .

It is tested that both Mamdani and Sugeno-FIS has no significant difference to each other in terms of PQMI until or unless a precise value is not required for the proposed microgrid system. The correlation coefficient is given by the equation (4.8).

$$r(x, y) = \frac{n \sum_{j=1}^n x_j y_j - \sum_{j=1}^n x_j \sum_{j=1}^n y_j}{\sqrt{\left[n \sum_{j=1}^n x_j^2 - \left(\sum_{j=1}^n x_j \right)^2 \right] \left[n \sum_{j=1}^n y_j^2 - \left(\sum_{j=1}^n y_j \right)^2 \right]}} \quad (4.8)$$

n = number of PQMI for five different loads i.e. 5.

x_j = PQMI displayed by Mamdani – FIS

y_j = PQMI displayed by Sugeno – FIS; $j = 1, 2, \dots, 5$.

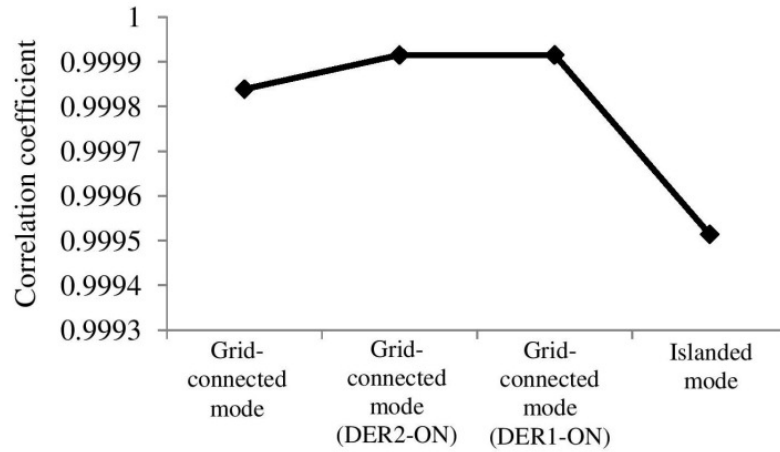


Figure 4.18. Correlation between Mamdani and Sugeno-FIS based on PQMI during grid-connected and islanded modes

It is observed that the correlation coefficient between Mamdani and Sugeno-FIS is closed to one during all modes of operation as shown in Figure 4.18. It is further evident that both FISs have displayed almost same results in terms of PQMI under different loading conditions during grid-connected and islanded modes. The same kind of observation is also found in air conditioning system [128]. Finally, the application of Mamdani or Sugeno-FIS has given almost same results to display the PQMI though it also depends upon the nature of the sampled system.

An effective decision making methodology is proposed for three-phase AC microgrid which is tested for the assessment of PQMI during grid-connected and islanded modes of operation. The PQMI is assessed for three-phase resistive, inductive, rotational, non-linear and dynamic loads. The PQMI is investigated and found satisfactory with the consideration of voltage deviation, frequency, power factor and THD. Further, the microgrid system is tested for its feasibility in all possible aspects such as voltage sag, swell, interruption and unbalance in three-phase system to check the status of PQMI. The proposed FIS-based scheme has shown good results to highlight the PQMI under the effect of voltage disturbances. The Mamdani-FIS is compared with Sugeno-FIS to verify the existence and correctness of the PQMI as per IEEE 1547 under different loading conditions. Hence, the magnitudes of PQMI are observed almost same in both the FISs. In addition, the results are analysed on the basis of standard deviation and correlation between Mamdani and Sugeno-FISs for PQMI. The PQMI is observed weak or very poor especially under islanded condition due to the presence of rotational, dynamic and non-linear loads in the range of 5 to 7 (average to poor) as per proposed FIS methodology.

In this chapter, the proposed methodology for PQMI has been applied in both single-phase and three-phase AC microgrid systems under different types of loads. The novel PQMI has been compared with significant developed methods [124–126] for its validation and feasibility in the area of microgrid topologies. A decision making methodology has been applied in three-phase AC microgrid system to assess PQMI for resistive, inductive, rotational, non-linear and dynamic loads.

POWER QUALITY CONTROL THROUGH AUTOMATED DEMAND SIDE MANAGEMENT IN MICROGRID EQUIPPED WITH BATTERY ENERGY STORAGE FOR PROTECTION

The battery energy storage (BES), intelligent protection and power quality are considered as independent issues, but these three factors can be interlinked effectively for control of microgrid through automated demand side management (ADSM). In this context, the proposed approach may change the conventional way of microgrid operation and control giving priority to the power quality issues considering protection and BES systems. The control algorithm is implemented through FIS based PQMI and ADSM.

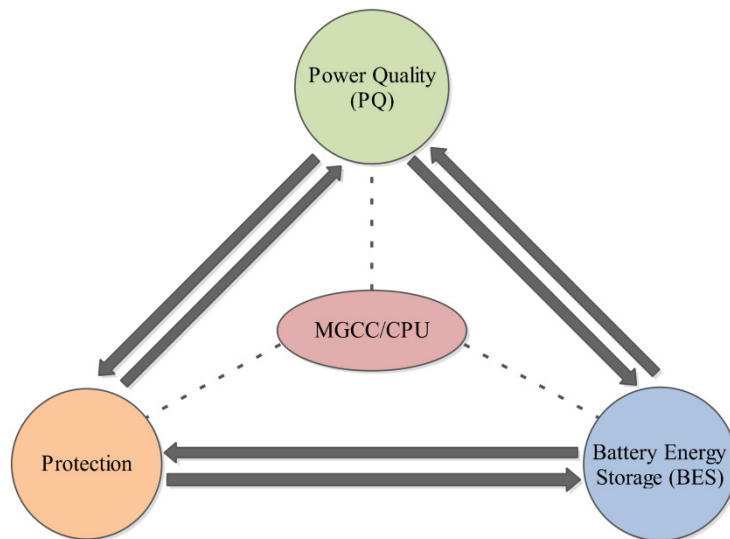


Figure 5.1. Graphical presentation of relation among microgrid PQ, protection coordination and BES

The microgrid central controller (MGCC) or central processing unit (CPU) proposes that it can coordinate with power quality, protection and BES to maintain the healthy operation of microgrid as shown in Figure 5.1. It is understood that the BES framework is required to guarantee smart insurance and approval through a re-enactment based contextual investigation for a sample microgrid, which has a novel insightful control using ADSM considering power quality as a principal issue for the sensitive or critical loads. So, this observation is a motivation for research to achieve the following goals in this chapter.

- To propose an intelligent power quality based control using ADSM to the critical load.
- To facilitate the microgrid system with proper coordination of battery energy storage for protection relay device and power quality for satisfactory operation.

The significant contributions of this chapter are listed as follows.

- Established relationship between power quality and BES as backup for relay device for CB chamber as a part of the protection system through ADSM.
- The proposed control algorithm is implemented through fuzzy inference system (FIS) based power quality monitoring index (PQMI) and ADSM for improving the power quality of microgrid.
- Logic table for CB coordination is developed without/with backup for relay device to analyze the functionality of CB.
- Power quality parameters such as voltage, frequency, THD and power factor are analyzed for sensitive loads with the impact of fault.
- Experimental validation is done using real-time simulator OP4510 RT-LAB-RCP/HIL which verifies existence of the proposed control algorithm equipped with power quality control in close coordination with protection and BES facility.

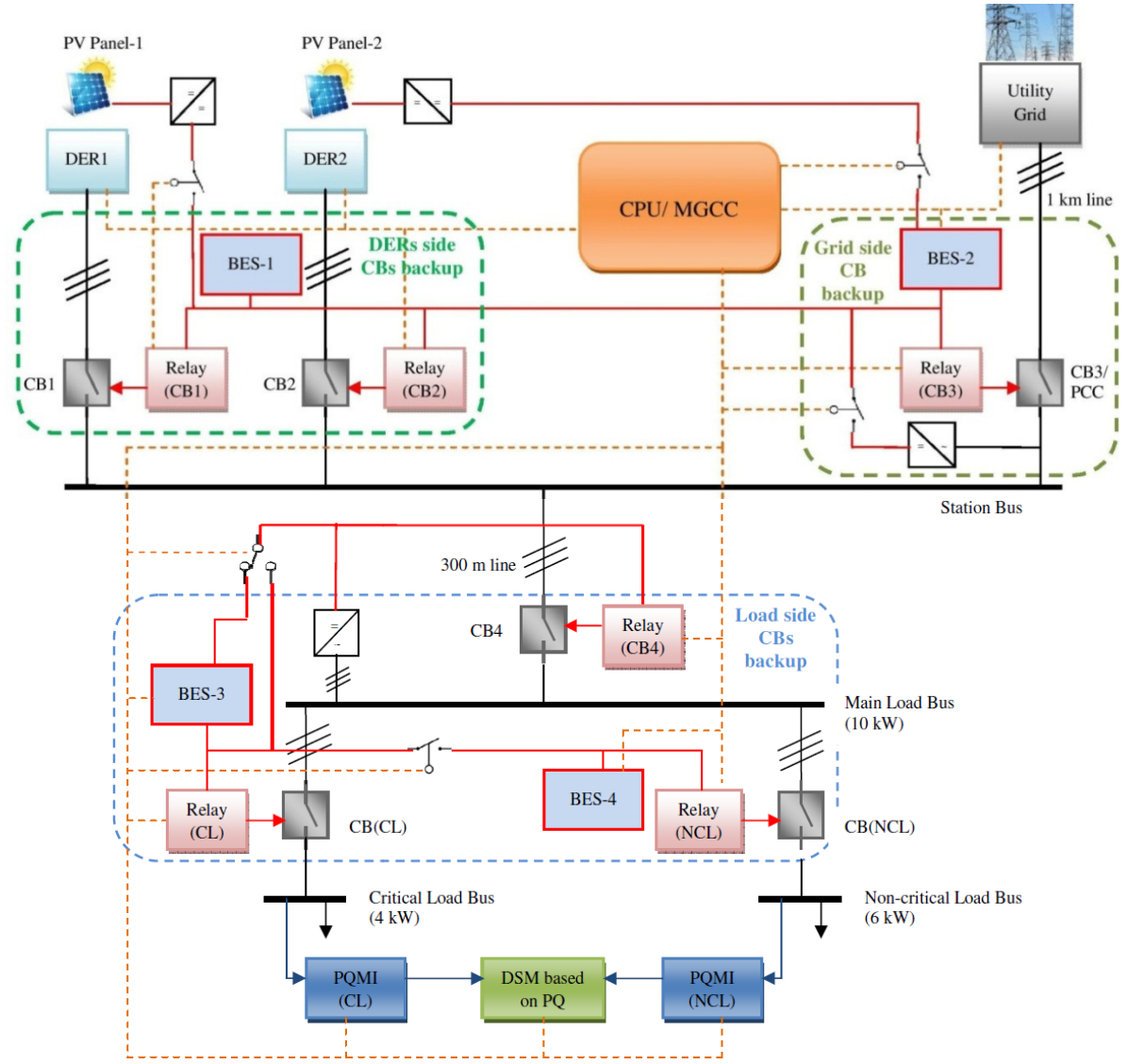
5.1 THREE-PHASE AC MICROGRID SYSTEM BASED ON ADSM INCLUDING BES

A 10 kW, 400 V, 50 Hz, three-phase AC microgrid model has been proposed with the combination of two DERs and one utility grid as shown in Figure 5.2(a). The DER1 and DER2 are equipped with their individual PV panels at rated capacity of 10 kW_p. Both DERs are interfaced at PCC with utility grid to ensure the stability of the microgrid system during insufficient availability of solar irradiance or lack of PV generation. The proposed three-phase AC microgrid system is settled in such a way that it will be satisfying the load from DERs and/or grid during day hours and/or night hours respectively. The simultaneous effects of both PV panels have been considered during the operation of CBs. As per Figure 5.2(a), the individual set of two BESs is placed on both station bus and load bus to make the smooth

and uninterrupted operation of all CBs. Like, BES-1 and BES-2 are placed near to CB1-CB2 and PCC while BES-3 and BES-4 are located close to critical load (CL) and non-critical load (NCL) breakers respectively. All relay devices are powered by 24 V DC supply to their respective three-phase CBs. There are three energy storage clusters which provide backup for DERs, grid and load side CBs, highlighted through dashed boxes as presented in Figure 5.2(a).

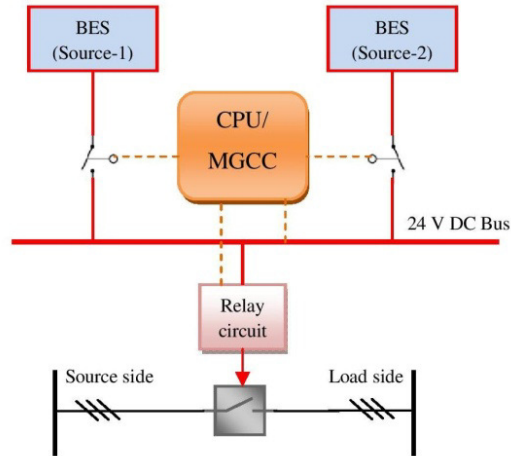
The BES-1 and BES-2 with 24 V DC supply are connected to each other and placed near to the relay cabin of CB1, CB2 and CB3 on the station bus. Similarly, 24 V DC supply from BES-3 and BES-4 are fed to the relay device of CB(CL) and CB(NCL) in reference to the main load bus. The utilization of one or more than one BESs depends upon the health status of relay device under the supervision of MGCC/CPU. MGCC/CPU monitors continuously the status of CBs, DERs, utility grid and load; and gives command to the devices accordingly by maintaining the power quality of the microgrid. The operational concept of BES is presented in Figure 5.2(b) under full control of MGCC to serve the secure and reliable operation of CB during transition or fault. In Figure 5.2(b), two BES systems (Source-1 and Source-2) are provided for relay device circuit in coordination with the respective CB chamber. In reference to 24 V DC supply, the role of MGCC/CPU is to monitor the health status of all relay devices, including DER1, DER2 and grid by taking corrective action whenever necessary. BES-1 and BES-2 can be charged from DERs in case of surplus power. If one of the supplies goes out (e.g. BES-1 or Source-1) then BES-2 or Source-2 will come immediately into operation and give command to CB for opening/closing of its contacts as referred in Figure 5.2(a) and 5.2(b).

In addition, this helps to segregate the voltage biasing of relay circuit breaker during its change in state. Further, this also checks the working status of MGCC continuously during its operation and maintains supply to the controller with negligible biasing in MGCC too. It is concluded that a CPU can coordinate intelligently with protection when it operates with uninterrupted power supply during its operation. Hence, relay coordination system must have energy backup for its reliable and stable operation under normal/abnormal working condition.



Legends: 3-phase AC line 24 V DC line Communication/Control signal

(a)



(b)

Figure 5.2. (a) Schematic diagram of a proposed microgrid model based on ADSM including storage system and, (b) BES system for continuous operation of relay circuit under the supervision of CPU/MGCC

5.2 PROPOSED METHODOLOGY: CONCEPT AND ALGORITHM

The concept of energy storage backup can be understood by proposing logic tables considering single BES and two BESs as shown in Table 5.1(a) and 5.1(b) respectively. Table 5.1(a) and 5.1(b) show the coordination between CB and BES during fault, which will be sensed by the overcurrent relay to choose the preferable state (on/off) of CB. For example, Case-III in Table 5.1(a), a three-phase fault is sensed by the overcurrent relay (digital logic: 1) and failure in the main DC supply to the relay coil without any backup or station battery (digital logic: 0), hence no instruction/command will be initiated to the respective CB chamber (digital logic: 0). So, this mis-operation of the CB can be rectified by providing BES system (station battery) as backup to make the smooth and reliable operation under the fault condition.

In Table 5.1(b), the same Case-III is now supported by the station battery which will make sure operation of CB (digital logic: 1) with preferable state either to open or close the breaker contacts, hence the overall system gets protected from the fault. It is realized from Table 5.1(b) that after providing the station battery as backup has converged Case-III similar to Case-IV. Further, the Case-I also becomes equivalent to the Case-II due to the backup support although there is no fault sensed by the overcurrent relay (digital logic: 0) so there will be no instruction to CB chamber. But, it can be used for manual state-of-transition of the CB with the station battery for scheduled maintenance or inspection.

Table 5.1.(a). Logic table for CB coordination with single BES

Case	Overcurrent digital relay or comparator	Station battery	Instruction to CB	Preferable state
I	0	0	0	×
II	0	1	0	✓
III*	1	0	0	×
IV	1	1	1	✓

Table 5.1.(b). Logic table for CB coordination with extra BES as backup

Case	Overcurrent digital relay or comparator	Station battery	Instruction to CB	Preferable state
I	0	1	0	✓
II	0	1	0	✓
III*	1	1	1	✓
IV	1	1	1	✓

Hence, Table 5.1(b) shows continuous backup to the relay device which will provide protection coordination by maintaining the power quality (or PQMI) immediately after the fault clearance. The same approach can be directed through a flowchart which is presented in Figure 5.3 to assess the FIS-based PQMI considering power quality parameters and BES backup for relay devices. The variations in voltage deviation (VD), frequency (F), total harmonic distortion (THD) and power factor (PF) have been considered with the inception of different reasons/causes like overvoltage/undervoltage, overloading, faults, failure in DER, non-linear and highly inductive loads. ADSM takes care about the feedback loop control and load adjustments (NCL/CL). By assessing PQMI at CL and NCL buses, it helps to take intelligent protection and controlling action based on ADSM with less reduction in the loads.

The algorithm presented in Figure 5.3 is executed followed by power quality parameters (VD, F, THD, PF), status of the CB chambers, ADSM and PQMI. It is suggested that MGCC will continuously monitor the status of VD, F, THD and PF; and check the reasons/causes for the same if any violation is found. The issues caused by these variables can be resolved through ADSM by applying feedback control or curtailment of the load. This concept can be executed using following steps.

Step 1. Read 3-phase line data such as voltage, current, VD, F, THD and PF.

Step 2. Check the range of power quality parameters as per international standards listed in Table 3. At the same time, also, check the status of CB chamber followed by the power supply to that of the respective relay device.

Step 3. Analyze the reasons/causes for any violation in VD, F, THD and PF.

Step 4. Rectify the problems as mentioned in step 3.

Step 5. Check the status of DC power supply to relay devices for tripping/closing the CBs.

Step 6. If one BES goes out of order then second BES will be connected to relay device to make the reliable operation of CB during fault or scheduled maintenance period.

Step 7. Implement the ADSM system followed by step 4 and step 6.

Step 8. Assess the PQMI to highlight the health status of microgrid.

Step 9. Check the value of PQMI in the range of 0 to 7. If $PQMI \geq$ average value of 3 then go to step 2, and repeat it again, otherwise stop.

The relay device is fully equipped with BES to provide backup for the successful operation of CB by maintaining good power quality and protection coordination in microgrid system. It is suggested that the continuous power supply to CL or sensitive load is highly preferable as compared to NCL under abnormal situation. Hence, an intelligent protection is presented with feedback control feature based on the ADSM utilizing PQMI to sensitive loads.

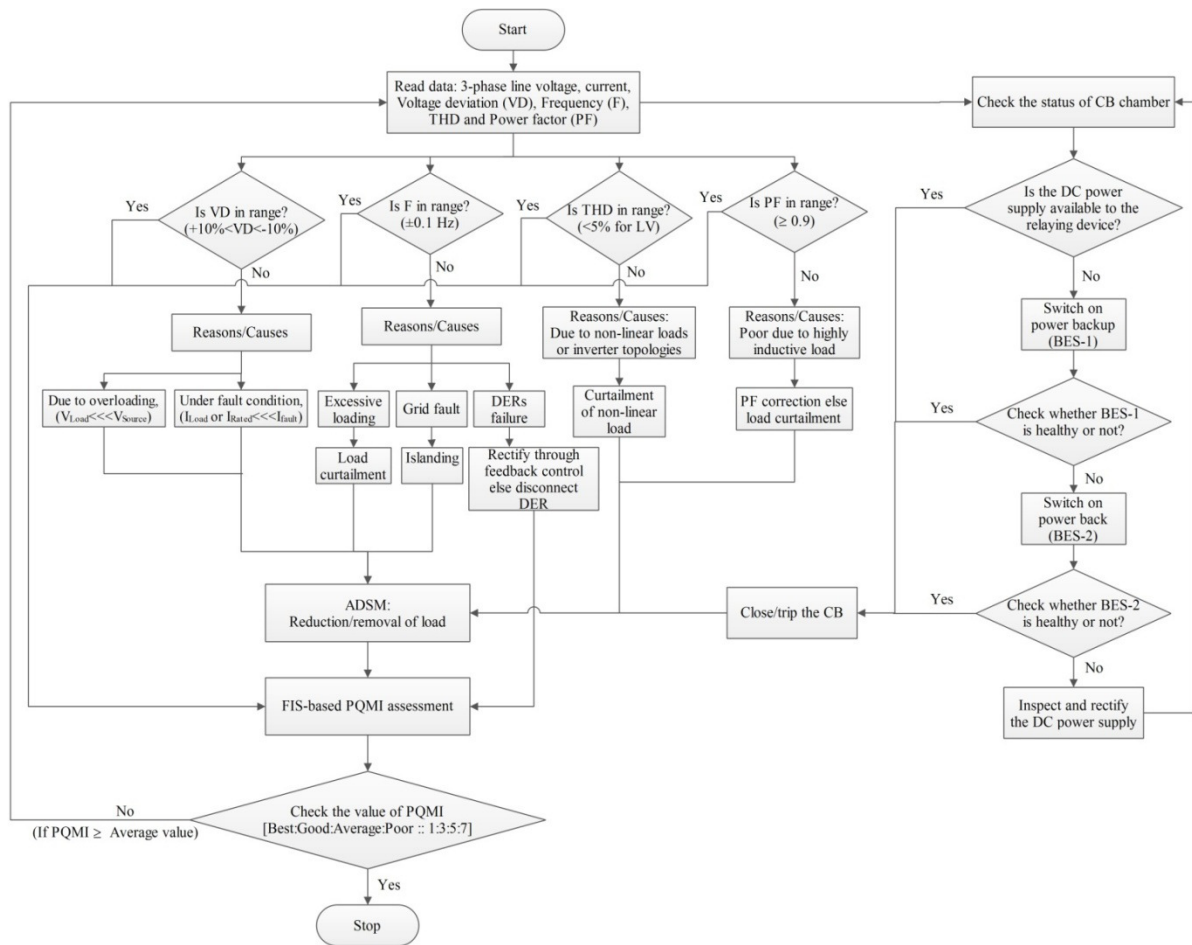


Figure 5.3. Flowchart of proposed algorithm showing relationship between power quality and BES as backup for relay device for CB chamber as a part of protection system through ADSM

5.2.1 Assessment of FIS based PQMI

The PQMI is developed in Chapter 3 to assess the status of AC microgrid under grid-connected and islanded conditions. The concept of FIS based on PQMI is extended to take

controlling action and enhancing the power quality under the coordination of protection and storage system. The FIS wizard with their membership functions have been formulated based on four input variables such as VD, F, THD and PF; and one output variable as PQMI. To quantify the fuzziness in random variation of power quality, a PQMI can be calculated using 256 (four membership functions with four input variables that is $4^4 = 256$) rules-based FIS for the proposed microgrid model. The ranges of input membership function variables have been selected as per international IEEE/IEC standards as given in Table 5.2. The PQMI can be displayed in the range of 1 to 7 (best PQMI: close to value 1 and poor PQMI: close to value 7) based on the status of four input variables as mentioned in Chapter 3.

Table 5.2. Acceptable range of membership function variables as per IEEE/IEC standards table for CB coordination with single BES

Parameter(s)	International standard	Range
Voltage deviation (%age)	IEEE Std. 1250-2011	$\pm 10\%$ for LV
Frequency (Hz)	IEEE Std. 1159-2009	± 0.1 Hz
THD (%age)	IEEE Std. 519-2014	5% for LV
Power factor	IEC 60831-1/2	Greater than 0.9
PQMI	As per novel FIS scheme	1 to 7

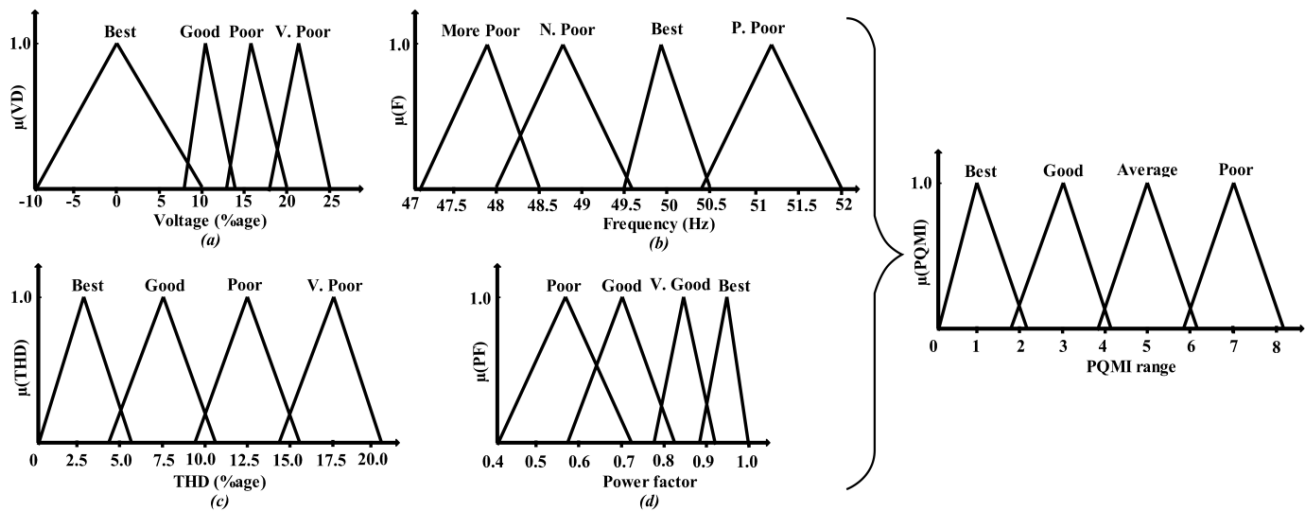


Figure 5.4. Membership functions of input variables (a) voltage deviation, (b) frequency, (c) THD and (d) power factor to generate output variable as PQMI

The relation among protection, control and BES through ADSM can be maintained with the application of FIS-based PQMI. The corrective action can be initiated by continuous monitoring of power quality parameters through flowchart as shown in Figure 5.3. The output membership function (PQMI) can be formulated based on the status of four input variables such as VD, F, THD and PF as shown in Figure 5.4. The range of VD, F, THD and PF are

specified as -10% to 25%, 47 Hz to 52 Hz, 0 to 20% and 0.4 to 1.0 as shown in Figure 5.4(a)-5.4(d) respectively. The sudden increase or decrease in load can disturb the PQMI of microgrid, so an immediate action will be taken through the ADSM. This reduces the burden on DERs under heavy load condition, and then forwards the command to the PQMI assessment meter (on right side of Figure 5.4) for the final checking of power quality.

5.3 EXPERIMENTAL SETUP

The proposed control scheme has been validated through experimental setup using a basic level OPAL-RT simulator OP4510 RT-LAB-RCP/HIL system. The OP4510 simulator can be used suitably for rapid control prototyping (RCP) and hardware-in-the-loop (HIL) simulation [129]. The OP4510 incorporates RT-Lab and FPGA authentic-time platform with the highest performance processors with industry standard, simulink and LabVIEW software. It comprises well-equipped power electronic controller system with the pre-defined simulation model. The input signals (VD, F, THD, PF, three-phase voltage, current etc.) are fed to slave block from master block through OpComm module. The experimental setup of the real-time OPAL-RT OP4510 simulator is shown in Figure 5.5, which shows the interfacing of microgrid test system with the host computer. The existence and feasibility of the proposed microgrid model has been validated using OPAL-RT OP4510 simulator and experimental results are discussed in the next Sub-section 5.4.

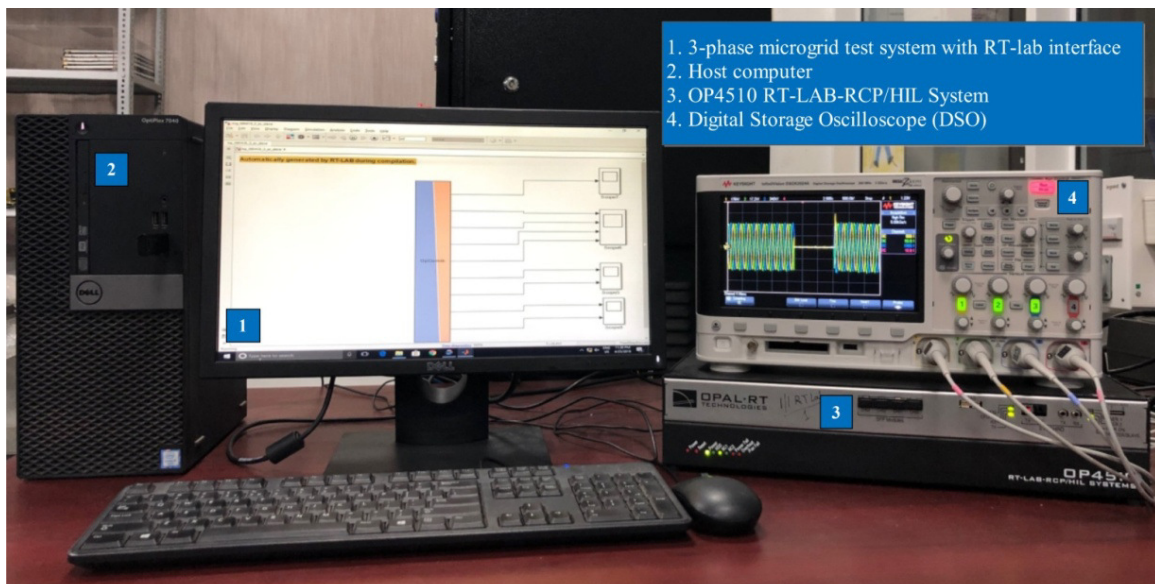


Figure 5.5. Experimental setup for a 3-phase microgrid system using OP4510 RT-LAB-RCP/HIL real-time simulator system

5.4 EXPERIMENTAL RESULTS AND DISCUSSIONS

The proposed three-phase AC microgrid model is simulated in the MATLAB-software environment and validated through the real-time simulator OP4510 RT-LAB-RCP/HIL system during grid-connected mode. The intelligent protection coordination and control have been investigated for CPU/MGCC module with the application of BES system especially for protection devices. In Sub-section 5.4.1, the relay circuit protection coordination with intelligent control is examined with or without BES system as backup. The MATLAB-software results are validated through experimental results which are discussed in Sub-section 5.4.2.

5.4.1 Relay device power backup

The CB configuration consists of relay circuit which is connected to two power backups as shown in Figure 5.1(b). The MGCC/CPU take care the status of power supply to the relay device under steady state and fault conditions. In Figure 5.6, it is shown that the relay device supply can be maintained to 24 V DC utilizing BES-1 and BES-2 if the main supply gets failed to support protection coordination among the CB chamber. It has been assumed that the main DC supply fails to power relay device from simulation time of 0.4 second to 1 second as shown in Figure 5.6(a). So, BES-1 (Source-1) will be switched-on immediately at 0.4 second as shown in Figure 5.6(b), but after 0.6 second there is a fall in DC voltage of BES-1 to 21.5 V (minimum acceptable voltage is 21.6 V as 10% of 24 V DC) due to non-sufficient charging of the battery. Hence, the standby source (BES-2) will be connected at 0.6 second and supplying the relay device up to simulation time of 1 second as shown in Figure 5.6(c). It can be seen from Figure 5.6(d) that the 24 V DC supply has been maintained continuously for intelligent protection coordination. Transients have been observed at 0.4 and 0.6 seconds due to transfer in the supply from main to BES-1 and BES-1 to BES-2 as shown in Figure 5.6(b)-5.6(d).

The Figure 5.7(a)-5.7(b) show the impact of three-phase fault on load voltage and current from 4.2 to 4.4 seconds if CB fails to operate due non-pickup of relay signal. During three-phase fault, line voltage becomes zero and line current increased abruptly very high as shown in Figure 5.7(a) and 5.7(b) respectively. So, the concept of Figure 5.6(d) is incorporated to maintain relay coil voltage signal for removing the fault as soon as possible. After providing

backup to the relay device, the breaker switched over the supply and maintained the three-phase supply to the load bus as shown in Figure 5.7(c) and 5.7(d).

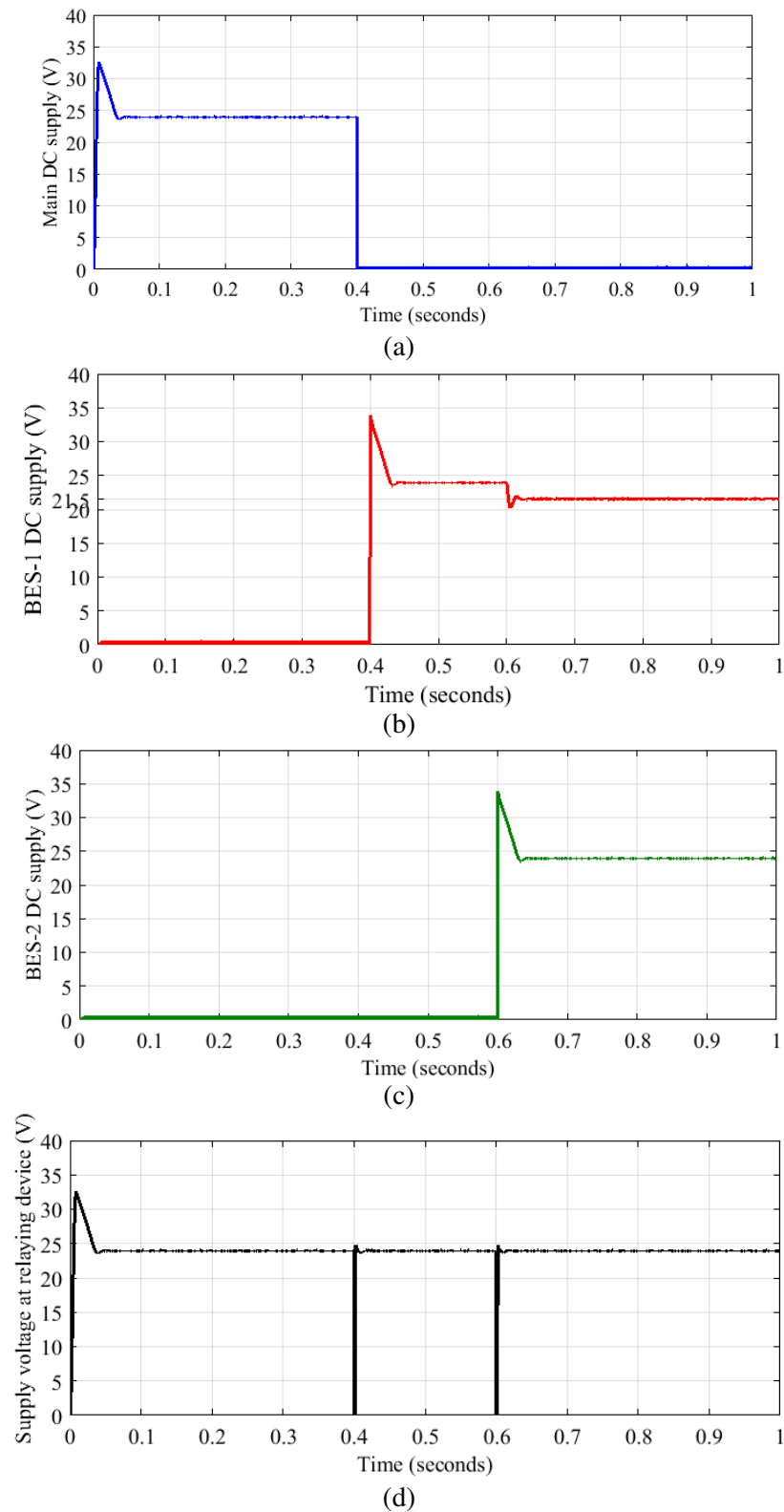
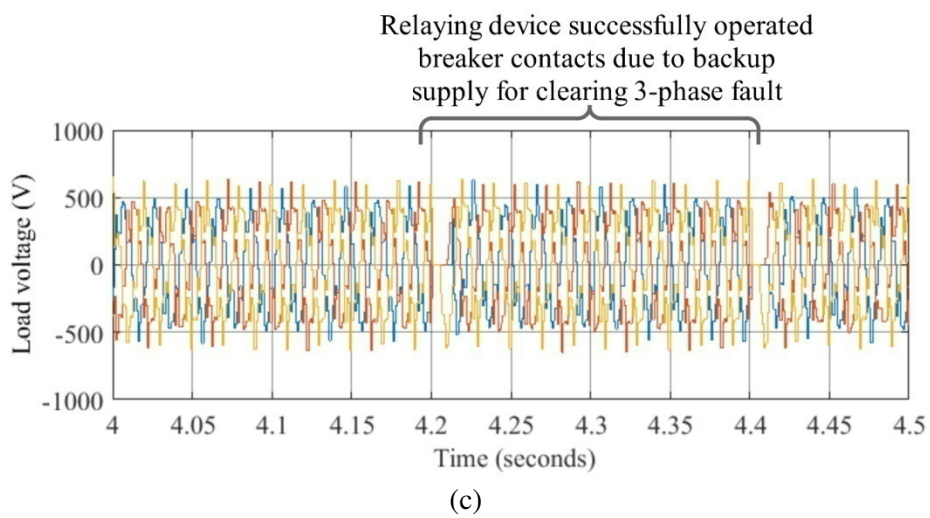
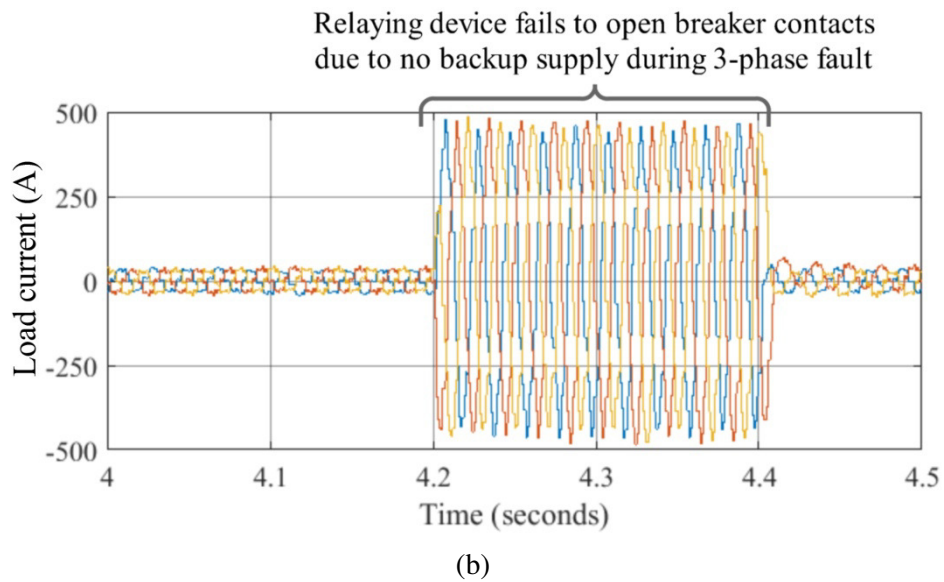
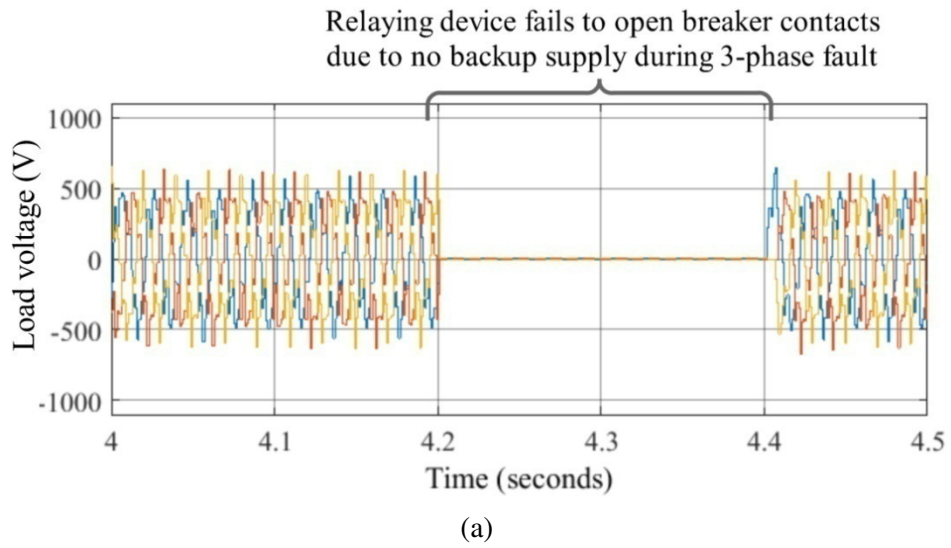


Figure 5.6. Relaying device supply voltage profile: (a) main DC supply, (b) BES-1 DC supply, (c) BES-2 DC supply and (d) at the terminal of relay coil in coordination with CB chamber



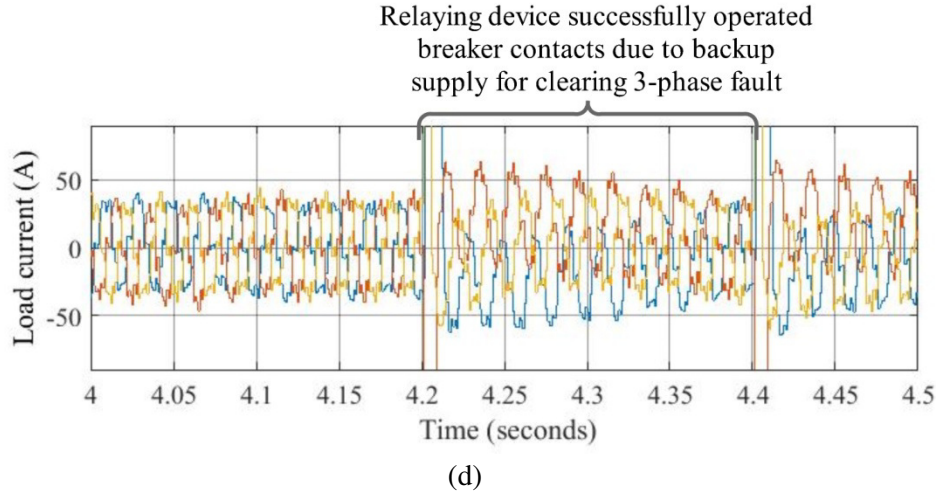


Figure 5.7. Microgrid operation: (i) no breaker operation due to no backup for relaying device during three-phase fault: (a) load voltage, (b) load current and, (ii) breaker operation with BES backup: (c) load voltage, (d) load current

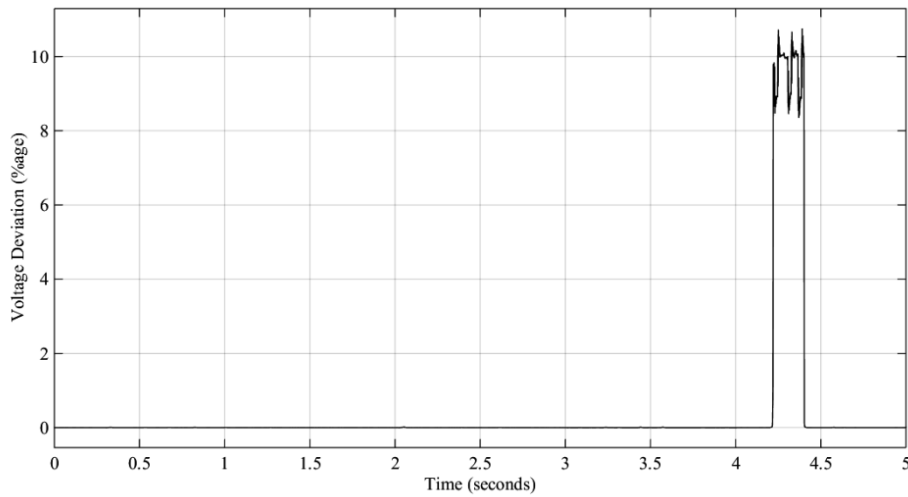
Also, this changeover has shown some delay as the breaker took time at 4.2 and 4.4 seconds from one to another state as presented in Figure 5.7(c) and 5.7(d). It is assumed that one pair of three-phase line gets fully short circuited (three-phase fault) and CB changeovers the supply through another pair of three-phase line. This analysis proves that BES as backup coordinated intelligent protection and control features, ensuring reliability in microgrid operation for MGCC/CPU.

5.4.2 Automated demand side management (ADSM) for loads

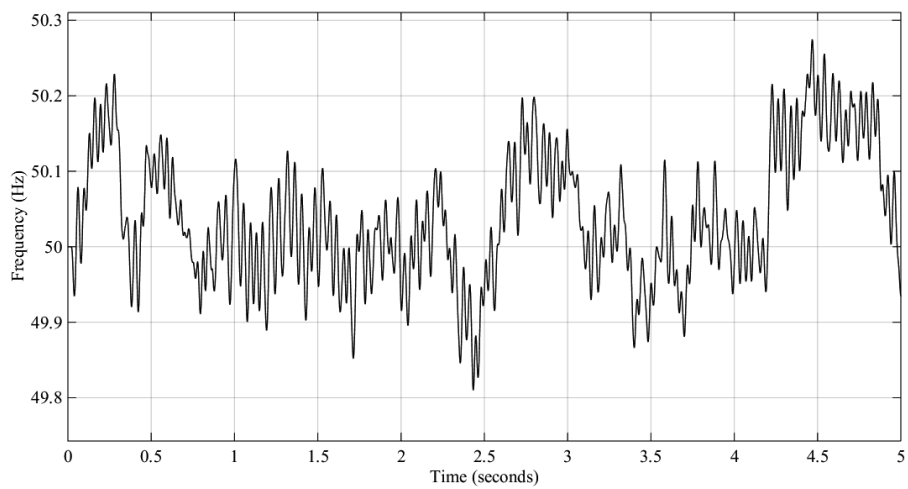
In this section, the power quality parameters have been analysed in MATLAB-software environment due to intelligent protection coordination and control features based on ADSM to the sensitive/critical load as per the algorithm presented in Figure 5.3. The concept of demand side management (DSM) is introduced to maintain the balance between generation and load. The DSM based on power quality has been proposed to maintain the sound health of microgrid in connection with CL and NCLs. Figure 5.8 depicts the overall change in variables, as per the ADSM applied on the CL bus due to the inductive load. The variation in PQMI for the sensitive load is shown in Figure 5.9(a) and PQMI waveform from experimental setup is shown in Figure 5.9(b). In this figure, the scale of the vertical axis has been considered as the numerical value of 1/division. The horizontal time axis has been scaled with value 2 second/division. The instantaneous value of PQMI varies within the range from 4 to 7 as per status of VD, F, THD and PF. It is suggested that when PQMI reaches to the value 7 (poor) then load responsible poor power quality should be curtailed through

ADSM strategy. The reason for getting poor PQMI as 7 is due to the violation in frequency (50.25 Hz) and THD (more than 5%) as shown in Figure 5.8(b) and 5.8(c) respectively. Hence, the sensitive loads are to be managed based on the value of PQMI at load end. The continuous monitoring of PQMI helps to implement DSM for satisfactory operation and control of microgrid under the supervision of MGCC/CPU.

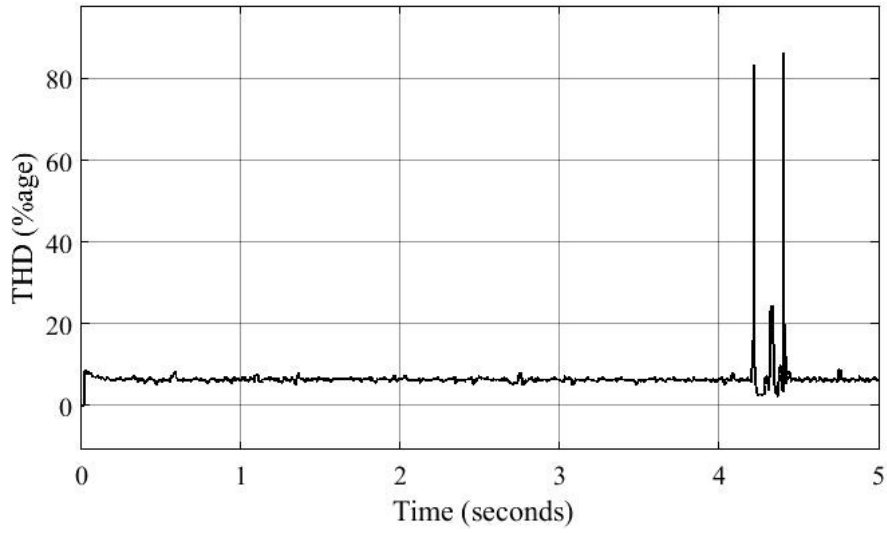
The three-phase AC microgrid results have been validated using the real-time simulator OP4510 RT-LAB-RCP/HIL system during grid-connected mode. The experimental results have shown feasibility and satisfactory outcomes of the proposed methodology in the area of microgrid intelligent protection coordination and control features. The Figure 5.10(a)-5.10(d) show the experimental waveforms of power quality parameters captured through the digital storage oscilloscope (DSO) under three-phase fault condition.



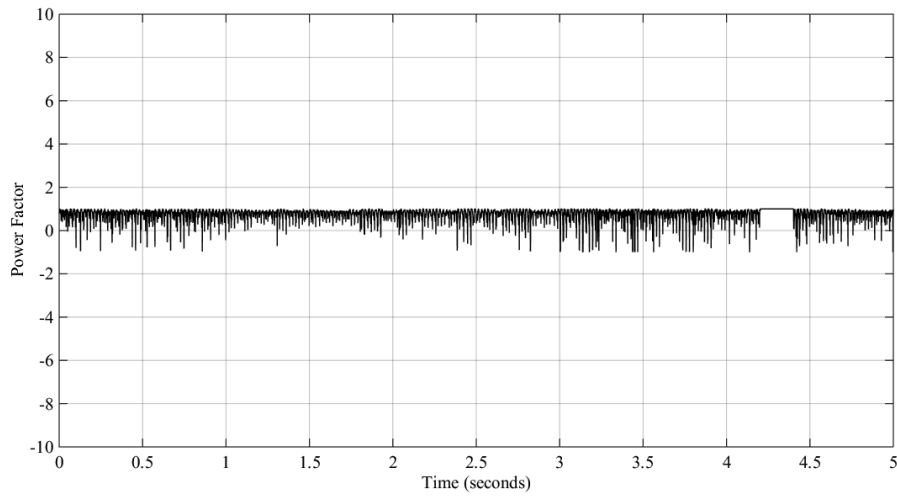
(a)



(b)



(c)



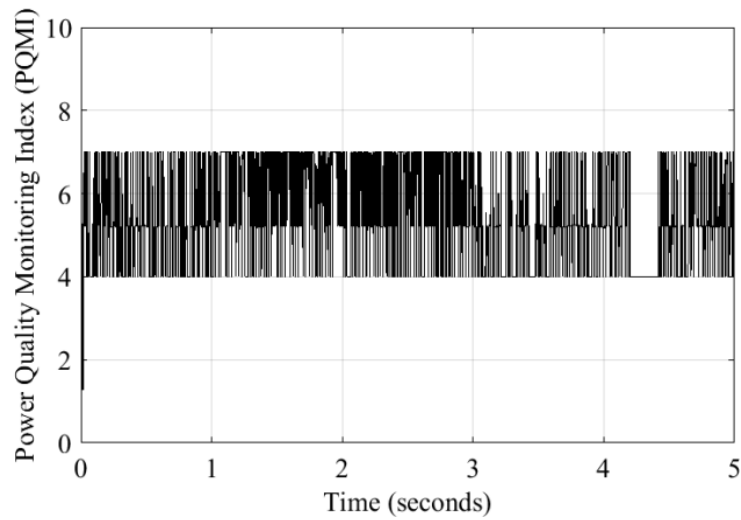
(d)

Figure 5.8. Power quality parameters for critical/sensitive load: (a) voltage deviation (b) frequency (c) THD and (d) power factor

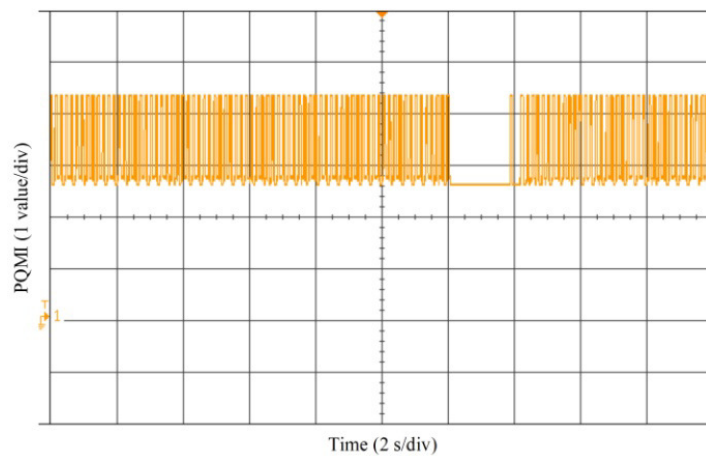
The VD waveform has shown overshoot during fault as shown in Figure 5.10(a) with the vertical and horizontal scale of 5 volt/division and 2 second/division respectively. In this figure, VD is obtained approximately 0% before and after clearing the fault, while it is observed as 16% in the fault period. The frequency waveform is presented in Figure 5.10(b) with the scale of 100 mHz/division along vertical axis and 20 msecond/division along horizontal axis. It is observed that there is a little change in frequency during fault; otherwise the frequency is maintained at 50 Hz. The waveform presented in Figure 5.10(c) has shown approximately 15% THD before and after the fault while it is 80% during the fault. Similarly, the power factor (PF) profile has shown steady waveform ($PF = 0.78$) before and after

clearing the fault while it is undefined during the inception of fault, as shown in Figure 5.10(d). Hence, the PQMI could be calculated based on the status of these four variables and it is found that the VD and THD values are responsible for poor power quality as shown in Figure 5.9(b).

In addition, the three-phase load voltage, current and active/reactive powers have been displayed on DSO during fault period through the real-time simulator. In Figure 5.11(a), the three-phase load voltage (phase-voltage) has shown maximum peak of 350 V (175 V/division) before and after the fault else it became zero during the fault period.

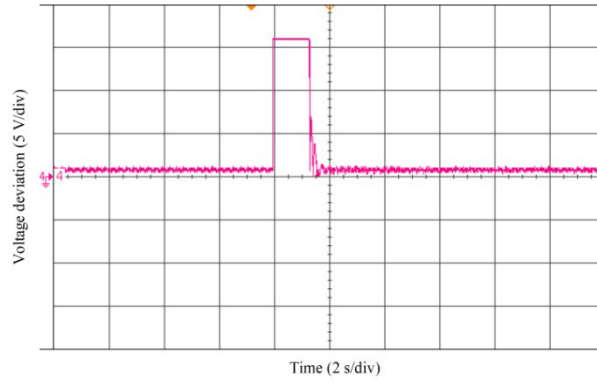


(a)

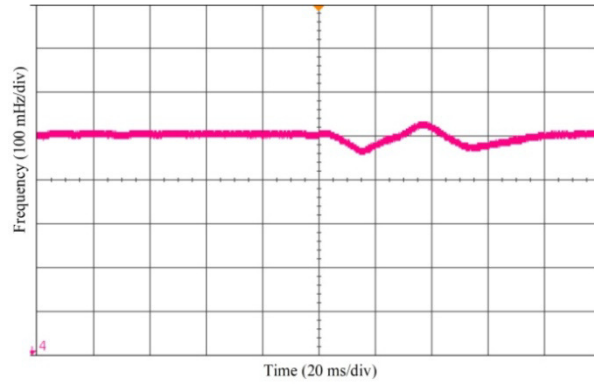


(b)

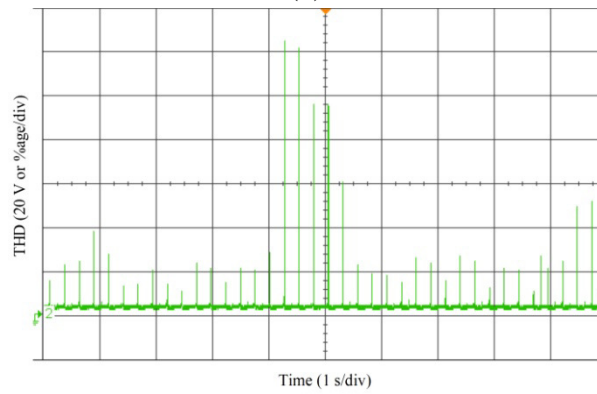
Figure 5.9. (a) PQMI obtained in simulation and (b) PQMI obtained from experimental setup



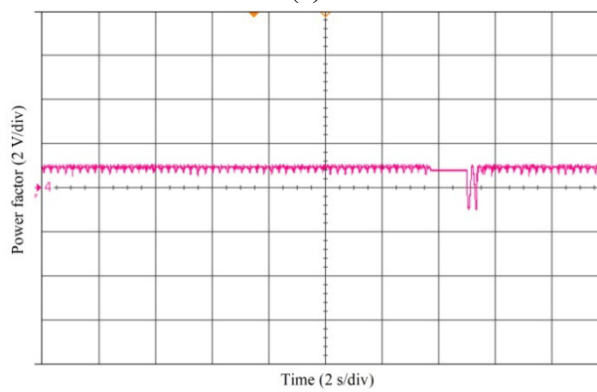
(a)



(b)



(c)



(d)

Figure 5.10. Experimental results under the impact of three-phase fault: (a) voltage deviation, (b) frequency, (c) THD and (d) power factor

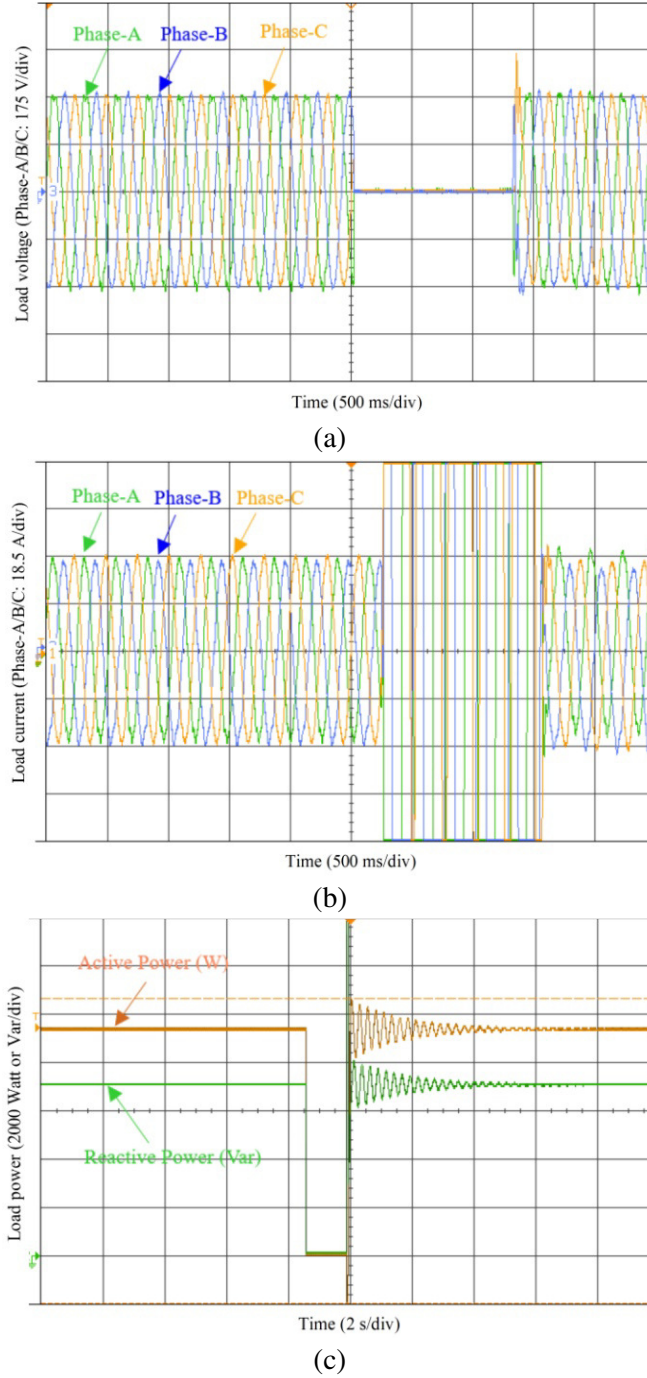


Figure 5.11. Experimental results under the impact of three-phase fault: (a) load voltage, (b) load current and (c) load powers

Similarly, the three-phase current (phase-current) has increased sharply beyond the rated peak value of 37 A (18.5 A/division) as shown in Figure 5.11(b). Active and reactive power profiles have been monitored and are found as 9.6 kW and 7.4 kVar respectively, before and after the fault period as presented in Figure 5.11(c). During the fault period, it is further investigated that both active and reactive powers across the load become zero because of no voltage supply to the load bus as refer in Figure 5.11(a). Hence, the experimental results have

shown the feasibility of the proposed microgrid model with the assessment of power quality parameters.

The proposed controller has demonstrated novelty and exceptionality, which could interlink the protection relay device using BES as backup by improving the power quality through ADSM of three-phase AC microgrid. The control algorithm is implemented through FIS-based PQMI including ADSM to improve the power quality parameters such as voltage, frequency, THD and power factor as per international IEEE/IEC standards. The intelligent protection logics have been developed for relay devices without and with BES as backup to analyze their functions under normal and abnormal conditions. The simulation results are validated experimentally using real-time simulator OP4510 RT-LAB-RCP/HIL, which show feasibility of the proposed control algorithm equipped with power quality control in close relation with protection and BES systems. In case of critical and non-critical loads, the ADSM is implemented and validated using real-time OPAL-RT simulator to maintain reasonably good PQMI. It is also investigated that the MGCC/CPU controller can be operated with the provision of extra storage facility for its reliable and stable operation in the application of microgrid.

The power quality control in microgrid through ADSM is discussed in this chapter with the application of BES system for protection. The control algorithm is implemented through FIS based PQMI and ADSM for three-phase AC microgrid system. The relation among microgrid power quality, protection coordination and BES has been framed in this chapter to reflect the effective interlink between them. The proposed control scheme has been validated through experimental setup using a basic level OPAL-RT simulator OP4510 RT-LAB-RCP/HIL system.

POWER QUALITY CONTROL USING ARTIFICIAL NEURAL NETWORK IN PV INTEGRATED AC MICROGRID

In the present scenario of microgrid system, conversion of electrical energy has initiated a challenge to maintain the power quality within a satisfactory range. It can be influenced by the voltage deviation, sag/swell, unbalancing, frequency, THD and power factor as per nature of local loads and the condition of DERs. The relationship between power quality and the set of these variables are non-linear in nature. The existing literature show that the above mentioned parameters are not considered simultaneously for the assessment and controlling of power quality in PV based AC microgrid. To minimize the effect of these variables, a novel artificial neural network (ANN) based control approach has been proposed which can control the power quality as per IEEE/IEC standards. The proposed method has shown fast, smooth and stable operation while the performance of the same is verified with that of the proportional-integral (PI) and fuzzy-PI controllers in the PV based three-phase AC microgrid using MATLAB-Simulink software.

The small size microgrid model is tested with the effect of line impedance and communication delay for the assessment of power quality parameters. This model is extended to a large size realistic microgrid structure for the feasibility of control methodology. The realistic microgrid structure is verified under the analysis of line impedance, communication delay, demand response and off-nominal conditions. The proposed control methodology is validated in a realistic microgrid structure and simulation results are presented to show the performance of proposed controller under different conditions.

It is also realized that the artificial neural network (ANN) based control topology can be implemented for large set of non-linear equations as compared to conventional methods. The major contributions and advantages of this control topology are listed below.

- The simultaneous effects of power quality parameters such as voltage deviation, THD, frequency and power factor have been assessed and controlled.

- Small size microgrid has been simulated without/with the effects of line impedance and communication delay on the performance of proposed controller during on-grid and off-grid operations.
- Existence of the proposed controller has been validated through the extended realistic three-phase AC microgrid structure.
- The performance of the proposed controller has been investigated with the effect of line impedance on power sharing and losses during on-grid and off-grid conditions for realistic microgrid structure.
- Demand response has been analyzed and the power quality parameters have been controlled with the effect of communication delay on controller action for a realistic microgrid structure. In addition, the off-nominal frequency condition with additive noise has also been incorporated and assessed for realistic microgrid structure.
- The proposed ANN-based controller can be used as multi-functional device for large size of DERs and loads as stated in realistic microgrid structure due to its flexibility and stability which has not been addressed in several literature such as conventional droop control, distributed proportional integral method, optimum power reconfiguration optimization tools, master-slave control, BES coordination control etc.

The Sub-section 6.1 describes the problem definition of the presented work. The system description along with the microgrid components is analyzed in Sub-section 6.2. The Sub-sections 6.3 and 6.4 discuss the proposed microgrid model and methodology respectively followed by small size and realistic microgrid structures. The conventional PI and fuzzy-PI controllers are discussed in Sub-section 6.5. The results are discussed for small size and realistic microgrid structures without/with the effect of line impedance, communication delay, demand response and off-nominal conditions in Sub-section 6.6.

6.1 PROBLEM DEFINITION

The operation of non-linear loads like power electronic based equipment generates harmonics and lead to poor quality of the power. The custom power devices such as DVR, DSTATCOM, AVR, UPQC etc. are used to maintain the power quality for both power

suppliers and consumers. These devices are installed to investigate the performance of microgrid system under the disturbances like voltage sag/swell, THD, power factor, frequency and unbalanced system. In microgrid system, the major problems are to maintain the power quality parameters within their acceptable ranges such that voltage deviation must lie within 10% of its nominal value as per IEEE Std. 1250-2011, the allowable change in frequency should be ± 0.1 Hz as framed in IEEE Std. 1159-2009, the voltage/current THD level should not be more than 5% as listed in IEEE Std. 519-2014 and the power factor of the system must be equal or greater than 0.9 as appended in IEC 60831-1/2 standard. The above problems show that an effective and reliable controller needs to be installed so that the power quality can be maintained sound and healthy during grid-connected and islanded modes of operation. The following parameters have been considered to assess the power quality in the proposed three-phase AC microgrid topology.

6.1.1 Voltage sag/swell and unbalanced system

The RMS voltage can be expressed based on its peak value and samples per cycle as shown in equation (6.1) [130].

$$V_i^{rms} = \sqrt{\frac{1}{M} \sum_{j=1}^{i+M-1} V_j^2} \quad (6.1)$$

where M is samples per cycle of the fundamental, V_j is j^{th} sample of the recorded voltage waveform, V_i^{rms} is i^{th} sample of the calculated RMS voltage. The RMS voltage is delayed relative to the phase voltage by $(M - 1)$ samples due to the M sample window. The equation (1) computes the true RMS value of the input signal and calculated over a running average window of one cycle of the specified fundamental frequency 50 Hz. As this uses a running average window, one cycle of simulation must complete before the output gives the correct value and the output is held to this specified initial RMS value for the first cycle of simulation. In case of voltage sag, the RMS voltage decreases for the duration of 0.5 cycle to 1 minute with typical values of 0.1 to 0.9 p.u and voltage increases from 1.1 to 1.8 p.u. for same duration of 0.5 cycle to 1 minute under condition of voltage swell [131]. The voltage (V_j) decides the status of sag and swell as per the samples of recorded waveform.

The voltage sag (or dip) and swell are most common type of problems to maintain the power quality in the power system. In case of islanded condition, the power quality is enhanced using proposed controller under the influence of voltage sag and swell. The proposed scheme can be tested by imposing three-phase or single-phase fault and sudden removal of heavy load as well to investigate the impact of voltage sag and swell on the power quality. The three-phase unbalance condition is initiated by changing the load impedance and mismatching of line-to-neutral voltages and phase angles.

For example, $[V_a, V_b, V_c] = [400, 200, 450]/\sqrt{3}$ and $[\phi_{ia}, \phi_{ib}, \phi_{ic}] = [0^\circ, -60^\circ, +180^\circ]$

6.1.2 Total harmonic distortion (THD)

The ratio of the RMS of harmonics to the fundamental signal is called THD and expressed by the equation (6.2) [131].

$$THD_V = \frac{\sqrt{\sum_{i=2}^N V_i^2}}{V_1} = \frac{\sqrt{V_{rms}^2 - V_1^2}}{V_1} \text{ and } THD_I = \frac{\sqrt{I_{rms}^2 - I_1^2}}{I_1} \quad (6.2)$$

6.1.3 Power factor (PF)

The size of capacitor is calculated by the given equation (6.3) and the actual working power factor is obtained using equation (6.4) [132].

$$kVAR_{ideal} = kVAR \times \sin[\cos^{-1}(PF)] \quad (6.3)$$

$$PF_{new} = \cos \left[\frac{\tan^{-1}(kVAR_{ideal} - kVAR_{actual})}{kVA \times PF} \right] \quad (6.4)$$

The $kVAR_{ideal}$ represents ideal value of the power factor correction (PFC) capacitor, PF is the current power factor of the system.

6.1.4 Frequency

The load frequency is maintained close to 50 Hz by utilizing the BES in addition with PV panel and is presented by equation (6.5) [133].

$$\Delta f = -(\Delta P_{PV} + \Delta P_{BES})\mathcal{R} \quad (6.5)$$

where $\mathcal{R}$ is the coefficient of frequency droop and it is assumed as 5%.

It is not possible completely to eliminate the causes of the power quality but the quality of power can be improved or maintained by the use of mitigation techniques like custom power devices and power conditioning equipment. Hence, an ANN based technique is proposed and simulated successfully by maintaining voltage dips, THD, power factor, frequency and unbalancing of the three-phase AC microgrid. The microgrid system comprises different components in its design which are discussed with their equations in the next Sub-section 6.2.

6.2 DESCRIPTION OF SYSTEM COMPONENTS

The proposed microgrid system comprises two PVs, BES, inverter, line impedance, loads and utility grid as shown in Figure 6.2. The specifications of microgrid system parameters are presented in Table 6.2 while designing a small microgrid model as presented in the current sub-section. This small microgrid model of Figure 6.2 can be extended to a medium size distribution network in the form of realistic microgrid structure as described in detail in Sub-section 6.3.3. The components of microgrid are discussed below which are used in designing, modelling and controlling the system operation. The system components have been described in the following Sub-sections 6.2.1 to 6.2.3.

6.2.1 PV panel model

A grid-connected PV system includes solar arrays, inverter and grid connecting equipment. The mathematical modelling of PV system is discussed below followed by equations (6.6) to (6.11) for microgrid operation. The module photo-current (I_{ph}) is given by equation (6.6).

$$I_{ph} = [I_{sc} + K_{sc}(T - 298)] \frac{I_r}{1000} \quad (6.6)$$

where I_{sc} is the short circuit current (A), K_{sc} is short circuit current of cell at 25°C and 1000 W/m² corresponding to standard test condition (STC), T is the operating temperature (K) and I_r is solar irradiation (W/m²). The module reverse saturation current (I_{rs}) is expressed by equation (6.7).

$$I_{rs} = I_{sc} / \left[\exp \left(\frac{qV_{oc}}{N_s k_B n T} \right) - 1 \right] \quad (6.7)$$

where q is electron charge (1.6×10^{-19} C), V_{oc} is open circuit voltage (V), N_s is the number of cells connected in series, n is the ideality factor of the diode and k_B is the Boltzmann's

constant ($1.3805 \times 10^{-23} \text{ J/K}$). The module saturation current (I_o) which varies with the cell temperature is presented by equation (6.8).

$$I_o = I_{rs} \left[\frac{T}{T_r} \right]^3 \exp \left[\frac{qE_{go}}{nk_B} \left(\frac{1}{T} - \frac{1}{T_r} \right) \right] \quad (6.8)$$

where T_r is nominal temperature (298.15 K), E_{go} is band gap energy of the semi-conductor (1.1 eV). The output current of PV module (I) can be calculated as presented in equation (6.9).

$$I = N_p I_{ph} - N_p I_o \left[\exp \left(\frac{V_t/N_s + I R_s/N_p}{nV_t} \right) - 1 \right] - I_{sh} \quad (6.9)$$

$$\text{where } V_t = k_B T / q \quad (6.10)$$

$$\text{and } I_{sh} = \frac{V_t(N_p/N_s) + I R_s}{R_{sh}} \quad (6.11)$$

Here, N_p represents number of PV modules connected in parallel, R_s is series resistance (Ω), R_{sh} is shunt resistance (Ω) and V_t is diode thermal voltage (V) [134].

6.2.2 Battery energy storage (BES) system model

The lead-acid batteries are highly recommended with the application of PV panel to harvest maximum capacity of battery. The battery discharges and charges its SoC at 20% and 80% respectively. The battery discharge and charge voltage equations are presented by equation (6.12) and (6.13) respectively.

$$V_{bat} = V_o - Ri - K \frac{Q}{Q - it} (it + i^*) + \exp(t) \quad (6.12)$$

$$V_{bat} = V_o - Ri - \left[K \frac{Q}{it - 0.1Q} \right] i^* - \left[K \frac{Q}{Q - it} \right] it + \exp(t) \quad (6.13)$$

where V_{bat} is battery voltage (V), V_o is battery constant voltage (V), K is polarisation constant (V/Ah) or polarisation resistance (Ω), Q is battery charge (Ah), $it = \int i dt$ is actual battery

charge (Ah), R is internal resistance (Ω), i is battery current (A) and i^* is filtered current (A) [135].

6.2.3 Inverter model

The three-phase inverter model can be implemented using universal three-phase power converter that consists of six power switches connected in a bridge configuration. The three-phase bridge converter is simulated using forced-commutated IGBT-diode device as shown in Figure 6.1(a) with following parameters; the values of snubber resistance (R_s) and capacitance (C_s) are considered as 5 k Ω and infinite respectively to get a resistive snubber. The internal resistance (R_{on}) of the IGBT-diode device is 1 m Ω while the forward voltages are selected as zero. The three-phase inverter control design consists of four major subsystems such as phase locked loop (PLL) regulator block, voltage direct current (VDC) regulator, current regulator and PWM generator as shown in Figure 6.1(b). The three-phase line voltage (V_{abc}) and current (I_{abc}) are fed to PLL regulator block which is required for synchronization and voltage/current measurements. This block generates dq parameters from three-phase abc parameters and the phase angle ωt for reference signal generation block.

The output DC voltage (V_{dc}) of PV panel is forwarded and compared with reference voltage (V_{dc-ref}) in VDC regulator which determines the active component of current (I_{d-ref}) as reference using PI controller. The feedforward current regulator block finds the converter reference voltages (V_{d-conv} and V_{q-conv}) through its internal PI controller utilizing signals from PLL and VDC regulator blocks. The converter generates active power (inverter mode) if I_d is positive and absorbs reactive power (inductive mode) in case of positive I_q . Now, the controlled variables (V_{d-conv} and V_{q-conv}) and ωt from current and PLL regulators respectively are transformed into three-phase abc reference parameters ($U_{abc-ref}$). The $U_{abc-ref}$ signal is fed to PWM generator through unit delay which holds and delays the input signal ($U_{abc-ref}$) as a separate channel by the specified sample period of the simulation. The PWM generator generates firing signals or pulses to the IGBT switches based on the reference voltage (U_{ref}) after unit delay block as shown in Figure 6.1(b).

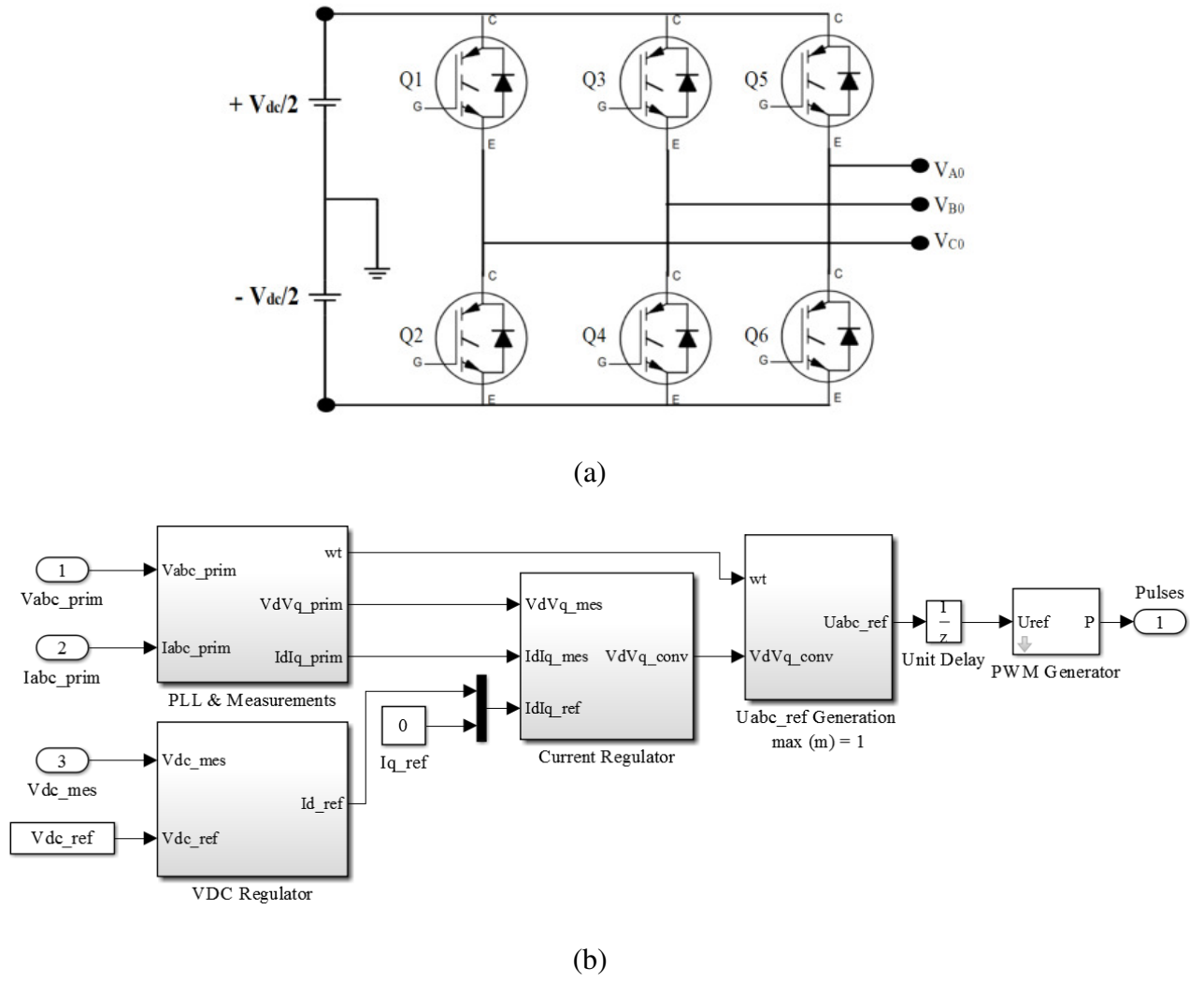


Figure 6.1. (a) IGBT-diode bridge configuration and (b) voltage source converter control for three-phase inverter model

Table 6.1. Switching logics for three-phase inverter with line to neutral voltages

Q1	Q3	Q5	V_{A0}	V_{B0}	V_{C0}
Q2	Q4	Q6			
0	0	0	$-V_{dc}/2$	$-V_{dc}/2$	$-V_{dc}/2$
0	0	1	$-V_{dc}/2$	$-V_{dc}/2$	$+V_{dc}/2$
0	1	0	$-V_{dc}/2$	$+V_{dc}/2$	$-V_{dc}/2$
0	1	1	$-V_{dc}/2$	$+V_{dc}/2$	$+V_{dc}/2$
1	0	0	$+V_{dc}/2$	$-V_{dc}/2$	$-V_{dc}/2$
1	0	1	$+V_{dc}/2$	$-V_{dc}/2$	$+V_{dc}/2$
1	1	0	$+V_{dc}/2$	$+V_{dc}/2$	$-V_{dc}/2$
1	1	1	$+V_{dc}/2$	$+V_{dc}/2$	$+V_{dc}/2$

The three-phase IGBT based inverter (Figure 6.1(a)) is supplied from DC source of 780 V which is a standard output of a PV panel, including LC filter on DC side with $L = 200 \mu H$

and $C = 5 \text{ pF}$ (Figure 6.6(a)). The values of L and C have been selected on the basis of observation for the satisfactory operation of the system to keep constant and pure DC voltage input for three-phase inverter. The inverter AC output is now fed to PCC through AC side filter with three-phase branch of $L = 2 \text{ mH}$ and capacitive reactive power (Q_c , star-grounded) $= 3 \text{ kVar}$ to filter the higher harmonic frequencies generated by the IGBT based inverter. The logic state of switches (Q1 to Q6) can be represented by 0 and 1 that is OFF and ON conditions respectively as shown in Table 6.1. For example, Q1&Q2 = 1, Q3&Q4 = 1 and Q5&Q6 = 0, so the line-to-neutral voltages $V_{A0} = V_{B0} = +V_{dc}/2$ and $V_{C0} = -V_{dc}/2$ as per logic 110 as presented in Table 6.1. The PWM signals are generated to provide gate pulses to six IGBT inverter switches with 120° phase difference followed by 0° , 120° and 240° phase angles. It is recommended that if input sample amplitude is higher than the carrier voltage amplitude then switches Q1, Q4 and Q5 will be switched ON and the other switches Q2, Q3 and Q6 will be switched OFF as shown in Figure 6.1(a). For this purpose, the input or reference signals are collected from the microgrid for phase synchronization.

6.3 PROPOSED MICROGRID MODEL

In this study, the power quality is enhanced by controlling gate pulses to the inverter circuit using proposed ANN-based MGCC. A 10 kW, three-phase AC microgrid has been proposed to fulfill the critical (4 kW) and non-critical (6 kW) loads. The majority of fulfilling the demand is given to the critical load especially under islanded condition, if grid supply gets failed or subjected to the maintenance. The entire load is specified with the combination of active and reactive powers, that is, 10 kW, 7.5 kVar, 400 V at 50 Hz frequency. The simple/small size microgrid, microgrid model with additional line impedances and realistic microgrid structure are discussed in Sub-sections 6.3.1, 6.3.2 and 6.3.3 respectively. The ANN based proposed control methodology is discussed in Sub-section 6.4 including mathematical analysis and implementation in proceeding Sub-sections 6.4.1 and 6.4.2 respectively. The conventional PI and fuzzy-PI controllers are briefly described in Sub-section 6.5.

Scenario 1. Simple/small size microgrid model

Scenario 2. Microgrid model with additional line impedances

Scenario 3. Realistic microgrid structure

6.3.1 Simple/small size microgrid model (Scenario 1)

A small size microgrid has been proposed which comprises grid connected two DERs through PCC including CL and NCL connected on main load bus as shown in Figure 6.2. The CL bus is further supported by a local BES system to maintain continuous supply in case of failure in grid or DER1/DER2. It is recognized that with the consideration of two same rating of PVs (DERs) have introduced high amount of harmonics under islanded condition. Due to the converter topology, they produce more voltage and current harmonics in the system during islanded mode of operation. The proposed microgrid system parameters are listed in Table 6.2. An ANN-based MGCC is presented in Figure 6.2 which communicates with DERs, utility grid, battery energy storage (BES) system and load bus through their respective circuit breakers (CBs) such as CB1 to CB5. The UG is located at a line distance of 500 m from the PCC and the main load bus is placed at a line distance of 50 m from the station bus.

A localized backup of power is installed using BES system fed by the local PV generator to serve the critical load under emergency case like non-availability of DER1, DER2 and utility grid as shown in Figure 6.2. The MGCC monitors the continuous status of DER1, DER2, UG, BES, station and load bus, PCC and load demand. In case of LV power system, the allowable limit or best value of voltage deviation must lie within 10% of the nominal value as per IEEE Std. 1250-2011. The allowable variation in power frequency is ± 0.1 Hz as listed in IEEE Std. 1159-2009. The non-linear loads are highly responsible for injection of harmonics in the overall microgrid system. Therefore, it is a prime duty of MGCC to maintain THD within the acceptable range of 5% as per IEEE Std. 519-2014. In addition, power factor (PF) is also considered as a major component of the power quality at load side and it is found from literature that the power factor is not considered frequently for assessment of the power quality. The acceptable range of PF is appended in the IEC 60831-1/2 standard, which recommends that the PF must be equal or greater than 0.9 otherwise low PF may damage the equipment or device due to excessive flow of current and heat.

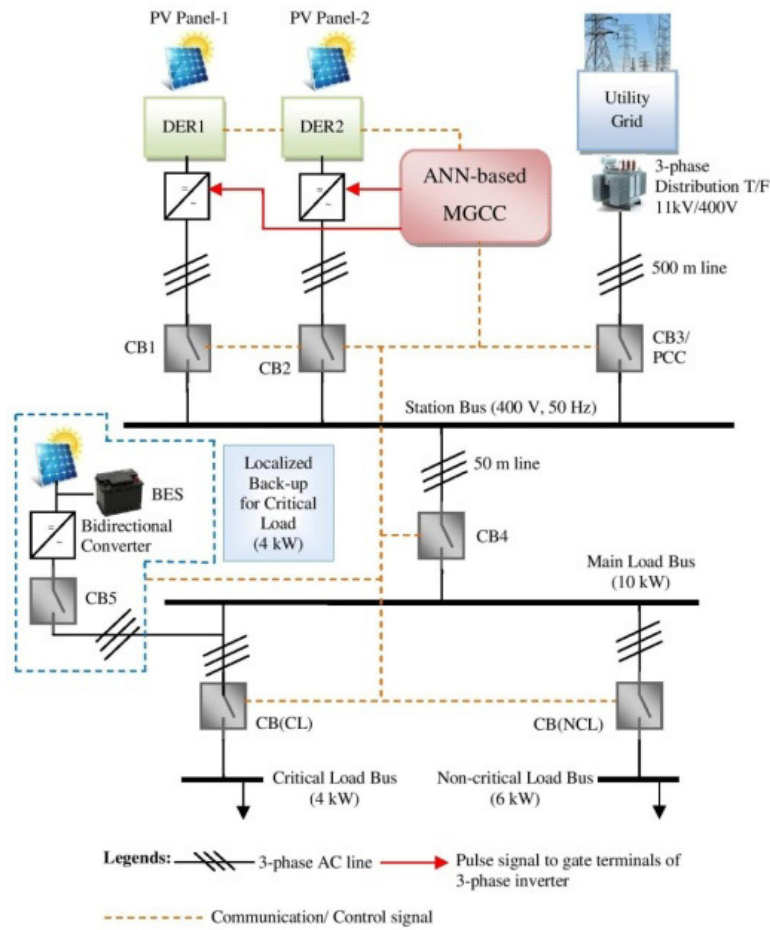


Figure 6.2. A three-phase AC microgrid system including ANN based MGCC

Table 6.2. Microgrid system parameters

Parameter(s)	Specification(s)
Converter Topology: Input DC voltage	820 V
Minimum start DC voltage	200 V
Rated active AC power	10000 W
Maximum apparent AC power	10000 VA
Nominal AC voltage	Line-to-line 400 V
Power frequency/ range	50/±0.5 Hz
Maximum output AC current	3×15 A
Power factor at rated power	> 0.99
THD at rated output	< 5%
Three-phase universal bridge IGBT inverter:	
Snubber resistance, R_s	5000 Ω
Snubber capacitor, C_s	Infinite
Power line (LV): Line resistance, R and reactance, X	R = 0.642 Ω /km, X = 0.083 Ω /km
PV panel (individual DER1 and DER2)	5 kW _p (270 W × 20 nos.)
BES system	12 V, 1250 Ah

6.3.2 Microgrid model with additional line impedance (Scenario – 2)

The same proposed microgrid system presented in Sub-section 6.3.1 can be investigated further by incorporating the effect of line impedance on the performance of microgrid and its power quality parameters/ indexes. A small size microgrid structure is shown in Figure 6.3 considering the additional effect of line impedance on microgrid performance. The line impedance can be calculated as per the R/X ratio in case of LV distribution system. It is well known that R/X ratio is high in case of LV distribution networks while supplying the load. The line resistance and reactance are considered as 0.642 Ω /km and 0.083 Ω /km respectively for LV power system. As per line length, impedances of the lines have been calculated which are presented in Table 6.3.

In Figure 6.3, the critical load (CL) of 4 kW and non-critical load (NCL) of 6 kW are placed at line distance of 50 m ($0.0321 + j0.00415 \Omega$) and 100 m ($0.0642 + j0.0083 \Omega$) respectively. DER1 and DER2 are much closer to PCC through station bus. The main load bus with the capacity of 10 kW is connected to station bus through CB4 with line length of 50 m as shown in Figure 6.3. The small size microgrid presented in Figure 6.3 has been analyzed with the effect of line impedance on power quality parameters, power sharing and power losses by utility grid and DERs. In addition, the effect of communication delay on power quality parameters is also discussed under Sub-section 6.6.2.

Table 6.3. Calculation of line impedance as per line length

Line length (m)	Line impedance (Ω)
50	$0.0321 + j0.00415 \Omega$
100	$0.0642 + j0.0083 \Omega$
300	$0.1926 + j0.0249 \Omega$
500 (UG side)	$0.321 + j0.0415 \Omega$

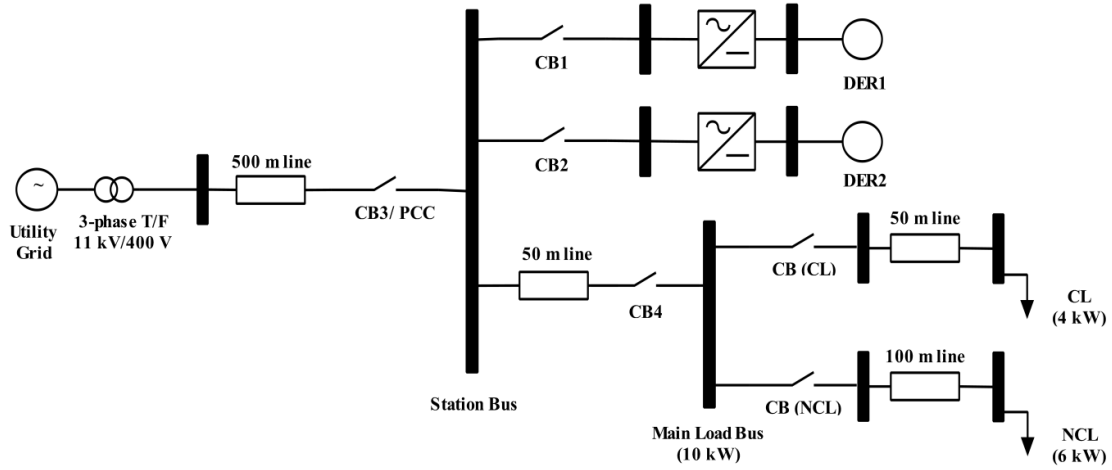


Figure 6.3. A small size microgrid structure with additional line impedance

6.3.3 Realistic microgrid structure (Scenario – 3)

The feasibility of the proposed concept can be validated through a realistic microgrid structure as it consists of real parameters of the distribution network such as generating sources, line impedance, bus-bars, effects of loads on generating units, converters and lines. Hence, it becomes important to extend the small size microgrid model to the realistic microgrid structure in the current research work.

The realistic or multi-layer microgrid structure or architecture can be designed based on the large number of DERs and loads that enables microgrid to operate in the wide range of operating points [136]. The power sharing, losses in sources and wires, effect of line impedance on power quality and communication delay can be analyzed for any set of locations. The demand response (DR) studies can be assessed by maintaining power balance between sources and loads. The consumers can be supplied through any one of the microgrids like MG1, MG2 and/or MG3 as shown in Figure 6.4. This realistic microgrid architecture shows the extended version of small size microgrid (scenario – 2). The distributed network is divided into three local microgrids such as MG1, MG2 and MG3 with the capacity of 4 kW, 4 kW and 6 kW respectively. The total capacity of networked microgrid is 14 kW which is connected to utility grid through PCC as shown in Figure 6.4. The islanded (off-grid) operation of realistic microgrid architecture can be initiated by disconnecting the utility grid through PCC while operating independently or jointly MG1, MG2 and MG3. The total maximum load of 14 kW can be supplied with the combination of MG1, MG2 and MG3 during off-grid condition.

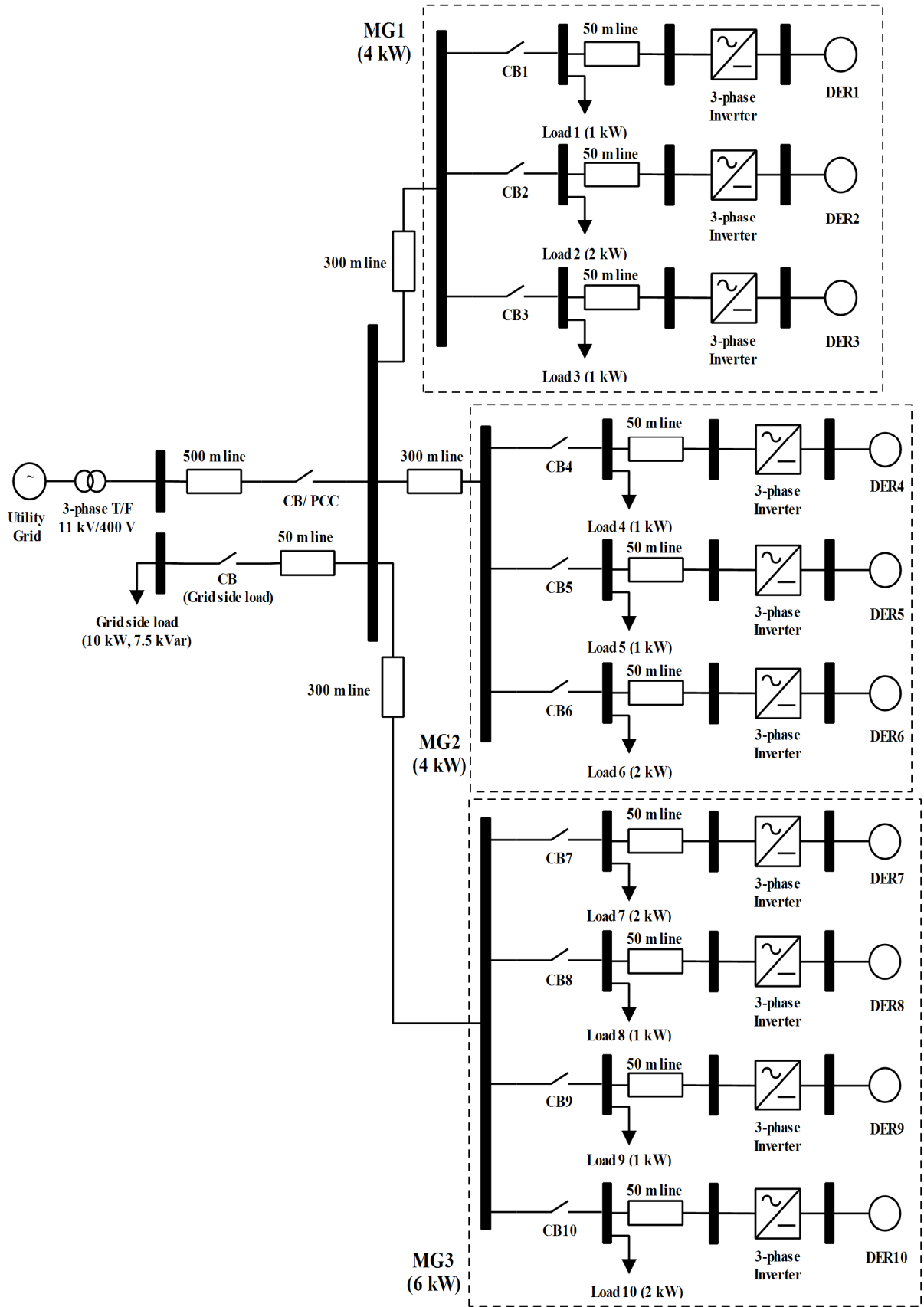


Figure 6.4. Realistic three-phase AC microgrid architecture/structure with the consideration of line impedances

6.4 PROPOSED METHODOLOGY

An ANN is the best suited approach for solving the non-linear problems with large number of variables. According to Levenberg-Marquardt (L-M) optimization method, a network trains the system by updating its weight and bias values. It is the fastest backpropagation algorithm as compared to other training algorithm like Bayesian regularization and scaled conjugate gradient methods. It is recommended for training the network because of less memory requirement followed by the supervised algorithm. The main features of ANN are self organizing, fast, parallel computation, dealing with non-linearity makes the system reliable and faster dynamic response over conventional controller like PI controller which has poor transient response while ANN responds faster for any sudden change. Some of the key features of ANN are listed below.

- ANN is a non-linear model which is easy to implement and understandable compared to other well-known statistical methods.
- ANN permits the modelling of physical parameters in large size systems without the requirement of unambiguous mathematical equations and experimental data.
- ANN is adaptive to complex problems and can handle different level of complexity by changing the network topology.

Although, ANN is quite easy and simple but it requires large amount of data related to input parameters to predict the output over a wide range of possibilities when training the same.

6.4.1 Mathematical analysis of ANN

As per the feedforward network, the expression of output units (y_k) based on input units (x_i) and hidden units (z_j) is represented by equation (6.14) [137].

$$y_k = f_n \left(\sum_{j=0}^H w_{(n)kj} z_j \right) \quad (6.14)$$

where $z_j = f_{n-1}(\sum_{i=0}^N w_{(n-1)ji} x_i)$, N = dimension of input layer, H = dimension of hidden layer, k = dimension of output layer, $w_{(n)kj}$ = weights of the output layer, $w_{(n-1)ji}$ = weights of hidden layer, f_n = activation function, $n = 1, 2, 3, \dots$

6.4.2 Implementation of ANN in microgrid control

A two-layer feed-forward system with sigmoid hidden neurons and straight or linear output neurons can fit multi-dimensional mapping issues, by giving reliable information and enough neurons in its concealed or hidden layer. The system is prepared with back-propagation algorithm, unless there is not sufficient memory, in which case scaled conjugate angle backpropagation will be utilized. As per the proposed ANN algorithm, the optimum adjustment of Δw pertained to the actual weight vector w can be represented by equation (6.15) [138].

$$\Delta w = [H + \lambda A]^{-1} g \quad (6.15)$$

where H is the Hessian matrix of same dimensions as identity matrix A and g is the gradient vector. λ is a loading or regularizing parameter which makes the sum of matrix $(H + \lambda A)$ to be positive definite throughout the computation process. Consider a multilayer perceptron with output neurons; the NN is to be trained by minimizing the cost function, which is given by equation (6.16).

$$\epsilon_{av}(w) = \frac{1}{2N} \sum_{i=1}^N [d(i) - F(x(i); w)]^2 \quad (6.16)$$

where $\{x(i), d(i)\}_{i=1}^N$ is the training sample of input variables (9 elements have been considered; $\{V_a, V_b, V_c, I_a, I_b, I_c, P_{ref}, Q_{ref}, F_{sw}\}$) and $F(x(i); w)$ is the approximating function realized by the network i.e. gate signals $\{G_1, G_2, G_3, G_4, G_5, G_6\}$. Further, the gradient and the Hessian parameters of the cost function $\epsilon_{av}(w)$ are represented by equation (6.17) and (6.18) respectively.

$$g(w) = \frac{\partial \epsilon_{av}(w)}{\partial w} = -\frac{1}{N} \sum_{i=1}^N [d(i) - F(x(i); w)] \frac{\partial F(x(i); w)}{\partial w} \quad (6.17)$$

$$\text{and } H(w) = \frac{\partial^2 \epsilon_{av}(w)}{\partial w^2}$$

$$= \frac{1}{N} \sum_{i=1}^N \left[\frac{\partial F(x(i); w)}{\partial w} \right] \left[\frac{\partial F(x(i); w)}{\partial w} \right]^T - \frac{1}{N} \sum_{i=1}^N [d(i) - F(x(i); w)] \frac{\partial^2 F(x(i); w)}{\partial w^2} \quad (6.18)$$

Therefore, substituting equations (6.17) and (6.18) into equation (6.15), the desired Δw is calculated for each iteration. In addition, if the dimension of weight vector w is high in that case the Hessian matrix can be approximated using equation (6.19) by neglecting the negative term from equation (6.18).

$$H(w) \approx \frac{1}{N} \sum_{i=1}^N \left[\frac{\partial F(x(i); w)}{\partial w} \right] \left[\frac{\partial F(x(i); w)}{\partial w} \right]^T \quad (6.19)$$

From equation (6.19), it is presented that the algorithm is a first-order optimization method which is suitable for non-linear least-squares estimation problems, based on equations (6.17) and (6.18). The value of λ must be adjusted large enough to keep the sum of matrix $(H+\lambda A)$ as positive definite. The steps involved in optimum weight calculation are given as

Step 1. Compute $\epsilon_{av}(w)$ at iteration $(n-1)$.

Step 2. Choose a diffident value for λ , say $\lambda = 10^{-3}$.

Step 3. Solve equation (6.15) for the optimum value of Δw at iteration n and evaluate $\epsilon_{av}(w + \Delta w)$.

Step 4. If $\epsilon_{av}(w + \Delta w) \geq \epsilon_{av}(w)$, then increase λ by a factor of 10 or by other suitable factor as per the given problem and go back to step 3.

Step 5. On other side, if $\epsilon_{av}(w + \Delta w) < \epsilon_{av}(w)$, then decrease λ by a factor of 10 or by other suitable factor as per the given problem and update the trial solution $w \rightarrow (w + \Delta w)$ and go back to step 3.

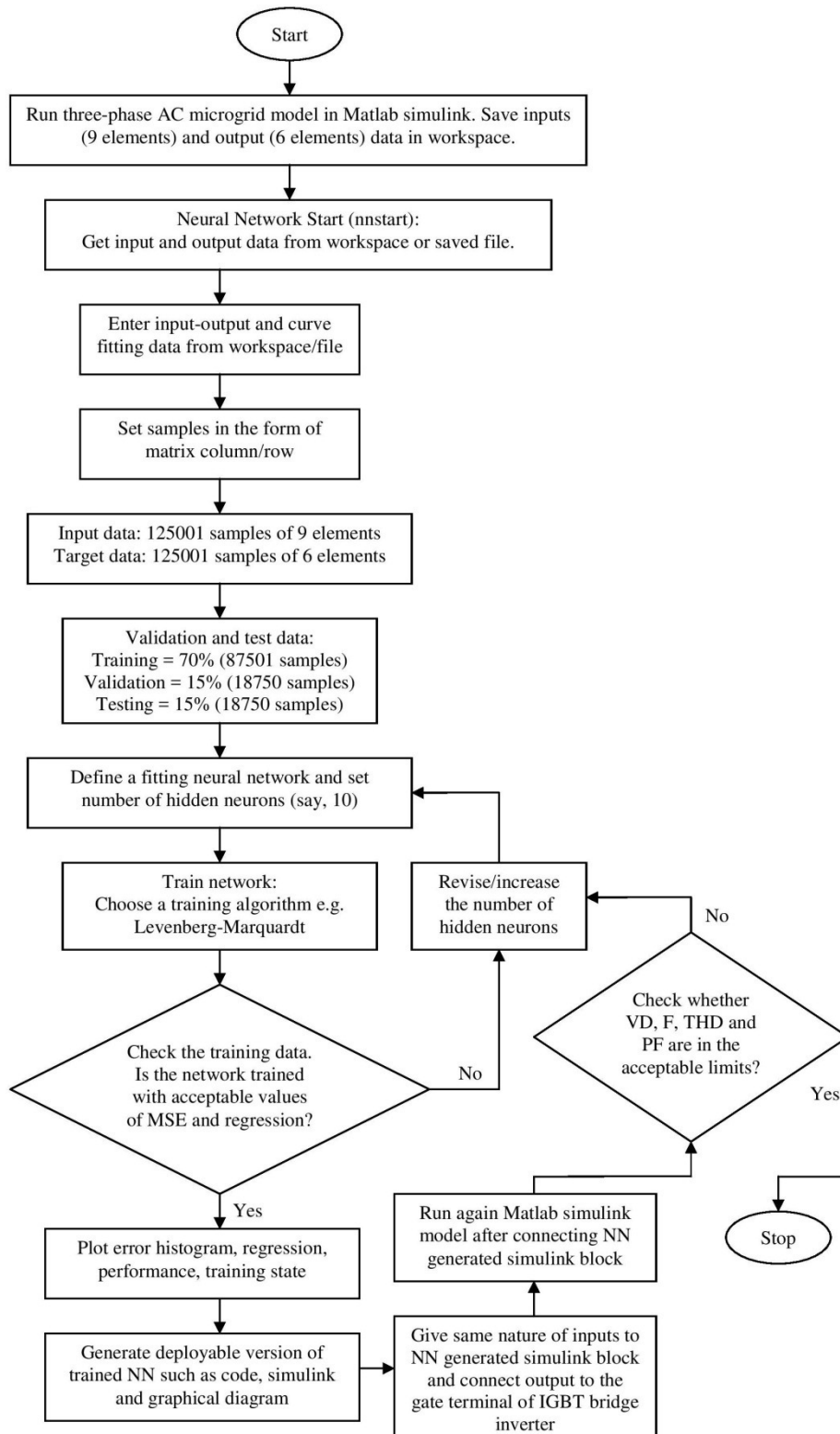
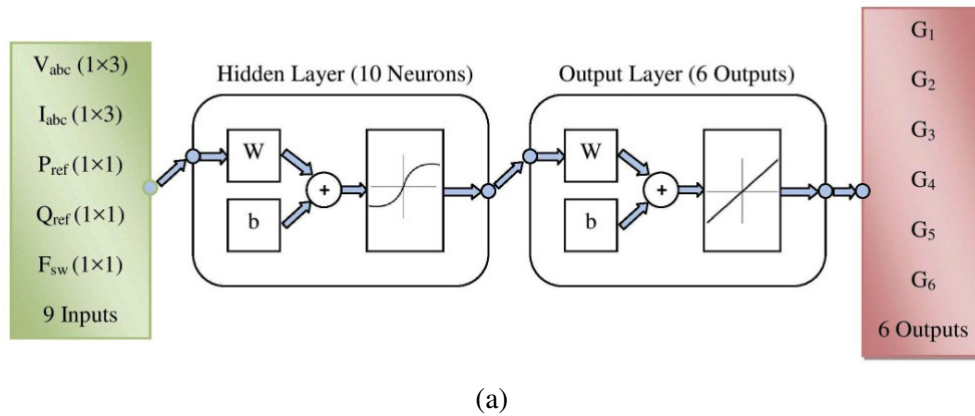


Figure 6.5. Implementation of ANN algorithm to enhance the power quality parameters in three-phase AC microgrid system

The Figure 6.5 shows the entire procedure of a two-layer feed-forward NN based on backpropagation training algorithm, which enhances the power quality of microgrid. It is

discussed that the proposed algorithm helps to maintain the voltage deviation (VD), frequency (F), THD and PF within acceptable limits as parts of the power quality. The Figure 6.5 presents reproducibility of the results for the readers from first to the last step. As per the proposed microgrid model shown in Figure 6.2, the power quality is maintained by considering 9 and 6 elements as input and output vectors respectively for designing ANN. The ANN model is trained with the combination of 125001 samples of nine input data ($V_a, V_b, V_c, I_a, I_b, I_c, P_{ref}, Q_{ref}, F_{sw}$) and the same 125001 samples of six output data ($G_1, G_2, G_3, G_4, G_5, G_6$) as shown in flowchart of Figure 6.5 and Figure 6.6(a). The input and output data or elements are selected from the small size microgrid simulink model as shown in Figure 6.6(b) without connecting function fitting neural network. Hence, in Figure 6.6(a)-6.6(b), The nine elements/inputs are selected from MATLAB simulink model such as three-phase voltage, three-phase current, reference active and reactive power, switching frequency; and the output layer generates 6 number of gate pulses to the three-phase inverter circuit. Finally, these sample values are saved on workspace and called as variables for ‘nnstart’ tool in training of the ANN. The inverter gate pulses are switched ON/OFF based on the inverter model as already presented in the Sub-section 6.2.3. In this study, the ten number of hidden layer neurons are considered for getting satisfactory optimum solution. After compiling/training the NN with acceptable range of mean squared error (MSE), a function fitting NN simulink block has been developed. Now, this function fitting NN simulink block is placed in the main proposed microgrid simulink model as shown in Figure 6.6(b) by injecting $V_{abc}, I_{abc}, P_{ref}, Q_{ref}$ and F_{sw} as input vectors. The output of function fitting NN is fed to the gate terminal of DER1 and DER2 inverter circuits.



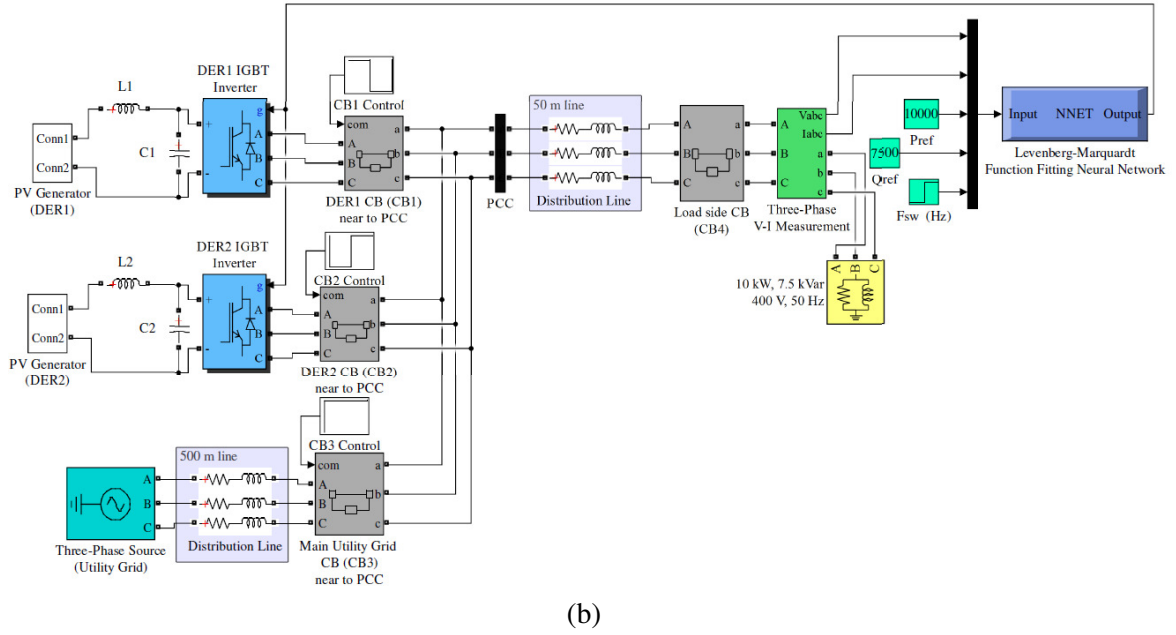


Figure 6.6. (a) A two-layer feed-forward NN for the assessment of the power quality in microgrid system, and (b) a proposed NN controller connected to PV inverters (DER1 and DER2)

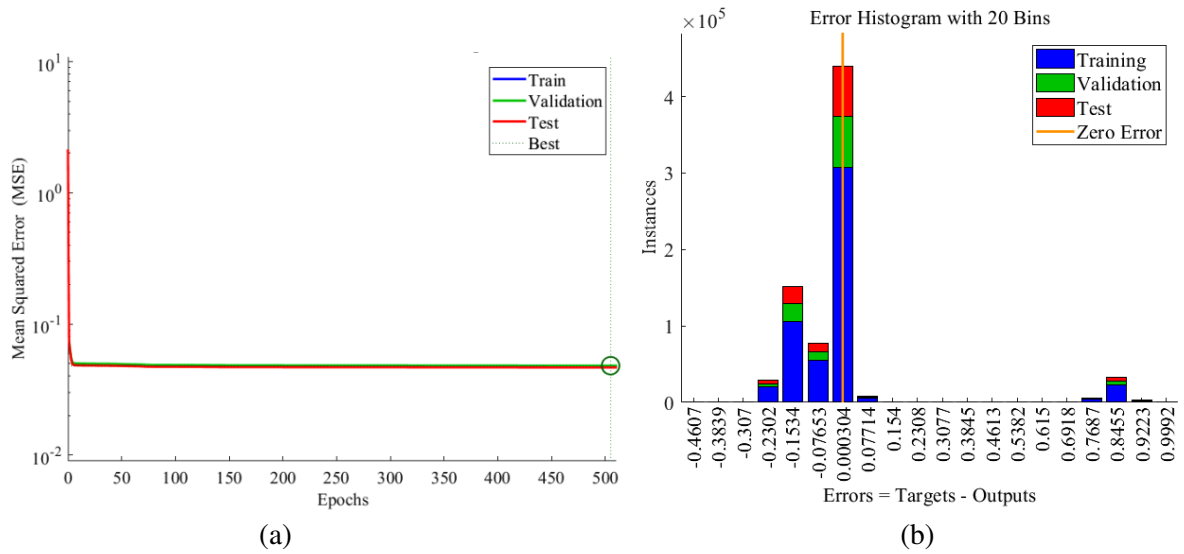


Figure 6.7. (a) Proposed system validation performance and (b) MSE histogram using backpropagation ANN algorithm

Table 6.4. Training results using proposed ANN controller

Observation	No. of samples	Mean squared error (MSE)
Training	87501	0.03599
Validation	18750	0.03658
Testing	18750	0.03711
Overall	125001	0.03656

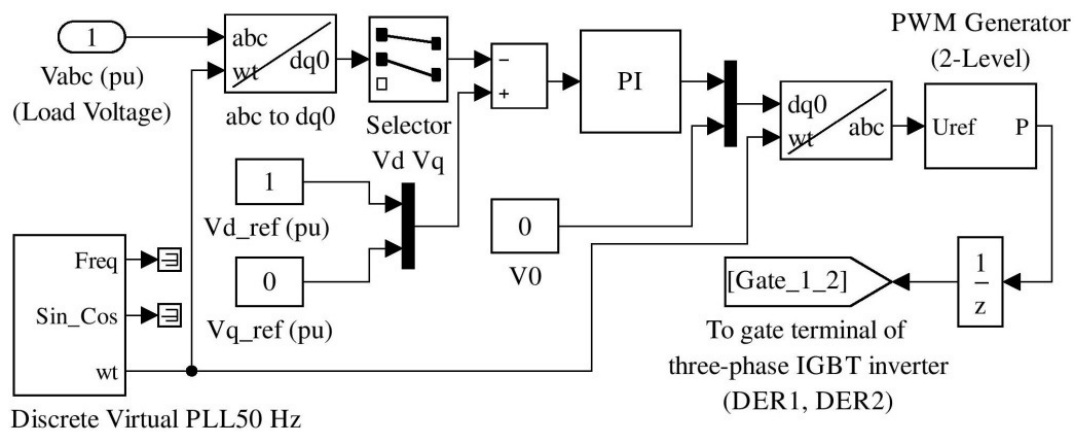
After training the two-layer feed-forward backpropagation method, the best optimum validation performance is found as 0.04805, which is achieved at 505 epochs out of

maximum 1000 epochs as shown in Figure 6.7(a). The mean square error (MSE) histogram is presented in Figure 6.7(b), which shows optimum error as 0.000304 in reference to zero error line. The MSEs of training, validation, testing and overall system are presented in Table 6.4, which confirms the feasibility of generated FFNN simulink block in this study.

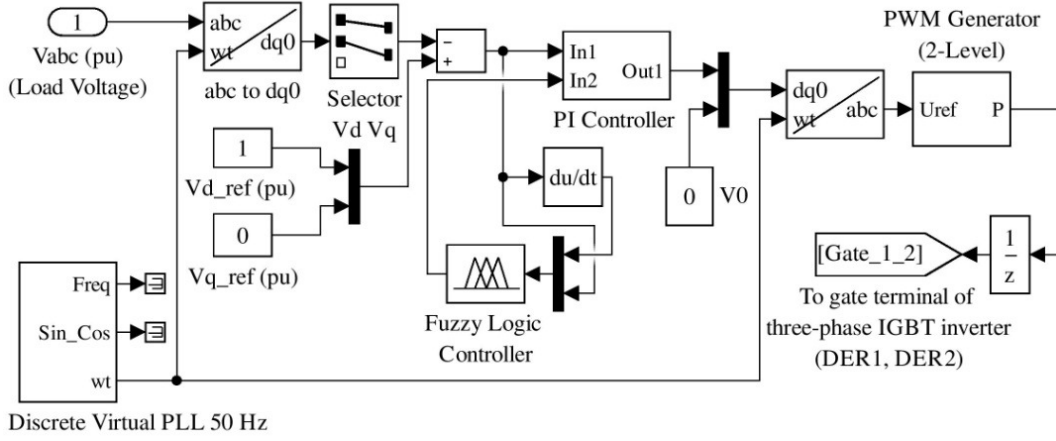
6.5 CONVENTIONAL PI AND FUZZY-PI CONTROLLERS

The proposed methodology is compared with conventional PI and fuzzy-PI controllers for its feasibility and existence in microgrid operation and control. The grid interfaced optimum PI controller can be used to improve the power quality of microgrid under normal and disturbed operating conditions [139–140]. A discrete PI controller is implemented to generate the PWM pulses during grid-connected and islanded modes of operation. The fuzzy-PI controller of grid interacted three-phase inverter is also introduced to compare the overall performance of the power quality [141]. The PI and fuzzy-PI schemes are presented in Figure 6.8(a) and 6.8(b) respectively as a part of centralized control of microgrid.

The load voltage is considered as a major input variable to the entire voltage regulator circuit as a part of PI controller and the direct axis reference voltage, V_d is selected as 1 pu as shown in Figure 6.8(a)-6.8(b). The gate terminals of three-phase IGBT based inverter circuit are triggered using PI-based PWM (with carrier frequency of 4000 Hz and modulation index of 0.83) and fuzzy-PI controllers. The results are discussed and compared with proposed neural network controller for its validation and feasibility in Sub-section 6.6.



(a)



(b)

Figure 6.8. Schematic diagram of (a) conventional PI and (b) fuzzy-PI controller

6.6 RESULTS AND DISCUSSION

The proposed approach is simulated and tested in MATLAB-simulink for three scenarios as already discussed in previous Sub-section 6.3. The results are discussed for small size microgrid without/with effect of line impedance and realistic microgrid structure in Sub-sections 6.6.1, 6.6.2 and 6.6.3 respectively.

6.6.1 Simple/small size microgrid model (Scenario – 1)

A three-phase AC microgrid is tested for the assessment of the power quality under grid connected and islanded conditions for satisfying the inductive load of 10 kW and 7.5 kVar. The results have been presented by considering the following cases.

Case 1. Power quality enhancement using VD, THD, F and PF

Case 2. Power quality enhancement using voltage sag/swell and unbalanced system

Case 3. Localized power backup for critical load

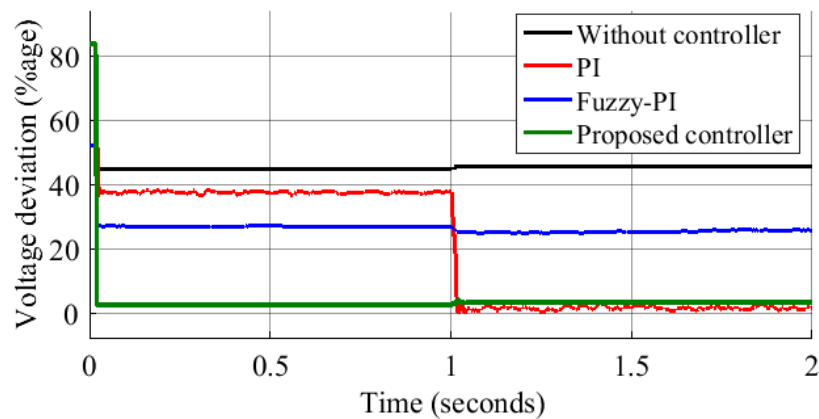
The above listed cases are discussed in next Sub-sections 6.6.1.1, 6.6.1.2 and 6.6.1.3 respectively.

6.6.1.1 Power quality enhancement using VD, THD, F and PF (Case 1)

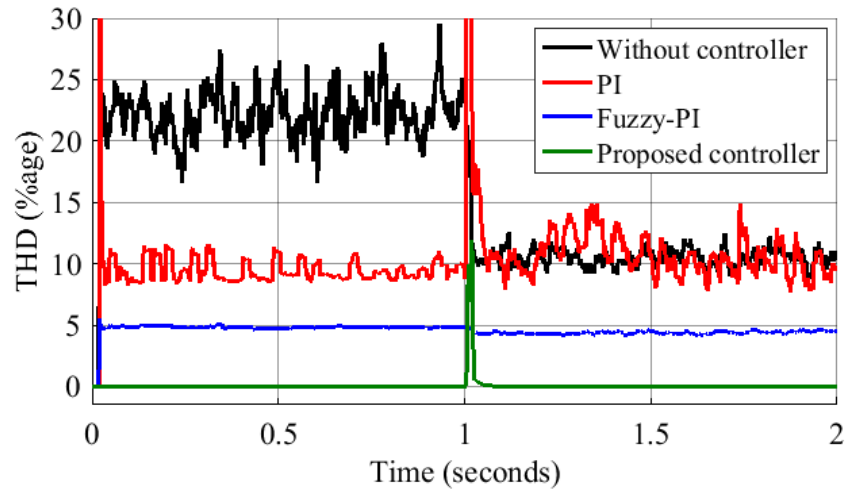
The proposed microgrid model is simulated for the period of 2 seconds. From 0 to 1 second, it operates in grid-connected mode while it works in islanded mode from 1 to 2 seconds. The conventional PI is tuned with preset proportional (K_p) and integral (K_i) values of 0.4 and 500

respectively to trigger the inverter gate signals. The fuzzy-PI is simulated with two input variable as error and change in error, and two output membership functions as K_p and K_i with the range of 0.2 to 0.8 and 300 to 800 respectively. It is further realized that conventional PI and fuzzy-PI take iteratively more time as compared to proposed algorithm due to large number of non-linear variables to achieve their optimum values of K_p and K_i for generating pulse signal. The VD profile is presented in Figure 6.9(a) and it is realized that the PI and fuzzy-PI have shown less deviation as compared to without controller while proposed controller has shown smooth and almost zero deviation. It is tested that the proposed NN controller can compensate high range of voltage deviation and THD that is more than 20% to 50% of the fundamental component as shown in Figure 6.9(a)-6.9(b).

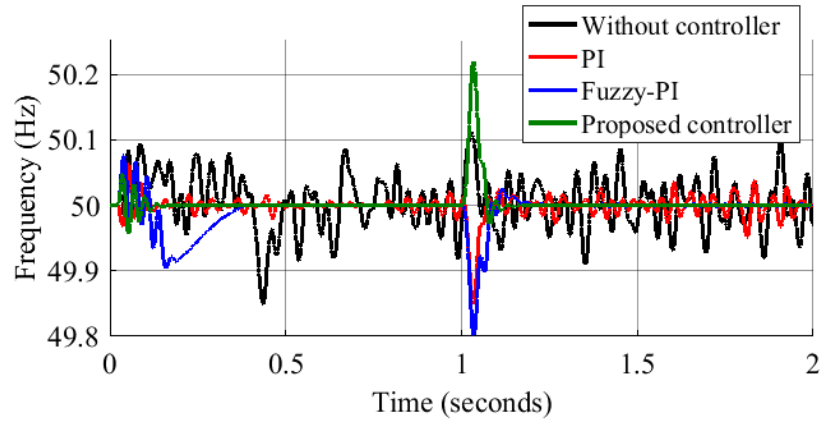
It is observed from Figure 6.9(a)-6.9(b) that the VD and THD are not in the acceptable range (as in case of without controller, PI and fuzzy-PI) as per IEEE Std. 1250-2011 and 519-2014 respectively. But, in case of proposed controller, VD and THD have shown smooth and almost zero variation except at the time of transition as shown in Figure 6.9(a)-6.9(b). In addition, the fluctuations are found in case of frequency and power factor waveforms under PI and fuzzy-PI controllers while proposed controller has shown smooth waveforms as presented in Figure 6.9(c)-6.9(d). The comparative analysis is framed in Table 6.5 and it is observed that proposed controller has shown minimum variation with respect to VD, THD, F and PF in support of the power quality under grid-connected and islanded conditions.



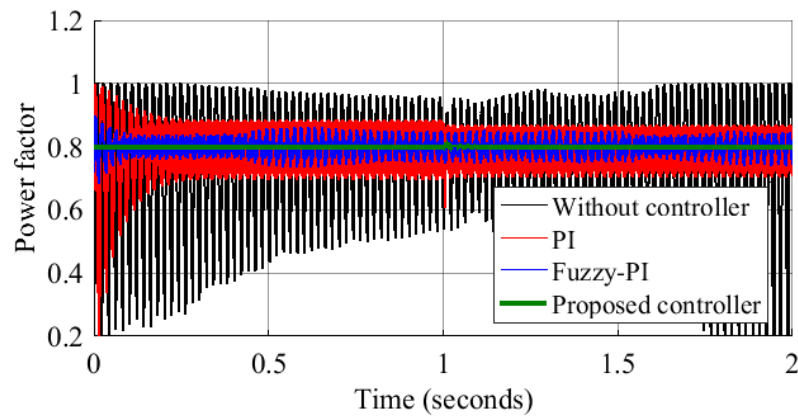
(a)



(b)



(c)



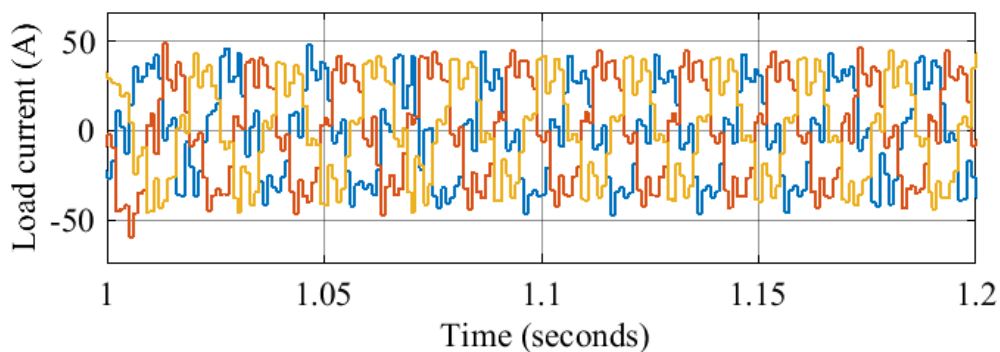
(d)

Figure 6.9. Comparison of microgrid power quality parameters based on (a) voltage deviation (VD), (b) total harmonic distortion (THD), (c) frequency and (d) power factor

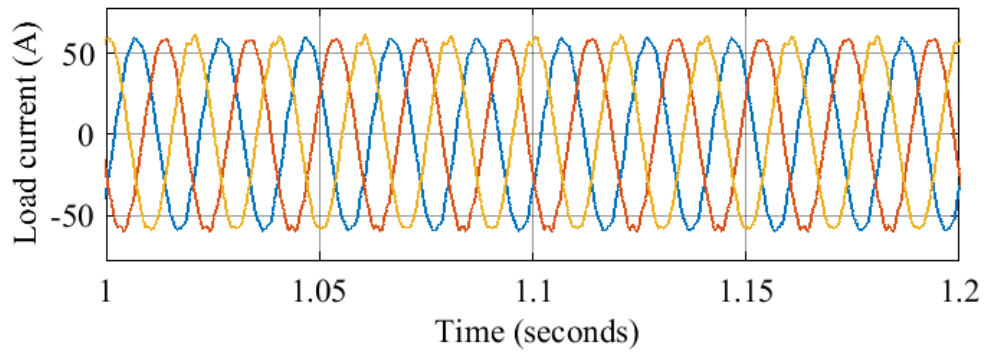
Thus, the power quality parameters are observed poor in case of conventional PI and fuzzy-PI based PWM controllers as compared to proposed controller. The VD and THD are obtained below 10% and 5% (for LV power system) respectively in case of proposed controller. The transient (or overshoot) has been observed at the instant (1 second) of breakers changeover during transition from grid to islanded mode as shown in Figure 6.9(a)-6.9(d). The current drawn by the load using conventional PI technique and proposed algorithm are shown in Figure 6.10(a) and 6.10(b) respectively. It is clearly observed that proposed controller has shown smooth three-phase current waveform as compared to the PI technique. Similarly, the consumptions of load active and reactive powers are shown in Figure 6.10(c)-6.10(d), and proposed controller has shown smooth response as compared to PI-based PWM controller.

Table 6.5. Comparison between PI, fuzzy-PI and proposed controllers

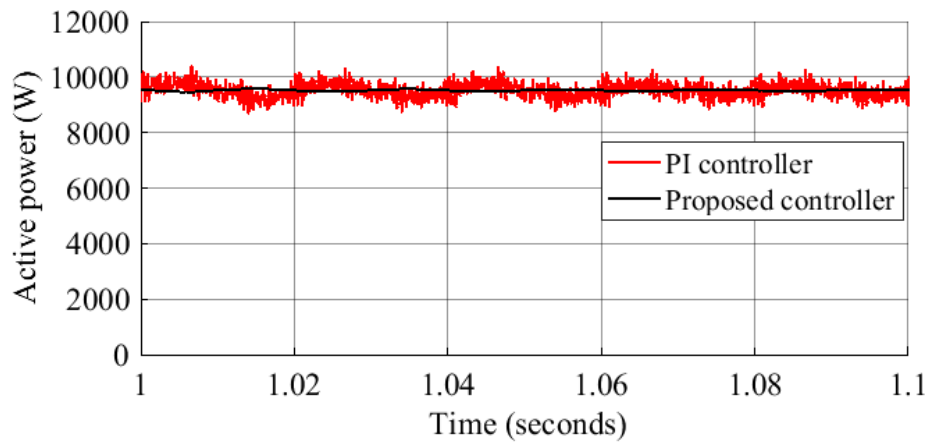
Parameters	Grid-connected mode (0-1 sec.)				Islanded mode (1-2 sec.)			
	Without controller	PI	Fuzzy-PI	Proposed controller	Without controller	PI	Fuzzy-PI	Proposed controller
VD (%age)	48	37	28	2	51	1.5	24	2.2
THD (%age)	25	10	5	0	12	14	4.5	0
F (Hz)	50.10	50.09	50.07	50	50.12	50.07	50	50
PF	0.4	0.6	0.75	0.8	0.4	0.6	0.75	0.8



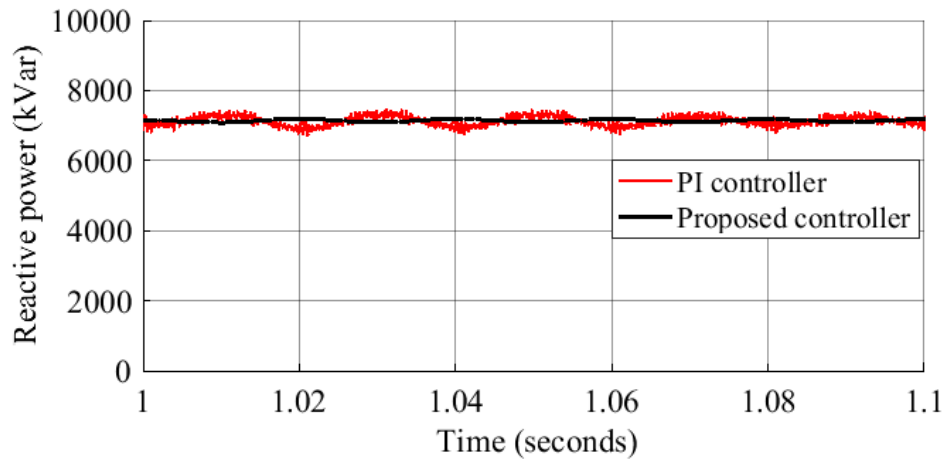
(a)



(b)



(c)



(d)

Figure 6.10. Load current profile with (a) conventional PI and (b) proposed controller Comparative load power profile (c) active power and (d) reactive power with conventional PI and proposed controller respectively

6.6.1.2 Power quality enhancement using voltage sag/swell and unbalanced system (Case 2)

The voltage sag is initiated from 0.05 second to 0.1 second under the influence of three-phase fault and voltage swell is carried out from 0.15 second to 0.2 second under sudden removal of three-phase heavy load. Here, the proposed three-phase AC microgrid is simulated for 0.25 second and the uncontrolled load voltage profile is shown in Figure 6.11(a).

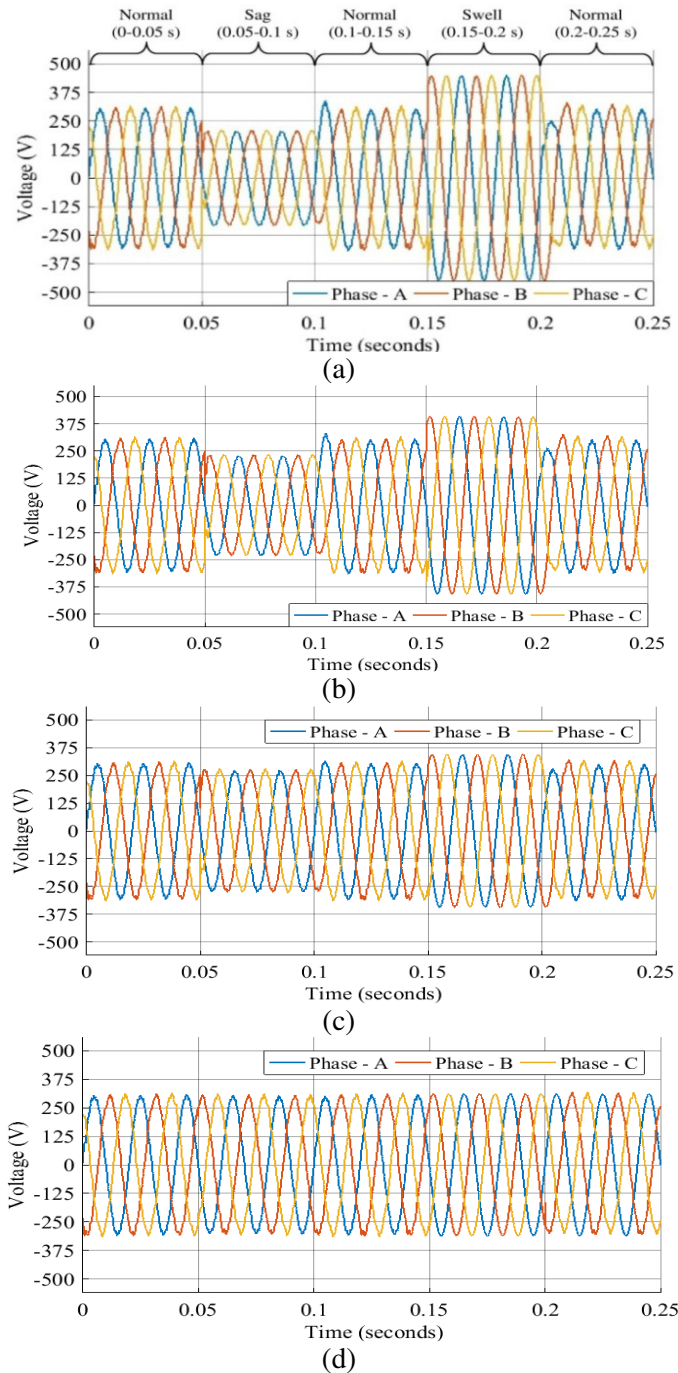
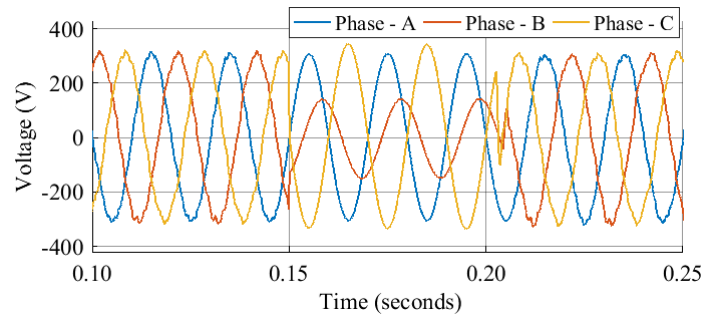
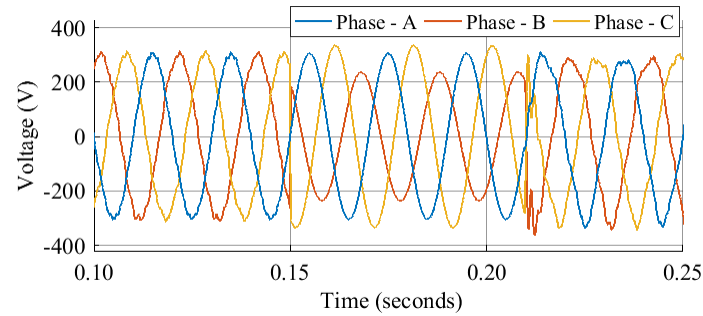


Figure 6.11. Microgrid performance during voltage sag and swell: (a) without controller, (b) PI, (c) fuzzy-PI and (d) proposed controller

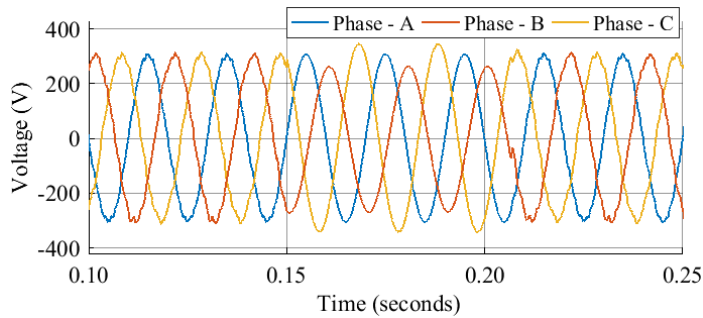
The improvement in voltage sag/swell is presented in Figure 6.11(b)-6.11(d) using conventional PI, fuzzy-PI and proposed controllers respectively by switching on the capacitors ($3 \times 33.2 \mu\text{F}$) in star-connected across the load bus with 1.67 kVar. It can be seen from Figure 6.11(d) that proposed controller has shown fast switching of capacitor bank to maintain smooth and healthy three-phase voltage profile as compared to PI and fuzzy-PI controllers. The load voltage profile is also maintained during unbalancing condition. The unbalancing condition is initiated from 0.15 second to 0.20 second as presented in Figure 6.12(a)-6.12(d). The voltage magnitude and phase angle are controlled by switching the inverter pulses in such a way so that all three phases become balanced quickly. From Figure 6.12(b)-6.12(d), it is observed that proposed controller has shown fast triggering of gate pulses by balancing voltage magnitude and phase angle as compared to conventional PI and fuzzy-PI controllers.



(a)



(b)



(c)

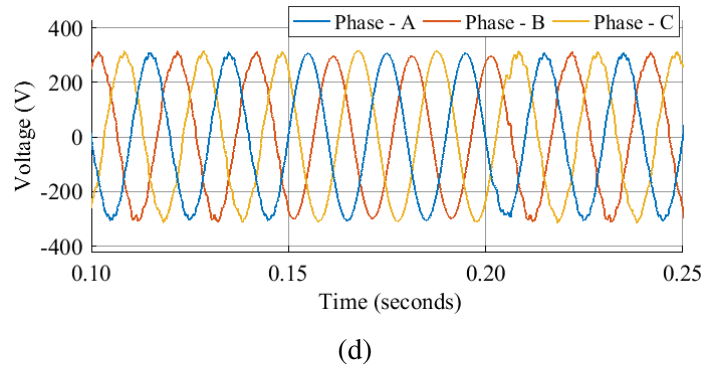


Figure 6.12. Microgrid performance during unbalanced condition: (a) without controller, (b) PI, (c) fuzzy-PI and (d) proposed controller

6.6.1.3 Localized power backup for critical load (Case 3)

The uninterrupted power could be supplied using isolated solar, wind and diesel integrated generators to enhance the telecommunication loads with sufficient amount of energy storage system [142]. The automatically controlled switches are implemented for the comprehensive stochastic energy management under the reconfigurable microgrid operation [143]. A localized BES system is provided to feed the critical load of 4 kW in case of failure in DER1, DER2 or utility grid as referred in Figure 6.2. The battery can be charged by providing local PV generator during day hours and also from grid side during non-availability of solar irradiance. The local power backup is introduced to cater the critical load by closing CB5 and CB (CL) while the other circuit breakers such as CB4 and CB (NCL) are kept open as shown in Figure 6.2.

It is assumed that from time periods of 0 to 0.05 second and 0.1 to 0.15 second, both DERs and utility grid are fully available to supply 10 kW of load as presented in Figure 6.13(a)-6.13(b). In addition, both DERs and utility grid are not available from 0.05 to 0.1 second as shown in Figure 6.13(a)-6.13(b), so, under this situation the voltage will be supplied by the BES system to run the critical load of 4 kW as shown in Figure 6.13(c). Before 0.05 second and after 0.1 second, the voltage supply given by BES system to the load is zero because at that time the load is supplied by DERs and utility grid. Further, the backup time of BES also depends upon the size of battery, usage and consumption of power at critical load bus. The active power load profile shared by DERs, utility grid and BES system is presented in Figure 6.13(d). Thus, it is concluded that the overall quality of power can be improved with the application of BES system for sound and healthy operation of a microgrid.

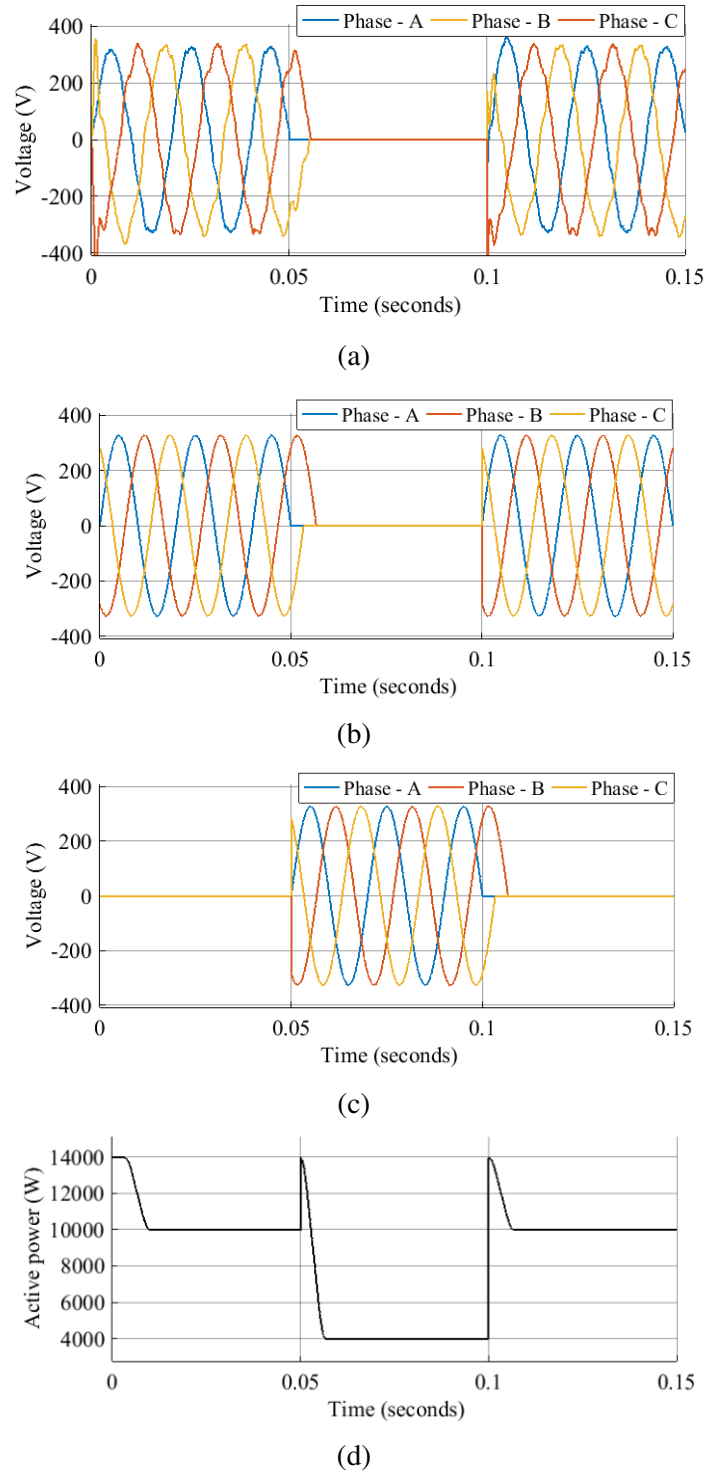


Figure 6.13. Voltage supplied by (a) DER1 and DER2, (b) utility grid, (c) BES system and (d) load power sharing profile

6.6.2 Microgrid model with additional line impedance (Scenario – 2)

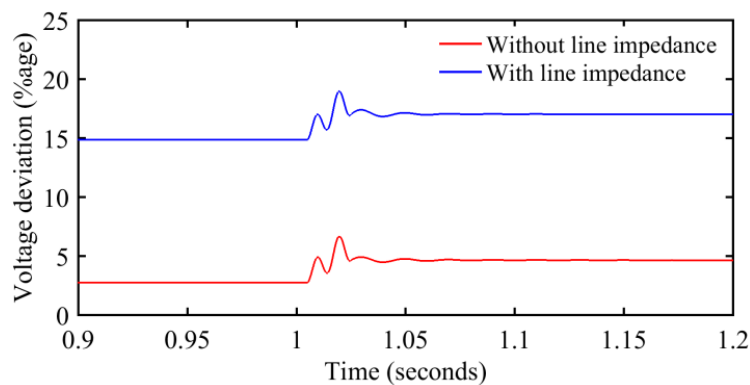
The three-phase AC microgrid model presented in Figure 6.3 has been tested for the assessment of power quality parameters considering the effect of line impedance. The power

sharing and losses in utility grid and DERs have also been calculated. In addition, the proposed controller has been tested under transient conditions due to the communication delay in controlling action and the power quality parameters have been assessed for the same condition. These conditions have been discussed in next Sub-sections 6.6.2.1, 6.6.2.2 and 6.6.2.3.

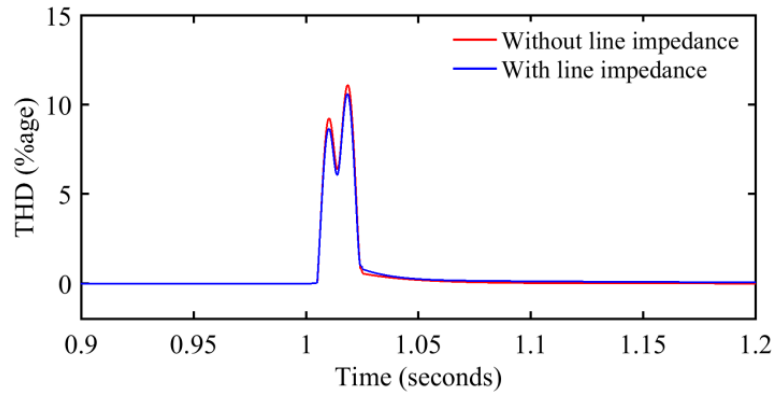
6.6.2.1 Effect of line impedance on power quality parameters

The three-phase AC microgrid system containing two DERs and one utility grid has been analyzed during on-grid and off-grid conditions. The transients have been observed when there is a change in status of microgrid from grid to islanded state with/without consideration of line impedances. The power quality parameters such as voltage deviation, THD, frequency and power factor have been assessed to ensure the performance of proposed controller during transition period as shown in Figure 6.14(a)-6.14(b).

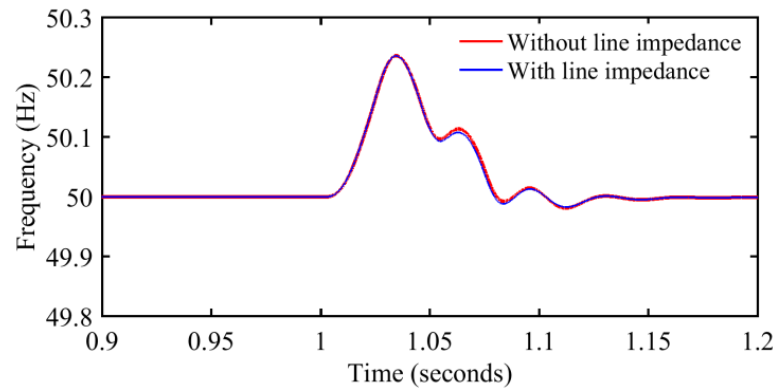
The transition from grid to islanded mode is initiated at one second as shown in Figure 6.14(a)-6.14(d). The performance of microgrid without line impedance (as shown in Figure 6.2) is compared with the effect of line impedance as shown in Figure 6.3. It is found that voltage deviation is higher (more than 15%) in case of effect of line impedance as shown in Figure 6.14(a) because of cumulative impedance due to utility grid (500 m line), station to main load bus (50 m line), CL (50 m line) and NCL (100 m line). There is no significant change in THD and frequency due to line impedance as presented in Figure 6.14(b)-6.14(c). The power factor has been improved slightly as shown in Figure 6.14(d) due to increase in overall line impedance because of high R/X ratio in case of LV distribution network. The transients have been observed at one second in all four power quality parameters due to change in circuit breaker state from grid to islanded modes of operation.



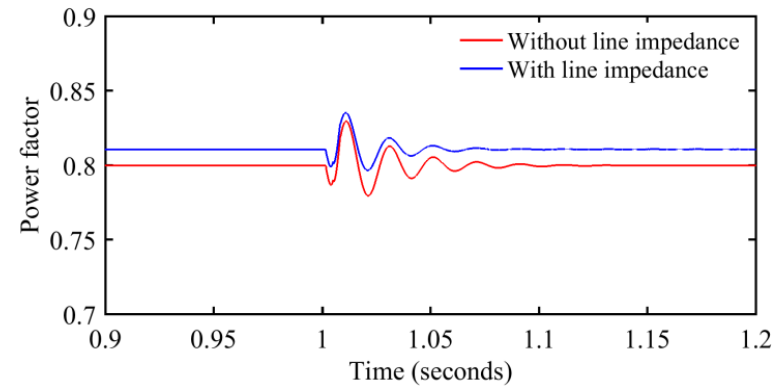
(a)



(b)



(c)



(d)

Figure 6.14. Power quality parameters with/without effect of line impedance: (a) voltage deviation, (b) THD, (c) frequency and (d) power factor

6.6.2.2 Power sharing and losses in utility grid and DERs

The active, reactive and apparent power shared by the DERs and utility grid have been measured with 0% and 100% availability of PV source as shown in Figure 6.15(a)-6.15(c). Figure 6.15(a) and 6.15(b) represent power shared by DERs and utility grid respectively when there is no PV source. It is found that DERs are absorbing the reactive power because of zero active power generation by justifying the basic concept of power system as shown in

Figure 6.15(a). Since the reactive power is negative (green line), it means that inverter is working in inductive mode (with positive I_q) and absorbing the reactive power. Therefore, the total or apparent power can be calculated as $\sqrt{(Active\ power)^2 + (Reactive\ power)^2}$ and shown with positive waveform in Figure 6.15(a). In the absence of DERs, utility grid supplies the load of 10 kW and 7.5 kVar. The active and reactive powers shared by the utility grid are shown in Figure 6.15(b).

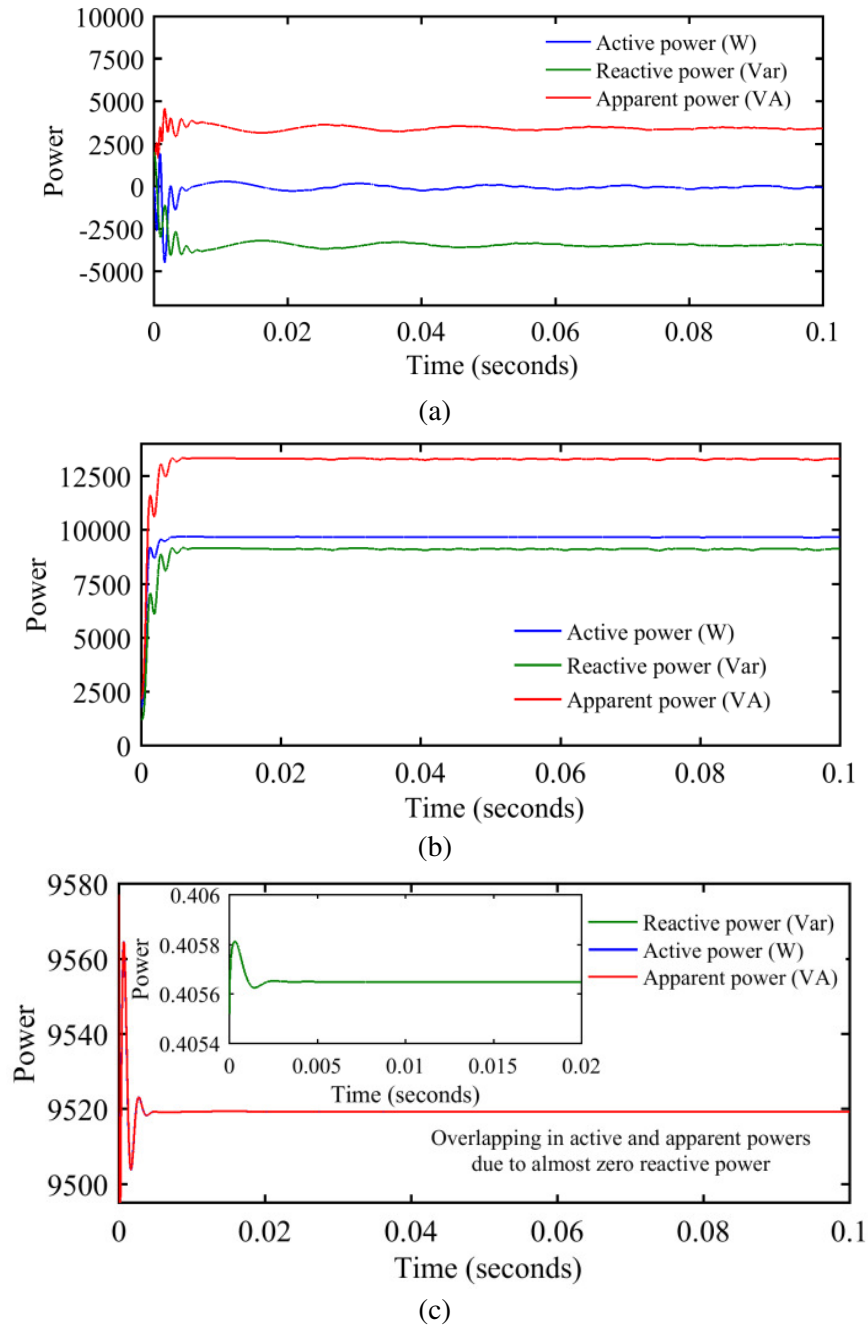


Figure 6.15. Power sharing profile in case of (a) DERs and (b) utility grid with 0% availability of PV source and (c) DERs with 100% availability of PV source

In addition, Figure 6.15(c) shows power shared by DER independently with 100% availability of PV source and it is evident that PV source (inverter side) worked as an active power source with almost negligible (close to zero) reactive power generation as shown in Figure 6.15(c). It is also observed that the apparent power overlaps the active power waveform due to no reactive power. The DER is supplying only the active power with amount of 9520 W during 100% availability of PV source as presented in Figure 6.15(c). The power losses due to line impedances on sources (DERs and utility grid) and distribution lines are shown in Table 6.6. During on-grid mode, the active power losses in the sources and distribution lines are high due to grid side line (500 m), NCL and CL side line (100 m and 50 m) impedances while in case of off-grid mode the active power losses due to distribution lines are very less as presented in Table 6.6.

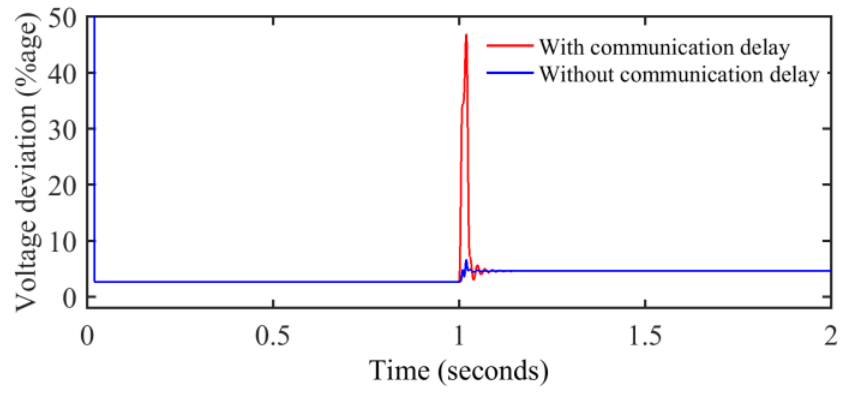
Table 6.6. Effect of line impedances on power loss in sources and distribution lines

Operating mode	Generation/source power loss (W)		Three-phase distribution lines power loss (W)		
	Grid side T/F	DER1, DER2	Grid side line (500 m)	NCL side line (100 m)	CL side line (50 m)
On-grid	470	540	152.85	30.60	15.26
Off-grid	0	423	0	12.25	4.35

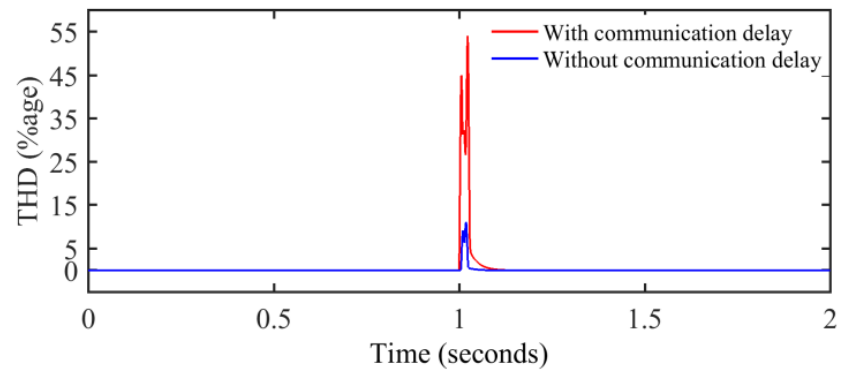
6.6.2.3 Effect of communication delay on power quality parameters

The performance of proposed controller as shown in Figure 6.3 can be tested by initiating the communication delay in breaker operation during transition from on-grid to off-grid condition. The controller action is delayed to assess the power quality parameters such as voltage deviation, THD, frequency and power as shown in Figure 6.16(a)-6.16(d). In case of communication delay, the large amount of voltage deviation (abnormally high about 45%) has been observed as compared to without communication delay (about 5%) at the time instant of 1 second while transition occurs from on-grid to off-grid condition as shown in Figure 6.16(a). Similarly, THD has been assessed in Figure 6.16(b) and realized that transient is high in case of communication delay as compared to without delay in controller action.

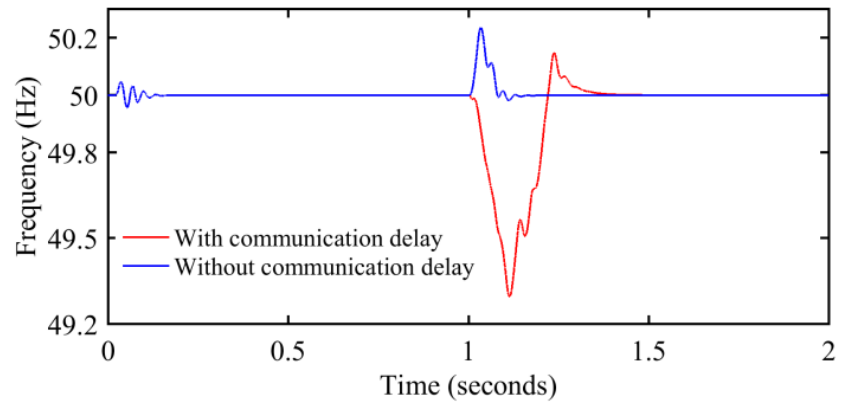
The microgrid frequency is highly affected by communication delay from 1 second to 1.4 second as shown in Figure 6.16(c) which may lead to synchronization failure between two DERs. There is a sharp decrease in frequency of 49.3 Hz after transition due to communication delay.



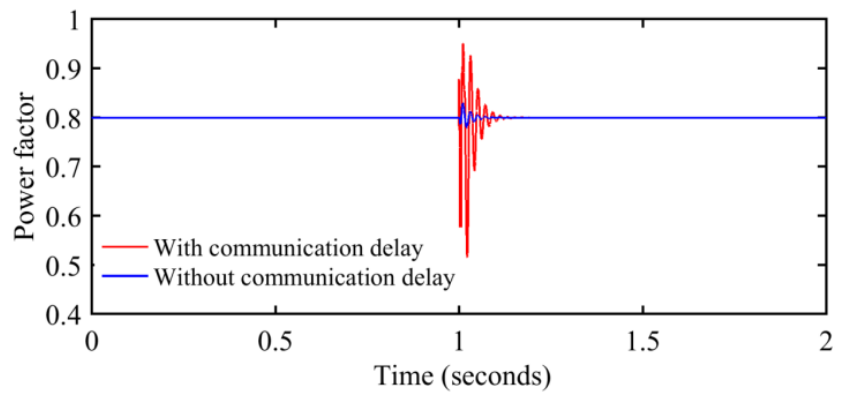
(a)



(b)



(c)



(d)

Figure 6.16. Effect of communication delay on (a) voltage deviation, (b) THD, (c) frequency and (d) power factor

In Figure 6.16(d), the waveform has shown high transients in case of communication delay while there is very less transients without considering the effect of communication delay in reference to the 0.8 power factor. Hence, it is concluded from Figure 6.16(a)-6.16(d) that the microgrid frequency is affected more for long time as compared to voltage deviation, THD and power factor which may further lead to failure in synchronization.

6.6.3 Realistic three-phase AC microgrid structure (Scenario – 3)

The realistic three-phase AC microgrid structure/architecture presented in Figure 6.4 has been examined in Sub-section 6.6.3.1 for power sharing among MG1, MG2, MG3 and utility grid during on-grid and off-grid conditions. The demand response has been studied in Sub-section 6.6.3.2 during off-grid condition when the load is supplied only by the local MG1, MG2 and MG3. The power quality parameters have been analyzed with the effect of communication delay in Sub-section 6.6.3.3 for MG1, MG2 and MG3 during off-grid condition. The realistic microgrid structure is also tested for off-nominal conditions with communication delay and additive noise in Sub-section 6.6.3.4.

6.6.3.1 Power sharing and losses in realistic three-phase AC microgrid structure

The loads rating of local MG1, MG2 and MG3 are settled to 4 kW, 4 kW and 6 kW respectively. The total active power generation from these three microgrids is 14 kW. If the load requirement becomes higher than 14 kW in that case the utility grid can be connected to cater the extra load demand. The percentage power loss depends mainly on the amount of distribution line/wire losses as per their distance from source to the load. The highest power loss of 7.5% is observed in case of MG3 during on-grid operation as shown in Table 6.7 because MG3 has four distribution wires which generates more losses as that of MG1 and MG2 as presented in Figure 6.4. The Table 6.8 shows active power generation, demand and losses of MG1, MG2 and MG3 during off-grid condition. It is realized that MG3 has 5.83% of loss as compared to 5% in case of MG1 and MG2. The power loss waveforms have been plotted for MG1, MG2, MG3 and utility grid during on-grid and off-grid conditions as shown in Figure 6.17. In case of off-grid, the overall active power losses are less as compared to on-grid condition because the loads are supplied through localized microgrids like MG1 to MG3. Since, the utility grid is disconnected in case of off-grid condition from PCC then power loss of utility grid side will come out to be zero as shown in Figure 6.17.

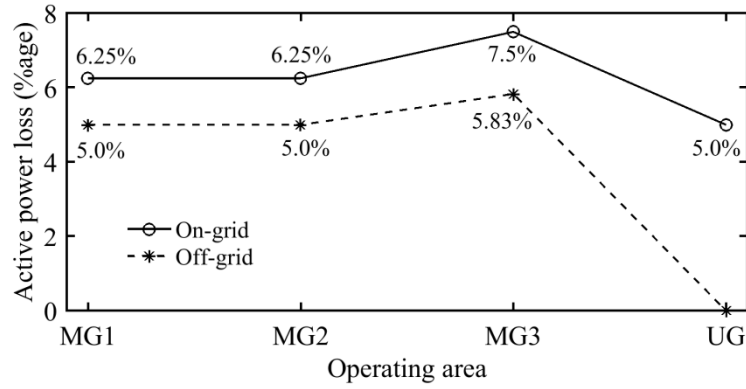


Figure 6.17. Power loss during on-grid and off-grid operations by MG1, MG2 and MG3

Table 6.7. On-grid power sharing and losses among MG1, MG2, MG3 and utility grid

Operating area	Generation (P_g , W)	Demand (P_d , W)	Power loss (P_{loss} , W)	Power loss (%)
MG1	4000	3750	250	6.25
MG2	4000	3750	250	6.25
MG3	6000	5550	450	7.5
Utility grid	10000	9500	500	5.0

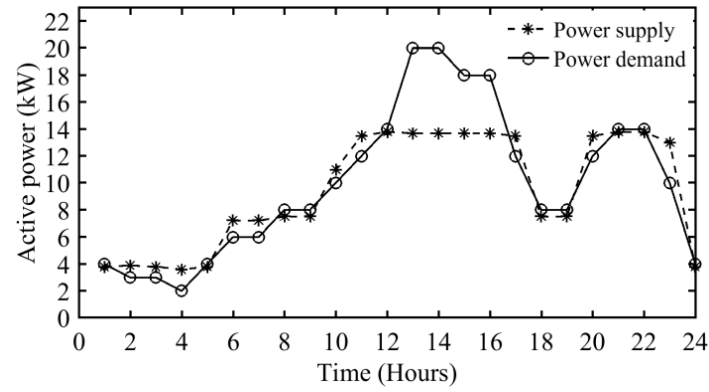
Table 6.8. Off-grid power sharing and losses among MG1, MG2 and MG3

Operating area	Generation (P_g , W)	Demand (P_d , W)	Power loss (P_{loss} , W)	Power loss (%)
MG1	4000	3800	200	5.0
MG2	4000	3800	200	5.0
MG3	6000	5650	350	5.83

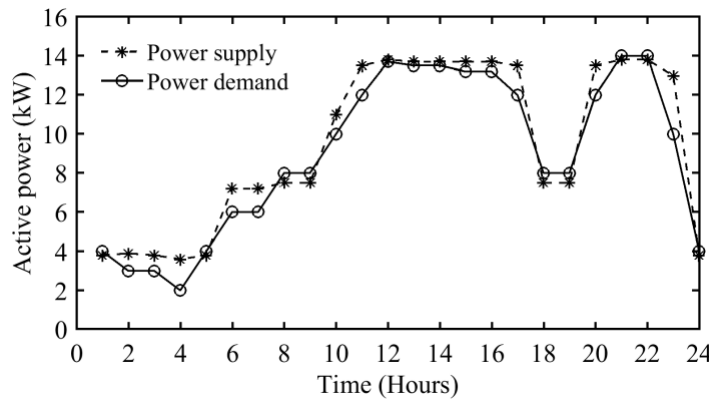
6.6.3.2 Demand response (DR) analysis

The maximum generation capacities of MG1, MG2 and MG3 are 4 kW, 4 kW and 6 kW respectively. So, the load demand of 14 kW can be fulfilled using all three microgrids (MG1, MG2 and MG3) during off-grid condition. The active power has been plotted against total 24 hours of time (one day) in reference to supply and load demand as shown in Figure 6.18(a)-6.18(c). The Figure 6.18(a) shows demand response curve of active power when load demand increased from 14 kW to 20 kW of generation from 12:00 hours to 17:00 hours without any extra BES backup. Since, there is no extra back of supply so the load has been curtailed beyond the generation capacity of 14 kW as shown in Figure 6.18(b). As the part of consumers' satisfaction, it is the responsibility of generating units to fulfil the load demand in all possible situations. Hence, the load can be shifted to the time period when the load demand is low/medium or can be supplied with extra support of BES. The load demand

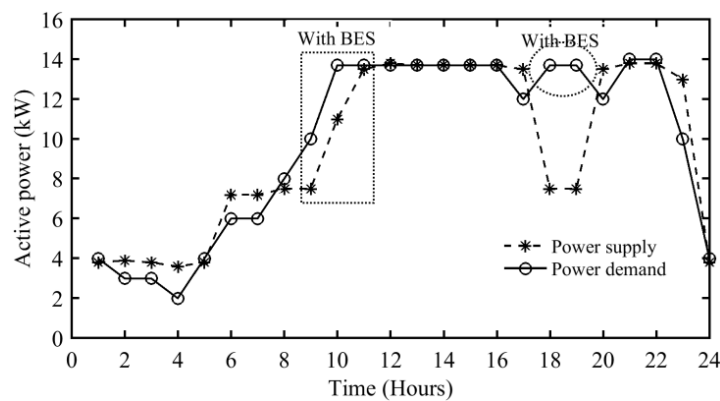
above to 14 kW is adjusted or shifted to the time window from 09:00 to 11:00 hours and 18:00 to 19:00 hours as shown in Figure 6.18(c). It is concluded from Figure 6.18(c) that the extra load demand can be fulfilled by shifting the load to the low consumption time period or connecting to extra BES support within the microgrids (MG1 to MG3).



(a)



(b)



(c)

Figure 6.18. Demand response profile during off-grid condition (a) without load curtailment, (b) with load curtailment and (c) load shifting/adjustment using BES

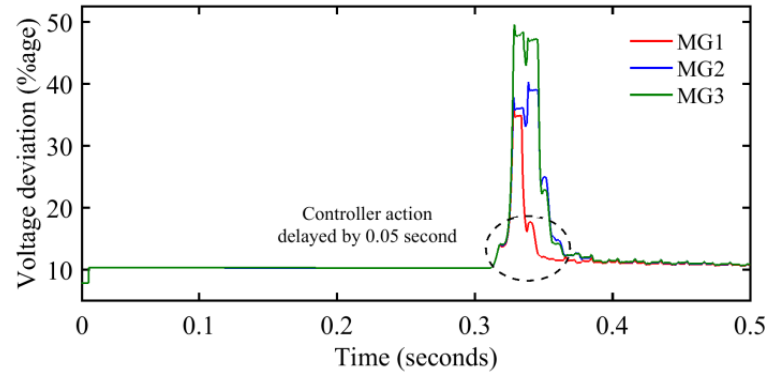
6.6.3.3 Power quality parameters assessment with the effect of communication delay in case of realistic microgrid structure

The realistic three-phase AC microgrid structure has capability to share the power among three small size microgrids through utility grid during on-grid and off-grid conditions as identified in previous Sub-sections 6.6.3.1 and 6.6.3.2. In this sub-section, the power quality parameters have been assessed to validate the operation of proposed controller for local microgrids such as MG1, MG2 and MG3 without/with communication delay. MG1 and MG2 include three DERs and three loads with total 4 kW of capacity and load as shown in Figure 6.4. The equivalent impedance of MG1 and MG2 is calculated as per distance of three parallel lines of 50 m and one 300 m line connected to utility grid through PCC. MG3 comprises four DERs connected with four load buses of total load capacity of 6 kW. Four parallel lines of 50 m each are connected in series with 300 m line and later connected with utility grid through PCC as shown in Figure 6.4.

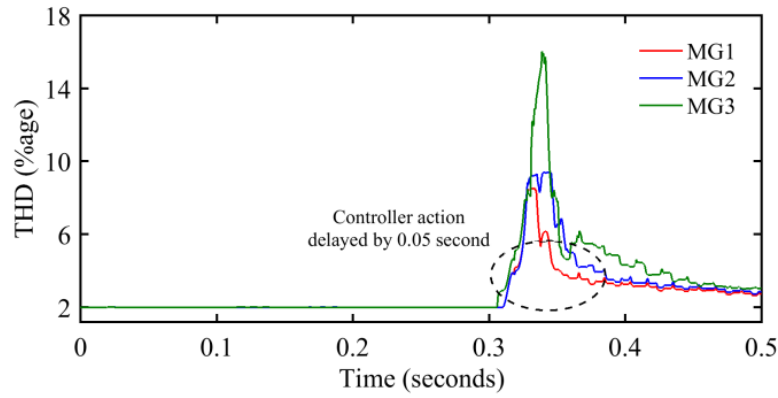
The different types of loads connected in MG1, MG2 and MG3 are presented in Table 6.9 which shows the rating of resistive, inductive and rotating loads. The quality of power among three microgrids depends on the nature of load and transition from on-grid to off-grid condition. The performance of proposed controller has been investigated during transition period with the effect of communication delay on power quality parameters. The Figure 6.19(a)-6.19(d) show the power quality parameters when the controller action is delayed by 0.05 second during transition from on-grid to off-grid condition.

Table 6.9. Types of loads connected in MG1, MG2 and MG3

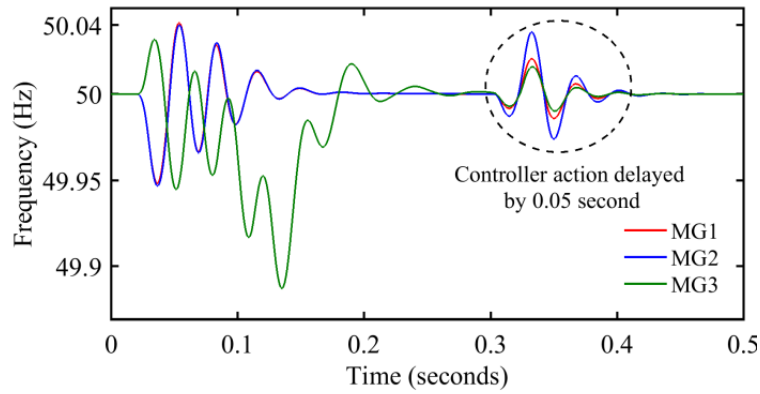
Load Bus	MG1 (4 kW)	MG2 (4 kW)	MG3 (6 kW)
Load 1	1 kW (Resistive load)		
Load 2	2 kW (Resistive load)		
Load 3	1 kW (Resistive load)		
Load 4		1 kW (Resistive load)	
Load 5		1 kW (Resistive load)	
Load 6		2 kW, 1.5 kVar (Inductive load)	
Load 7			2 kW (Resistive load)
Load 8			1 kW (Induction motor)
Load 9			1 kW, 0.75 kVar (Inductive load)
Load 10			2 kW (Resistive load)



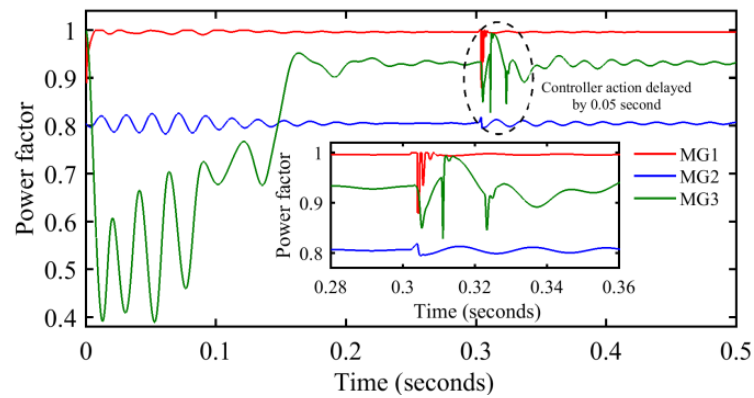
(a)



(b)



(c)



(d)

Figure 6.19. Power quality parameters assessment of realistic microgrid architecture with the effect of communication delay on (a) voltage deviation, (b) THD, (c) frequency and (d) power factor

The realistic three-phase AC microgrid structure is simulated for 0.5 second using MATLAB software. The transition (on-grid to off-grid) occurs at 0.3 second when utility grid is disconnected from PCC and the 14 kW of load will be catered by the local microgrids MG1, MG2 and MG3. Figure 6.19(a) shows the variation of voltage deviation which concluded that MG1 has least deviation at the time of transition as compared to MG2 and MG3 because of its least equivalent impedance. After transition, the voltage becomes stable at 0.38 second under off-grid condition subjected to controller action delayed by 0.05 second just after 0.3 second as shown in Figure 6.19(a). Similarly, it is found in Figure 6.19(b) that MG1 has minimum deviation in THD at the time of transition due to resistive load of 4 kW while MG3 has shown large transients at 0.3 second due to combination of resistive, inductive and rotating loads of 6 kW. But after 0.45 second the THDs of MG1, MG2 and MG3 have settled to 3.5% which is less than the allowable range of 5% as per IEEE Std. 519-2014. It is realized that there is large amount of THD in between 0.30 and 0.36 seconds due to delay of 0.05 second in breaker operation as a part of controller action.

The frequency variations have been analyzed and observed that MG3 has shown initial dip in frequency of 49.85 Hz at 0.14 second due to starting of 1 kW induction motor connected on load 9. During transition time of 0.3 second, there are frequency variations in MG1 to MG3 but these variations are ranging within the allowable value of ± 0.5 Hz which will not affect the performance of microgrid. Further, the frequencies of all microgrids (MG1 to MG3) have been settled to steady state after 0.4 second during off-grid condition. The communication delay can also create transients in the power factor as per the nature of loads.

It is observed that MG3 has experienced large transients at the time of change over from on-grid to off-grid due to delay in control action by 0.05 second as shown in Figure 6.19(d). This happened due to the rotational load which is connected in MG3 on load 9. Also, at the time of starting the 1 kW induction motor the power factor is poor that is 0.4 and when motor attains its rated speed at 0.17 second then power factor reached to the steady state value of 0.92 as shown in Figure 6.19(d). It is further found that the power factor values of MG1 and MG2 are stable and smooth due to static resistive and inductive loads. Hence, MG3 is affected more due to its large size (6 kW), equivalent impedance and nature of loads (static and rotational) with the impact of communication delay in overall operation and performance of a realistic three-phase AC microgrid structure.

6.6.3.4 Off-nominal frequency conditions with change of communication delay and additive noise

The realistic microgrid structure shown in Figure 6.4 is tested for off-nominal conditions with communication delay and additive noise. The realistic microgrid structure is presented with the capability of communication delay and additive noise when off-grid condition starts at $t = 0.25$ second. The noise variance can be represented as the function of active power variance and written as $f_{pji}(P_j(t - \tau) - P_i(t - \tau))$ which shows the state measurement of DER i from neighbour DER j ; τ represents the time delay [144]. The additive noise with variance 0.2 and communication delay of 0.15 second are applied during the transition from on-grid to off-grid condition at time $t = 0.25$ second. It is seen from Figure 6.20 that the fundamental frequencies of MG1, MG2 and MG3 are restored to 50 Hz after 1 second by the proposed controller.

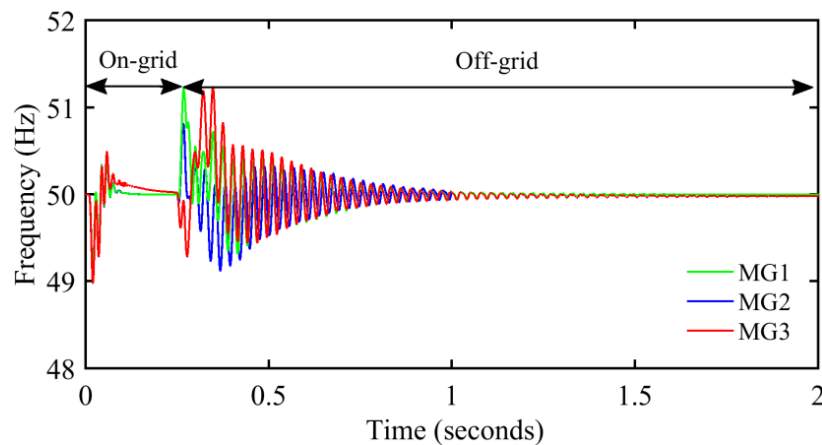


Figure 6.20. Frequency waveforms of realistic microgrid structure (MG1, MG2 and MG3) during off-nominal conditions with communication delay and additive noise

In Figure 6.20, the transients in frequency waveforms have been observed as per the nature of connected loads in MG1 (static-resistive load), MG2 (static-inductive load) and MG3 (static-resistive, inductive and rotational loads) as framed in Table 6.9. It is observed that when the additive noise is added with the variance 0.2 the frequency waveforms of MG1, MG2 and MG3 become unstable, hence, the communication links are affected by the delay and additive noise in distributed types of microgrids. It is concluded that the proposed controller has shown desirable performance under the consideration of off-nominal conditions with communication delay and additive noise in reference to the fundamental frequency 50 Hz.

This chapter describes power quality control based on voltage sag/swell, unbalancing, frequency, THD and power factor using ANN in PV integrated AC microgrid. A simple microgrid model has been extended to a realistic structure/architecture of microgrid considering the effect of line impedance as a part of distribution network. The effect of line impedance on power quality parameters have been analyzed during on-grid and off-grid operation of microgrid. The power sharing and reactive power circulation have been assessed with and without availability of PV system. The power losses in sources and distribution wires have been measured to maintain balance between demand and supply.

CONCLUSIONS AND FUTURE SCOPE OF RESEARCH

7.1 CONCLUSIONS

In this work, modelling and simulation of a single-phase AC microgrid system is conducted using MATLAB–Simulink software. The results are validated for grid-connected and islanded conditions. The method entails the use of Mamdani-FIS which recommends 256 numbers of rules for four input variables such as voltage deviation, frequency, power factor and THD, and one output variable as PQMI. This technique enables PQ monitoring at various load points which is key for customer satisfaction. The validation of simulated results is performed using OP4510 RT-LAB-RCH/HIL. The planning and design of a microgrid system should be done as per IEEE Recommended Practice Std. 2030.9-2019 which has been followed in the modelling and simulation of AC microgrid system. It has been found that this standard recommends power quality monitoring issues in the planning and design of microgrid system. The supplemental parameters for power quality issues may be considered as voltage dips, interruptions, unbalance etc. In several cases; such as, rotational, dynamic and non-linear loads, poor power quality index is observed during grid-connected and islanded operation of microgrid.

The proposed PQMI approach is found simple by the use of FIS as compared to MCDM which is verified and compared in Sub-section 4.2.1. As discussed in Sub-sections 4.2.2 and 4.3.3 in comparison to [125] and [126], it is observed that the comprehensive evaluation of the power quality at a specific point may not be sufficient for an islanded or grid-connected AC microgrid. Preferably, the power quality to be monitored at various load points aiming consumers' satisfaction which can be achieved using the proposed PQMI. It is realized that the status of power quality should be determined considering maximum number of related parameters for proper monitoring and control of microgrid system. So, the proposed methodology is advantageous to consider the fuzziness in variation of different parameters using FIS. One limitation of this proposed PQMI approach is that numbers of linguistic variables are more while the number of rules for FIS is large. It is also observed that more number of rules can monitor power quality satisfactorily considering the fuzziness in variation of large number of electrical parameters.

The modelling and simulation technique proposed for single-phase AC microgrid can be modified and implemented for three-phase AC microgrid to evaluate its status of power quality. The proposed simulation approach can be effectively used in the stage of design of AC microgrid equipped with power quality monitoring device before on-site installation of the actual system reducing the cost of research and development.

An effective decision making methodology is proposed for three-phase AC microgrid which is tested for the assessment of power quality monitoring index (PQMI) during grid-connected and islanded modes of operation. The PQMI is assessed for three-phase resistive, inductive, rotational, non-linear and dynamic loads. Further, the microgrid system is tested for its feasibility in all possible aspects such as voltage sag, swell, interruption and unbalance in three-phase system to check the status of PQMI. The FIS-based scheme yields good results to highlight the PQMI.

The Mamdani-FIS is compared with Sugeno-FIS to verify the correctness of PQMI as per IEEE 1547 under different loading conditions. Hence, the magnitudes of PQMI are observed almost same in both the FISs. In addition, the results are analysed on the basis of standard deviation and correlation between Mamdani and Sugeno-FISs for PQMI. To maintain the sound health of microgrid, it becomes essential to propose one microgrid central controller based on PQMI.

The control algorithm is implemented through FIS-based PQMI including ADSM to improve the power quality parameters such as voltage, frequency, THD and power factor as per international IEEE/IEC standards. The simulation results are validated experimentally using real-time simulator OP4510 RT-LAB-RCP/HIL, which show feasibility of the proposed control algorithm equipped with power quality control in close relation with protection and BES systems. It is investigated that the MGCC/CPU controller can be operated with the provision of extra storage facility for its reliable and stable operation in the application of microgrid.

From this research, it is revealed that maintaining power quality should be given priority while satisfactory operation and control of microgrid is most desirable issue. It is concluded that quantification of power quality and taking corrective action will be beneficial for microgrid system along with conventional control approach. Another benefit of the proposed method is that the power quality of a microgrid can be assessed in the stage of design if the

rating and nature of all the resources and load components are properly identified which will be useful for the power engineers to know the performance of microgrid prior to on-site installation. Even, the adverse effect of undesirable non-linear loading of microgrid can be removed using ADSM strategy in the practical system.

During research, it is revealed that the proposed ANN based controller can work satisfactorily even if the nature of DERs is changed irrespective of the geographical location of a microgrid system considering different international standards to maintain the power quality. Due to large number of variables with non-linear set of equations, it is seen that the proposed controller delivers fast, smooth and stable response in microgrid to enhance the overall performance. The proposed ANN controller is duly compared with the PI and fuzzy-PI controllers resulting in better performance using MATLAB-simulink software.

The realistic microgrid structure is implemented and analyzed for the assessment of power quality parameters during on-grid and off-grid conditions. The performance of proposed control methodology is tested satisfactorily with the effect of communication delay when there is a transition from on-grid to off-grid condition. It is observed that the proposed controller has shown transients and little sluggish response due to delay in controller action during transition period. The three sets of localized realistic microgrids (MG1, MG2 and MG3) have shown reasonable amount of power sharing and losses among the DERs and utility grid. The load sharing profile is analyzed with the application of demand response which has shown balance between power supply and demand during off-grid condition. Further, the realistic microgrid structure is also simulated successfully for off-nominal frequency conditions with change of communication delay and additive noise during the transition from on-grid to off-grid condition.

7.2 FUTURE SCOPE OF RESEARCH

The present work has a good aspect for future research which is appended below.

1. In future, all these research outcomes can be verified for a real hardware model of three-phase hybrid microgrid system. Even, apart from PV and wind DERs, the same approach may be verified for any other kind of DERs such as diesel generator, fuel cell, micro-turbine etc.

2. The natural uncertainty in PV and wind generators may affect the performance of microgrid system. It may deteriorate the power quality of microgrid system. So, this important feature will be studied in future research.
3. In the present work, the effects of different types of loads such as static, rotational, linear/non-linear and dynamic loads have been analyzed for determination of PQMI. As an extension of this approach of research, the simultaneous effect of multiple loads fluctuation on power quality will be studied. Since, the microgrid model is tested for three-phase induction motor as rotational load so effects of other kinds of rotational loads such as DC motors, synchronous motors etc. will be analyzed to study the performance of microgrid.
4. Development and commercialization of PQMI display device in combination with data acquisition system has a good scope of research.
5. Apart from ANN, the other kinds of intelligent techniques will also be implemented for proposed control methodologies in future.
6. Different types of inverter control topologies will be tested based on proposed PQMI.
7. The concept of PQMI will be extended to the DC microgrid based on the power quality control.

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APPENDIX

A.1

TABLE A. Determination of PQMI (z_i) and truth value (w_i)

Rule No.	VD (a)	Frequency (b)	PF (c)	THD (d)	PQMI (z_i)	Truth value (w_i)
1.	Best=5	More Poor=48.5	Poor=0.7	Best=2.5	Poor=7	Min(a, b, c, d)=0.7
2.	Best=5	More Poor=48.5	Poor=0.7	Average=7.5	Poor=7	Min(a, b, c, d)=0.7
3.	Best=5	More Poor=48.5	Poor=0.7	Poor=15	Poor=7	Min(a, b, c, d)=0.7
4.	Best=5	More Poor=48.5	Poor=0.7	V Poor=25	Poor=7	Min(a, b, c, d)=0.7
5.	Best=5	More Poor=48.5	Good=0.85	Best=2.5	Average=5	Min(a, b, c, d)=0.85
6.	Best=5	More Poor=48.5	Good=0.85	Average=7.5	Average=5	Min(a, b, c, d)=0.85
7.	Best=5	More Poor=48.5	Good=0.85	Poor=15	Poor=7	Min(a, b, c, d)=0.85
8.	Best=5	More Poor=48.5	Good=0.85	V Poor=25	Poor=7	Min(a, b, c, d)=0.85
9.	Best=5	More Poor=48.5	V Good=0.9	Best=2.5	Average=5	Min(a, b, c, d)=0.9
10.	Best=5	More Poor=48.5	V Good=0.9	Average=7.5	Average=5	Min(a, b, c, d)=0.9
11.	Best=5	More Poor=48.5	V Good=0.9	Poor=15	Poor=7	Min(a, b, c, d)=0.9
12.	Best=5	More Poor=48.5	V Good=0.9	V Poor=25	Poor=7	Min(a, b, c, d)=0.9
13.	Best=5	More Poor=48.5	Best=1.0	Best=2.5	Average=5	Min(a, b, c, d)=1.0
14.	Best=5	More Poor=48.5	Best=1.0	Average=7.5	Average=5	Min(a, b, c, d)=1.0
15.	Best=5	More Poor=48.5	Best=1.0	Poor=15	Poor=7	Min(a, b, c, d)=1.0
16.	Best=5	More Poor=48.5	Best=1.0	V Poor=25	Poor=7	Min(a, b, c, d)=1.0
17.	Best=5	N Poor=49.6	Poor=0.7	Best=2.5	Poor=7	Min(a, b, c, d)=0.7
18.	Best=5	N Poor=49.6	Poor=0.7	Average=7.5	Poor=7	Min(a, b, c, d)=0.7
19.	Best=5	N Poor=49.6	Poor=0.7	Poor=15	Poor=7	Min(a, b, c, d)=0.7
20.	Best=5	N Poor=49.6	Poor=0.7	V Poor=25	Poor=7	Min(a, b, c, d)=0.7
21.	Best=5	N Poor=49.6	Good=0.85	Best=2.5	Average=5	Min(a, b, c, d)=0.85
22.	Best=5	N Poor=49.6	Good=0.85	Average=7.5	Average=5	Min(a, b, c, d)=0.85
23.	Best=5	N Poor=49.6	Good=0.85	Poor=15	Poor=7	Min(a, b, c, d)=0.85
24.	Best=5	N Poor=49.6	Good=0.85	V Poor=25	Poor=7	Min(a, b, c, d)=0.85
25.	Best=5	N Poor=49.6	V Good=0.9	Best=2.5	Good=3	Min(a, b, c, d)=0.9
26.	Best=5	N Poor=49.6	V Good=0.9	Average=7.5	Average=5	Min(a, b, c, d)=0.9
27.	Best=5	N Poor=49.6	V Good=0.9	Poor=15	Poor=7	Min(a, b, c, d)=0.9
28.	Best=5	N Poor=49.6	V Good=0.9	V Poor=25	Poor=7	Min(a, b, c, d)=0.9
29.	Best=5	N Poor=49.6	Best=1.0	Best=2.5	Good=3	Min(a, b, c, d)=1.0
30.	Best=5	N Poor=49.6	Best=1.0	Average=7.5	Average=5	Min(a, b, c, d)=1.0
31.	Best=5	N Poor=49.6	Best=1.0	Poor=15	Poor=7	Min(a, b, c, d)=1.0
32.	Best=5	N Poor=49.6	Best=1.0	V Poor=25	Poor=7	Min(a, b, c, d)=1.0
33.	Best=5	Best=50.2	Poor=0.7	Best=2.5	Average=5	Min(a, b, c, d)=0.7
34.	Best=5	Best=50.2	Poor=0.7	Average=7.5	Average=5	Min(a, b, c, d)=0.7
35.	Best=5	Best=50.2	Poor=0.7	Poor=15	Poor=7	Min(a, b, c, d)=0.7
36.	Best=5	Best=50.2	Poor=0.7	V Poor=25	Poor=7	Min(a, b, c, d)=0.7
37.	Best=5	Best=50.2	Good=0.85	Best=2.5	Good=3	Min(a, b, c, d)=0.85
38.	Best=5	Best=50.2	Good=0.85	Average=7.5	Average=5	Min(a, b, c, d)=0.85
39.	Best=5	Best=50.2	Good=0.85	Poor=15	Average=5	Min(a, b, c, d)=0.85
40.	Best=5	Best=50.2	Good=0.85	V Poor=25	Average=5	Min(a, b, c, d)=0.85
41.	Best=5	Best=50.2	V Good=0.9	Best=2.5	Good=3	Min(a, b, c, d)=0.9
42.	Best=5	Best=50.2	V Good=0.9	Average=7.5	Average=5	Min(a, b, c, d)=0.9
43.	Best=5	Best=50.2	V Good=0.9	Poor=15	Average=5	Min(a, b, c, d)=0.9
44.	Best=5	Best=50.2	V Good=0.9	V Poor=25	Average=5	Min(a, b, c, d)=0.9
45.	Best=5	Best=50.2	Best=1.0	Best=2.5	Best=1	Min(a, b, c, d)=1.0

46.	Best=5	Best=50.2	Best=1.0	Average=7.5	Good=3	Min(a, b, c, d)=1.0
47.	Best=5	Best=50.2	Best=1.0	Poor=15	Average=5	Min(a, b, c, d)=1.0
48.	Best=5	Best=50.2	Best=1.0	V Poor=25	Average=5	Min(a, b, c, d)=1.0
49.	Best=5	P Poor=53	Poor=0.7	Best=2.5	Poor=7	Min(a, b, c, d)=0.7
50.	Best=5	P Poor=53	Poor=0.7	Average=7.5	Poor=7	Min(a, b, c, d)=0.7
51.	Best=5	P Poor=53	Poor=0.7	Poor=15	Poor=7	Min(a, b, c, d)=0.7
52.	Best=5	P Poor=53	Poor=0.7	V Poor=25	Poor=7	Min(a, b, c, d)=0.7
53.	Best=5	P Poor=53	Good=0.85	Best=2.5	Average=5	Min(a, b, c, d)=0.85
54.	Best=5	P Poor=53	Good=0.85	Average=7.5	Average=5	Min(a, b, c, d)=0.85
55.	Best=5	P Poor=53	Good=0.85	Poor=15	Poor=7	Min(a, b, c, d)=0.85
56.	Best=5	P Poor=53	Good=0.85	V Poor=25	Poor=7	Min(a, b, c, d)=0.85
57.	Best=5	P Poor=53	V Good=0.9	Best=2.5	Average=5	Min(a, b, c, d)=0.9
58.	Best=5	P Poor=53	V Good=0.9	Average=7.5	Poor=7	Min(a, b, c, d)=0.9
59.	Best=5	P Poor=53	V Good=0.9	Poor=15	Poor=7	Min(a, b, c, d)=0.9
60.	Best=5	P Poor=53	V Good=0.9	V Poor=25	Poor=7	Min(a, b, c, d)=0.9
61.	Best=5	P Poor=53	Best=1.0	Best=2.5	Average=5	Min(a, b, c, d)=1.0
62.	Best=5	P Poor=53	Best=1.0	Average=7.5	Poor=7	Min(a, b, c, d)=1.0
63.	Best=5	P Poor=53	Best=1.0	Poor=15	Poor=7	Min(a, b, c, d)=1.0
64.	Best=5	P Poor=53	Best=1.0	V Poor=25	Poor=7	Min(a, b, c, d)=1.0
65.	Good=10	More Poor=48.5	Poor=0.7	Best=2.5	Poor=7	Min(a, b, c, d)=0.7
66.	Good=10	More Poor=48.5	Poor=0.7	Average=7.5	Poor=7	Min(a, b, c, d)=0.7
67.	Good=10	More Poor=48.5	Poor=0.7	Poor=15	Poor=7	Min(a, b, c, d)=0.7
68.	Good=10	More Poor=48.5	Poor=0.7	V Poor=25	Poor=7	Min(a, b, c, d)=0.7
69.	Good=10	More Poor=48.5	Good=0.85	Best=2.5	Average=5	Min(a, b, c, d)=0.85
70.	Good=10	More Poor=48.5	Good=0.85	Average=7.5	Poor=7	Min(a, b, c, d)=0.85
71.	Good=10	More Poor=48.5	Good=0.85	Poor=15	Poor=7	Min(a, b, c, d)=0.85
72.	Good=10	More Poor=48.5	Good=0.85	V Poor=25	Poor=7	Min(a, b, c, d)=0.85
73.	Good=10	More Poor=48.5	V Good=0.9	Best=2.5	Average=5	Min(a, b, c, d)=0.9
74.	Good=10	More Poor=48.5	V Good=0.9	Average=7.5	Poor=7	Min(a, b, c, d)=0.9
75.	Good=10	More Poor=48.5	V Good=0.9	Poor=15	Poor=7	Min(a, b, c, d)=0.9
76.	Good=10	More Poor=48.5	V Good=0.9	V Poor=25	Poor=7	Min(a, b, c, d)=0.9
77.	Good=10	More Poor=48.5	Best=1.0	Best=2.5	Average=5	Min(a, b, c, d)=1.0
78.	Good=10	More Poor=48.5	Best=1.0	Average=7.5	Poor=7	Min(a, b, c, d)=1.0
79.	Good=10	More Poor=48.5	Best=1.0	Poor=15	Poor=7	Min(a, b, c, d)=1.0
80.	Good=10	More Poor=48.5	Best=1.0	V Poor=25	Poor=7	Min(a, b, c, d)=1.0
81.	Good=10	N Poor=49.6	Poor=0.7	Best=2.5	Poor=7	Min(a, b, c, d)=0.7
82.	Good=10	N Poor=49.6	Poor=0.7	Average=7.5	Poor=7	Min(a, b, c, d)=0.7
83.	Good=10	N Poor=49.6	Poor=0.7	Poor=15	Poor=7	Min(a, b, c, d)=0.7
84.	Good=10	N Poor=49.6	Poor=0.7	V Poor=25	Poor=7	Min(a, b, c, d)=0.7
85.	Good=10	N Poor=49.6	Good=0.85	Best=2.5	Average=5	Min(a, b, c, d)=0.85
86.	Good=10	N Poor=49.6	Good=0.85	Average=7.5	Poor=7	Min(a, b, c, d)=0.85
87.	Good=10	N Poor=49.6	Good=0.85	Poor=15	Poor=7	Min(a, b, c, d)=0.85
88.	Good=10	N Poor=49.6	Good=0.85	V Poor=25	Poor=7	Min(a, b, c, d)=0.85
89.	Good=10	N Poor=49.6	V Good=0.9	Best=2.5	Average=5	Min(a, b, c, d)=0.9
90.	Good=10	N Poor=49.6	V Good=0.9	Average=7.5	Poor=7	Min(a, b, c, d)=0.9
91.	Good=10	N Poor=49.6	V Good=0.9	Poor=15	Poor=7	Min(a, b, c, d)=0.9
92.	Good=10	N Poor=49.6	V Good=0.9	V Poor=25	Poor=7	Min(a, b, c, d)=0.9
93.	Good=10	N Poor=49.6	Best=1.0	Best=2.5	Average=5	Min(a, b, c, d)=1.0
94.	Good=10	N Poor=49.6	Best=1.0	Average=7.5	Poor=7	Min(a, b, c, d)=1.0
95.	Good=10	N Poor=49.6	Best=1.0	Poor=15	Poor=7	Min(a, b, c, d)=1.0
96.	Good=10	N Poor=49.6	Best=1.0	V Poor=25	Poor=7	Min(a, b, c, d)=1.0
97.	Good=10	Best=50.2	Poor=0.7	Best=2.5	Average=5	Min(a, b, c, d)=0.7
98.	Good=10	Best=50.2	Poor=0.7	Average=7.5	Poor=7	Min(a, b, c, d)=0.7

99.	Good=10	Best=50.2	Poor=0.7	Poor=15	Poor=7	Min(a, b, c, d)=0.7
100.	Good=10	Best=50.2	Poor=0.7	V Poor=25	Poor=7	Min(a, b, c, d)=0.7
101.	Good=10	Best=50.2	Good=0.85	Best=2.5	Good=3	Min(a, b, c, d)=0.85
102.	Good=10	Best=50.2	Good=0.85	Average=7.5	Average=5	Min(a, b, c, d)=0.85
103.	Good=10	Best=50.2	Good=0.85	Poor=15	Average=5	Min(a, b, c, d)=0.85
104.	Good=10	Best=50.2	Good=0.85	V Poor=25	Poor=7	Min(a, b, c, d)=0.85
105.	Good=10	Best=50.2	V Good=0.9	Best=2.5	Good=3	Min(a, b, c, d)=0.9
106.	Good=10	Best=50.2	V Good=0.9	Average=7.5	Average=5	Min(a, b, c, d)=0.9
107.	Good=10	Best=50.2	V Good=0.9	Poor=15	Average=5	Min(a, b, c, d)=0.9
108.	Good=10	Best=50.2	V Good=0.9	V Poor=25	Poor=7	Min(a, b, c, d)=0.9
109.	Good=10	Best=50.2	Best=1.0	Best=2.5	Good=3	Min(a, b, c, d)=1.0
110.	Good=10	Best=50.2	Best=1.0	Average=7.5	Average=5	Min(a, b, c, d)=1.0
111.	Good=10	Best=50.2	Best=1.0	Poor=15	Average=5	Min(a, b, c, d)=1.0
112.	Good=10	Best=50.2	Best=1.0	V Poor=25	Poor=7	Min(a, b, c, d)=1.0
113.	Good=10	P Poor=53	Poor=0.7	Best=2.5	Poor=7	Min(a, b, c, d)=0.7
114.	Good=10	P Poor=53	Poor=0.7	Average=7.5	Poor=7	Min(a, b, c, d)=0.7
115.	Good=10	P Poor=53	Poor=0.7	Poor=15	Poor=7	Min(a, b, c, d)=0.7
116.	Good=10	P Poor=53	Poor=0.7	V Poor=25	Poor=7	Min(a, b, c, d)=0.7
117.	Good=10	P Poor=53	Good=0.85	Best=2.5	Average=5	Min(a, b, c, d)=0.85
118.	Good=10	P Poor=53	Good=0.85	Average=7.5	Poor=7	Min(a, b, c, d)=0.85
119.	Good=10	P Poor=53	Good=0.85	Poor=15	Poor=7	Min(a, b, c, d)=0.85
120.	Good=10	P Poor=53	Good=0.85	V Poor=25	Poor=7	Min(a, b, c, d)=0.85
121.	Good=10	P Poor=53	V Good=0.9	Best=2.5	Average=5	Min(a, b, c, d)=0.9
122.	Good=10	P Poor=53	V Good=0.9	Average=7.5	Poor=7	Min(a, b, c, d)=0.9
123.	Good=10	P Poor=53	V Good=0.9	Poor=15	Poor=7	Min(a, b, c, d)=0.9
124.	Good=10	P Poor=53	V Good=0.9	V Poor=25	Poor=7	Min(a, b, c, d)=0.9
125.	Good=10	P Poor=53	Best=1.0	Best=2.5	Average=5	Min(a, b, c, d)=1.0
126.	Good=10	P Poor=53	Best=1.0	Average=7.5	Poor=7	Min(a, b, c, d)=1.0
127.	Good=10	P Poor=53	Best=1.0	Poor=15	Poor=7	Min(a, b, c, d)=1.0
128.	Good=10	P Poor=53	Best=1.0	V Poor=25	Poor=7	Min(a, b, c, d)=1.0
129.	Poor=15	More Poor=48.5	Poor=0.7	Best=2.5	Poor=7	Min(a, b, c, d)=0.7
130.	Poor=15	More Poor=48.5	Poor=0.7	Average=7.5	Poor=7	Min(a, b, c, d)=0.7
131.	Poor=15	More Poor=48.5	Poor=0.7	Poor=15	Poor=7	Min(a, b, c, d)=0.7
132.	Poor=15	More Poor=48.5	Poor=0.7	V Poor=25	Poor=7	Min(a, b, c, d)=0.7
133.	Poor=15	More Poor=48.5	Good=0.85	Best=2.5	Poor=7	Min(a, b, c, d)=0.85
134.	Poor=15	More Poor=48.5	Good=0.85	Average=7.5	Poor=7	Min(a, b, c, d)=0.85
135.	Poor=15	More Poor=48.5	Good=0.85	Poor=15	Poor=7	Min(a, b, c, d)=0.85
136.	Poor=15	More Poor=48.5	Good=0.85	V Poor=25	Poor=7	Min(a, b, c, d)=0.85
137.	Poor=15	More Poor=48.5	V Good=0.9	Best=2.5	Average=5	Min(a, b, c, d)=0.9
138.	Poor=15	More Poor=48.5	V Good=0.9	Average=7.5	Poor=7	Min(a, b, c, d)=0.9
139.	Poor=15	More Poor=48.5	V Good=0.9	Poor=15	Poor=7	Min(a, b, c, d)=0.9
140.	Poor=15	More Poor=48.5	V Good=0.9	V Poor=25	Poor=7	Min(a, b, c, d)=0.9
141.	Poor=15	More Poor=48.5	Best=1.0	Best=2.5	Average=5	Min(a, b, c, d)=1.0
142.	Poor=15	More Poor=48.5	Best=1.0	Average=7.5	Poor=7	Min(a, b, c, d)=1.0
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144.	Poor=15	More Poor=48.5	Best=1.0	V Poor=25	Poor=7	Min(a, b, c, d)=1.0
145.	Poor=15	N Poor=49.6	Poor=0.7	Best=2.5	Poor=7	Min(a, b, c, d)=0.7
146.	Poor=15	N Poor=49.6	Poor=0.7	Average=7.5	Poor=7	Min(a, b, c, d)=0.7
147.	Poor=15	N Poor=49.6	Poor=0.7	Poor=15	Poor=7	Min(a, b, c, d)=0.7
148.	Poor=15	N Poor=49.6	Poor=0.7	V Poor=25	Poor=7	Min(a, b, c, d)=0.7
149.	Poor=15	N Poor=49.6	Good=0.85	Best=2.5	Average=5	Min(a, b, c, d)=0.85
150.	Poor=15	N Poor=49.6	Good=0.85	Average=7.5	Poor=7	Min(a, b, c, d)=0.85
151.	Poor=15	N Poor=49.6	Good=0.85	Poor=15	Poor=7	Min(a, b, c, d)=0.85

152.	Poor=15	N Poor=49.6	Good=0.85	V Poor=25	Poor=7	Min(a, b, c, d)=0.85
153.	Poor=15	N Poor=49.6	V Good=0.9	Best=2.5	Average=5	Min(a, b, c, d)=0.9
154.	Poor=15	N Poor=49.6	V Good=0.9	Average=7.5	Poor=7	Min(a, b, c, d)=0.9
155.	Poor=15	N Poor=49.6	V Good=0.9	Poor=15	Poor=7	Min(a, b, c, d)=0.9
156.	Poor=15	N Poor=49.6	V Good=0.9	V Poor=25	Poor=7	Min(a, b, c, d)=0.9
157.	Poor=15	N Poor=49.6	Best=1.0	Best=2.5	Average=5	Min(a, b, c, d)=1.0
158.	Poor=15	N Poor=49.6	Best=1.0	Average=7.5	Poor=7	Min(a, b, c, d)=1.0
159.	Poor=15	N Poor=49.6	Best=1.0	Poor=15	Poor=7	Min(a, b, c, d)=1.0
160.	Poor=15	N Poor=49.6	Best=1.0	V Poor=25	Poor=7	Min(a, b, c, d)=1.0
161.	Poor=15	Best=50.2	Poor=0.7	Best=2.5	Average=5	Min(a, b, c, d)=0.7
162.	Poor=15	Best=50.2	Poor=0.7	Average=7.5	Poor=7	Min(a, b, c, d)=0.7
163.	Poor=15	Best=50.2	Poor=0.7	Poor=15	Poor=7	Min(a, b, c, d)=0.7
164.	Poor=15	Best=50.2	Poor=0.7	V Poor=25	Poor=7	Min(a, b, c, d)=0.7
165.	Poor=15	Best=50.2	Good=0.85	Best=2.5	Good=3	Min(a, b, c, d)=0.85
166.	Poor=15	Best=50.2	Good=0.85	Average=7.5	Average=5	Min(a, b, c, d)=0.85
167.	Poor=15	Best=50.2	Good=0.85	Poor=15	Poor=7	Min(a, b, c, d)=0.85
168.	Poor=15	Best=50.2	Good=0.85	V Poor=25	Poor=7	Min(a, b, c, d)=0.85
169.	Poor=15	Best=50.2	V Good=0.9	Best=2.5	Good	Min(a, b, c, d)=0.9
170.	Poor=15	Best=50.2	V Good=0.9	Average=7.5	Average=5	Min(a, b, c, d)=0.9
171.	Poor=15	Best=50.2	V Good=0.9	Poor=15	Poor=7	Min(a, b, c, d)=0.9
172.	Poor=15	Best=50.2	V Good=0.9	V Poor=25	Poor=7	Min(a, b, c, d)=0.9
173.	Poor=15	Best=50.2	Best=1.0	Best=2.5	Good=3	Min(a, b, c, d)=1.0
174.	Poor=15	Best=50.2	Best=1.0	Average=7.5	Average=5	Min(a, b, c, d)=1.0
175.	Poor=15	Best=50.2	Best=1.0	Poor=15	Poor=7	Min(a, b, c, d)=1.0
176.	Poor=15	Best=50.2	Best=1.0	V Poor=25	Poor=7	Min(a, b, c, d)=1.0
177.	Poor=15	P Poor=53	Poor=0.7	Best=2.5	Poor=7	Min(a, b, c, d)=0.7
178.	Poor=15	P Poor=53	Poor=0.7	Average=7.5	Poor=7	Min(a, b, c, d)=0.7
179.	Poor=15	P Poor=53	Poor=0.7	Poor=15	Poor=7	Min(a, b, c, d)=0.7
180.	Poor=15	P Poor=53	Poor=0.7	V Poor=25	Poor=7	Min(a, b, c, d)=0.7
181.	Poor=15	P Poor=53	Good=0.85	Best=2.5	Poor=7	Min(a, b, c, d)=0.85
182.	Poor=15	P Poor=53	Good=0.85	Average=7.5	Poor=7	Min(a, b, c, d)=0.85
183.	Poor=15	P Poor=53	Good=0.85	Poor=15	Poor=7	Min(a, b, c, d)=0.85
184.	Poor=15	P Poor=53	Good=0.85	V Poor=25	Poor=7	Min(a, b, c, d)=0.85
185.	Poor=15	P Poor=53	V Good=0.9	Best=2.5	Poor=7	Min(a, b, c, d)=0.9
186.	Poor=15	P Poor=53	V Good=0.9	Average=7.5	Poor=7	Min(a, b, c, d)=0.9
187.	Poor=15	P Poor=53	V Good=0.9	Poor=15	Poor=7	Min(a, b, c, d)=0.9
188.	Poor=15	P Poor=53	V Good=0.9	V Poor=25	Poor=7	Min(a, b, c, d)=0.9
189.	Poor=15	P Poor=53	Best=1.0	Best=2.5	Average=5	Min(a, b, c, d)=1.0
190.	Poor=15	P Poor=53	Best=1.0	Average=7.5	Poor=7	Min(a, b, c, d)=1.0
191.	Poor=15	P Poor=53	Best=1.0	Poor=15	Poor=7	Min(a, b, c, d)=1.0
192.	Poor=15	P Poor=53	Best=1.0	V Poor=25	Poor=7	Min(a, b, c, d)=1.0
193.	V Poor=27	More Poor=48.5	Poor=0.7	Best=2.5	Poor=7	Min(a, b, c, d)=0.7
194.	V Poor=27	More Poor=48.5	Poor=0.7	Average=7.5	Poor=7	Min(a, b, c, d)=0.7
195.	V Poor=27	More Poor=48.5	Poor=0.7	Poor=15	Poor=7	Min(a, b, c, d)=0.7
196.	V Poor=27	More Poor=48.5	Poor=0.7	V Poor=25	Poor=7	Min(a, b, c, d)=0.7
197.	V Poor=27	More Poor=48.5	Good=0.85	Best=2.5	Poor=7	Min(a, b, c, d)=0.85
198.	V Poor=27	More Poor=48.5	Good=0.85	Average=7.5	Poor=7	Min(a, b, c, d)=0.85
199.	V Poor=27	More Poor=48.5	Good=0.85	Poor=15	Poor=7	Min(a, b, c, d)=0.85
200.	V Poor=27	More Poor=48.5	Good=0.85	V Poor=25	Poor=7	Min(a, b, c, d)=0.85
201.	V Poor=27	More Poor=48.5	V Good=0.9	Best=2.5	Poor=7	Min(a, b, c, d)=0.9
202.	V Poor=27	More Poor=48.5	V Good=0.9	Average=7.5	Poor=7	Min(a, b, c, d)=0.9
203.	V Poor=27	More Poor=48.5	V Good=0.9	Poor=15	Poor=7	Min(a, b, c, d)=0.9
204.	V Poor=27	More Poor=48.5	V Good=0.9	V Poor=25	Poor=7	Min(a, b, c, d)=0.9

205.	V Poor=27	More Poor=48.5	Best=1.0	Best=2.5	Poor=7	Min(a, b, c, d)=1.0
206.	V Poor=27	More Poor=48.5	Best=1.0	Average=7.5	Poor=7	Min(a, b, c, d)=1.0
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208.	V Poor=27	More Poor=48.5	Best=1.0	V Poor=25	Poor=7	Min(a, b, c, d)=1.0
209.	V Poor=27	N Poor=49.6	Poor=0.7	Best=2.5	Poor=7	Min(a, b, c, d)=0.7
210.	V Poor=27	N Poor=49.6	Poor=0.7	Average=7.5	Poor=7	Min(a, b, c, d)=0.7
211.	V Poor=27	N Poor=49.6	Poor=0.7	Poor=15	Poor=7	Min(a, b, c, d)=0.7
212.	V Poor=27	N Poor=49.6	Poor=0.7	V Poor=25	Poor=7	Min(a, b, c, d)=0.7
213.	V Poor=27	N Poor=49.6	Good=0.85	Best=2.5	Poor=7	Min(a, b, c, d)=0.85
214.	V Poor=27	N Poor=49.6	Good=0.85	Average=7.5	Poor=7	Min(a, b, c, d)=0.85
215.	V Poor=27	N Poor=49.6	Good=0.85	Poor=15	Poor=7	Min(a, b, c, d)=0.85
216.	V Poor=27	N Poor=49.6	Good=0.85	V Poor=25	Poor=7	Min(a, b, c, d)=0.85
217.	V Poor=27	N Poor=49.6	V Good=0.9	Best=2.5	Poor=7	Min(a, b, c, d)=0.9
218.	V Poor=27	N Poor=49.6	V Good=0.9	Average=7.5	Poor=7	Min(a, b, c, d)=0.9
219.	V Poor=27	N Poor=49.6	V Good=0.9	Poor=15	Poor=7	Min(a, b, c, d)=0.9
220.	V Poor=27	N Poor=49.6	V Good=0.9	V Poor=25	Poor=7	Min(a, b, c, d)=0.9
221.	V Poor=27	N Poor=49.6	Best=1.0	Best=2.5	Poor=7	Min(a, b, c, d)=1.0
222.	V Poor=27	N Poor=49.6	Best=1.0	Average=7.5	Poor=7	Min(a, b, c, d)=1.0
223.	V Poor=27	N Poor=49.6	Best=1.0	Poor=15	Poor=7	Min(a, b, c, d)=1.0
224.	V Poor=27	N Poor=49.6	Best=1.0	V Poor=25	Poor=7	Min(a, b, c, d)=1.0
225.	V Poor=27	Best=50.2	Poor=0.7	Best=2.5	Poor=7	Min(a, b, c, d)=0.7
226.	V Poor=27	Best=50.2	Poor=0.7	Average=7.5	Poor=7	Min(a, b, c, d)=0.7
227.	V Poor=27	Best=50.2	Poor=0.7	Poor=15	Poor=7	Min(a, b, c, d)=0.7
228.	V Poor=27	Best=50.2	Poor=0.7	V Poor=25	Poor=7	Min(a, b, c, d)=0.7
229.	V Poor=27	Best=50.2	Good=0.85	Best=2.5	Average=5	Min(a, b, c, d)=0.85
230.	V Poor=27	Best=50.2	Good=0.85	Average=7.5	Poor=7	Min(a, b, c, d)=0.85
231.	V Poor=27	Best=50.2	Good=0.85	Poor=15	Poor=7	Min(a, b, c, d)=0.85
232.	V Poor=27	Best=50.2	Good=0.85	V Poor=25	Poor=7	Min(a, b, c, d)=0.85
233.	V Poor=27	Best=50.2	V Good=0.9	Best=2.5	Average=5	Min(a, b, c, d)=0.9
234.	V Poor=27	Best=50.2	V Good=0.9	Average=7.5	Poor=7	Min(a, b, c, d)=0.9
235.	V Poor=27	Best=50.2	V Good=0.9	Poor=15	Poor=7	Min(a, b, c, d)=0.9
236.	V Poor=27	Best=50.2	V Good=0.9	V Poor=25	Poor=7	Min(a, b, c, d)=0.9
237.	V Poor=27	Best=50.2	Best=1.0	Best=2.5	Average=5	Min(a, b, c, d)=1.0
238.	V Poor=27	Best=50.2	Best=1.0	Average=7.5	Poor=7	Min(a, b, c, d)=1.0
239.	V Poor=27	Best=50.2	Best=1.0	Poor=15	Poor=7	Min(a, b, c, d)=1.0
240.	V Poor=27	Best=50.2	Best=1.0	V Poor=25	Poor=7	Min(a, b, c, d)=1.0
241.	V Poor=27	P Poor=53	Poor=0.7	Best=2.5	Poor=7	Min(a, b, c, d)=0.7
242.	V Poor=27	P Poor=53	Poor=0.7	Average=7.5	Poor=7	Min(a, b, c, d)=0.7
243.	V Poor=27	P Poor=53	Poor=0.7	Poor=15	Poor=7	Min(a, b, c, d)=0.7
244.	V Poor=27	P Poor=53	Poor=0.7	V Poor=25	Poor=7	Min(a, b, c, d)=0.7
245.	V Poor=27	P Poor=53	Good=0.85	Best=2.5	Poor=7	Min(a, b, c, d)=0.85
246.	V Poor=27	P Poor=53	Good=0.85	Average=7.5	Poor=7	Min(a, b, c, d)=0.85
247.	V Poor=27	P Poor=53	Good=0.85	Poor=15	Poor=7	Min(a, b, c, d)=0.85
248.	V Poor=27	P Poor=53	Good=0.85	V Poor=25	Poor=7	Min(a, b, c, d)=0.85
249.	V Poor=27	P Poor=53	V Good=0.9	Best=2.5	Poor=7	Min(a, b, c, d)=0.9
250.	V Poor=27	P Poor=53	V Good=0.9	Average=7.5	Poor=7	Min(a, b, c, d)=0.9
251.	V Poor=27	P Poor=53	V Good=0.9	Poor=15	Poor=7	Min(a, b, c, d)=0.9
252.	V Poor=27	P Poor=53	V Good=0.9	V Poor=25	Poor=7	Min(a, b, c, d)=0.9
253.	V Poor=27	P Poor=53	Best=1.0	Best=2.5	Poor=7	Min(a, b, c, d)=1.0
254.	V Poor=27	P Poor=53	Best=1.0	Average=7.5	Poor=7	Min(a, b, c, d)=1.0
255.	V Poor=27	P Poor=53	Best=1.0	Poor=15	Poor=7	Min(a, b, c, d)=1.0
256.	V Poor=27	P Poor=53	Best=1.0	V Poor=25	Poor=7	Min(a, b, c, d)=1.0

LIST OF PUBLICATIONS FROM RESEARCH WORK

Science Citation Index (SCI) Papers:

1. Jitender Kaushal and Prasenjit Basak, “Power quality control based on voltage sag/swell, unbalancing, frequency, THD and power factor using artificial neural network in PV integrated AC microgrid”, *Sustainable Energy, Grids and Networks – Elsevier*, vol. 23, pp. 1-23, 2020. **(Impact Factor: 2.532)**
DOI: <https://doi.org/10.1016/j.segan.2020.100365>
2. Jitender Kaushal and Prasenjit Basak, “Power quality control through automated demand side management in microgrid equipped with battery energy storage for protection”, *IET Generation, Transmission & Distribution*, vol. 14, issue 12, pp. 2389-2398, 2020. **(Impact Factor: 2.862)**
DOI: <https://doi.org/10.1049/iet-gtd.2019.1042>
3. Jitender Kaushal and Prasenjit Basak, “A Decision Making Methodology to Assess Power Quality Monitoring Index of an AC Microgrid Using Fuzzy Inference Systems”, *Electrical Power Components and Systems, Taylor & Francis*, vol. 47, issue 14-15, pp. 1349-1361, 2019. **(Impact Factor: 0.824)**
DOI: <https://doi.org/10.1080/15325008.2019.1689448>
4. Jitender Kaushal and Prasenjit Basak, “A Novel Approach for Determination of Power Quality Monitoring Index of an AC Microgrid Using Fuzzy Inference System”, *Iranian Journal of Science and Technology, Transactions of Electrical Engineering, Springer*, vol. 42, issue 4, pp. 429-450, 2018. **(Impact Factor: 0.657)**
DOI: <https://doi.org/10.1007/s40998-018-0087-z>

National/International Conferences and Non-SCI Papers:

1. Jitender Kaushal and Prasenjit Basak, “Frequency control of islanded microgrid using fuzzy-PI and autotuned controllers”, *International Journal of Advances in Applied Sciences (IJAAS)*, vol. 8, issue 1, pp. 64-72, March 2019.
2. Jitender Kaushal and Prasenjit Basak, “A typical layout of microgrid and scope of its industrial application”, *7th India International Conference on Power Electronics (IICPE)*, Patiala, pp. 1-5, 2016.
3. Jitender Kaushal and Prasenjit Basak, “The Deployment of Microgrid as an Emerging Power System in India and its Simulation using Matlab-Simulink”, *International*

Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering, vol. 3, issue 4, pp. 9163-9170, April 2014.

4. Jitender Kaushal and Prasenjit Basak, “Microgrid: An Emerging Power System and its Deployment in Indian Power Scenario”, *TEQIP Sponsored National Conference on Integrated Computational Techniques in Electrical Engineering (ICTEE-2014)*, pp. 1-6, 18-19 January 2014.