Design of Modified Droop Controller and Aggregator for Frequency Support in Microgrid using Electric Vehicles

A Dissertation submitted in fulfillment of the requirements for the Degree

of

Master of Engineering

in

Power Systems

Submitted By

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DECLARATION

I hereby certify that the work which is presented in dissertation entitled, "**Design of Modified Droop Controller and Aggregator for Frequency Support in Microgrid using Electric Vehicles**", in partial fulfillment of the requirements for the award of the degree of **Master of Engineering** in **Power Systems**, submitted to Electrical & Instrumentation Engineering Department of Thapar University, Patiala is as authentic record of my own work carried under the supervision of **Dr. Mukesh Singh**. It refers others researcher's work which are duly listed in the reference section. The matter contained in this dissertation has not been submitted, neither in part nor in full to any other degree to any other university or institute except as reported in text and references.

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It is certified that the above statement made by the student is correct to the best of my knowledge and belief.

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CERTIFICATE

Certified that the dissertation entitled, **"Design of Modified Droop Controller and Aggregator for Frequency Support in Microgrid using Electric Vehicles"**, which is being submitted by Rubi Rana in partial fulfillment of the requirements for the award of the Master of Engineering in Power Systems, to Thapar University, Patiala, is a bona-fide record of the candidate's own work carried out by her under my supervision and guidance. The matter contained in this dissertation has not been submitted, neither in part nor in full to any other university or institute for award of any degree.

Place: Patiala
Date: 13/07/16

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ABSTRACT

Residential, commercial, and industrial sector's dependency on electricity is increasing day by day. However, the generated electricity provided to them is limited which have imposed a lot of burden on existing grids. This increasing load needs to be managed in an efficient manner so as to fulfil the growing demands of electricity of the end users in an uninterrupted, and efficient manner. Hence, rapid demand growth has led to the emergence of distributed energy sources (DES) such as-solar, wind etc. These DES when connected to a low voltage distribution network forms a microgrid (MG). However, the combination of inertial and non-inertial DES leads to various frequency fluctuations in MG.

To cater frequency fluctuations at MG, droop control has been extensively used by academia and industry. This controller generates series of reference signals for various DES based on their respective maximum capacities. The integration of varieties of DES in MG is still debatable amongst researchers. On the same line, Electric Vehicles (EVs) are considered the future for reliable DES, since they have rechargeable batteries. However, due to their random arrival and departure patterns, their capacity varies rapidly. Thus, conventional droop controller cannot dispatch reference signals to EVs. Hence, the need arises to feed back their instantaneous information to droop controller so that they can be utilized in frequency support. For this purpose, conventional droop control has been integrated with a feedback mechanism and is referred as modified droop controller (MDC) in the proposed scheme. With this feedback mechanism, MDC would be now able to dispatch reference signals to both diesel generator and EVs. However, for meeting reference signal given to fleet of EVs, an aggregator (AG) is proposed. AG can alter the charging and discharging rates of EVs' thereby satisfying EVs' needs in terms of battery's state of charge (SoC). Extensive simulations have been done using the proposed scheme on data available from Santa Rita Jails' MG.

Keywords: *Charging station, Distributed energy sources, Electric vehicles, Droop based controller and Microgrid*

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LIST OF SYMBOLS

C_i^{rate}	Charging rate of i^{th} electric vehicle's battery.
D_i^{rate}	Discharging rate of i^{th} electric vehicle's battery.
E_i^{req}	Amount of energy either required or available with the i^{th} electric vehicle for charging and discharging respectively.
E_i^{rem}	Remaining amount of energy either required or available with the i^{th} electric vehicle for charging and discharging respectively.
E^{rated}	Rated capacity of electric vehicle's battery.
Δf	Change in frequency.
$f_{nominal}$	The rated frequency.
k	Droop coefficient.
N_{char}	Number of Electric vehicles seeking charging.
M	Inertia constant.
N_{dis}	Number of Electric vehicles seeking discharging.
P_{dg}	Amount of power generated by diesel generator.
P_{dg}^{max}	The maximum capacity of diesel generator.
P_{EV}^{char}	The power required by EVs seeking charging.
P_{EV}^{dis}	The power available from EVs seeking discharging.
P_{EV}^{tot}	Cumulative power available from EVs.
P_{PV}^{max}	The maximum capacity of photovoltaic source.
$P_{net\_ref}^{AG}$	The net power given by aggregator.
$P_{net\_ref}^{dg}$	The net power given by diesel generator.
P_{ref}^{dg}	Power reference signal for diesel generator.
P_{ref}^{AG}	Power reference signal for aggregator.
SoC_i^{exp}	Expected state of charge of the i^{th} electric vehicle battery.
SoC_i^{in}	Initial state of charge of i^{th} electric vehicle.
SoC_i^{met}	State of charge met by i^{th} electric vehicle.
SoC_i^{rem}	State of charge remaining of i^{th} electric vehicle.
T_i^{char}	Time duration during which i^{th} electric vehicle seeks charging upto the expected state of charge.
T_i^{dis}	Time duration during which i^{th} electric vehicle seeks discharging upto the expected state of charge.

LIST OF ABBREVIATIONS

AG	Aggregator
CS	Charging station
DES	Distributed energy sources
DG	Distributed generation
DGC	Diesel generator controller
EV	Electric vehicle
MG	Micro Grid
MDC	Modified droop controller
PVC	Photovoltaic controller
WTC	Wind turbine controller
SoC	State of charge
V2G	Vehicle-to-Grid

Chapter 1

INTRODUCTION

Electricity is the backbone of each modern societies, growing economies, and technological developments. It has become a necessity of modern life, and its demand is increasing at a rapid pace. The increased dependence of the developed, and developing countries on continuous power supply with respect to various sectors such as-electronics, agriculture, IT, industrial production etc., makes today's society much more dependent on electricity. It is supplied via an interconnected network of power plants, substations, and transformers. These interconnected networks which carry electricity straight from power plants to consumers are called electric grids. However, conventional electric grids follows centralized power generation approach. In this approach, electricity is to be transmitted over long distances. In addition to this, the conventional electric grids suffer from frequent power failures, load shedding, power supply interruptions, and environmental issues. These concerns and rapid energy growth, lead to the shifting from centralized power generation towards distributed generation (DG) [1]. The DG includes both renewable and non-renewable energy sources such as-diesel generator, PV, and wind. However, to provide a reliable integration of these distributed energy sources (DES), the concept of microgrids (MGs) has been introduced [2].

1.1 Microgrid

The MG can be defined as small power system which incorporates DES along with power electronic interfaces and control. Moreover, the International electrotechnical commission (IEC) 62257-

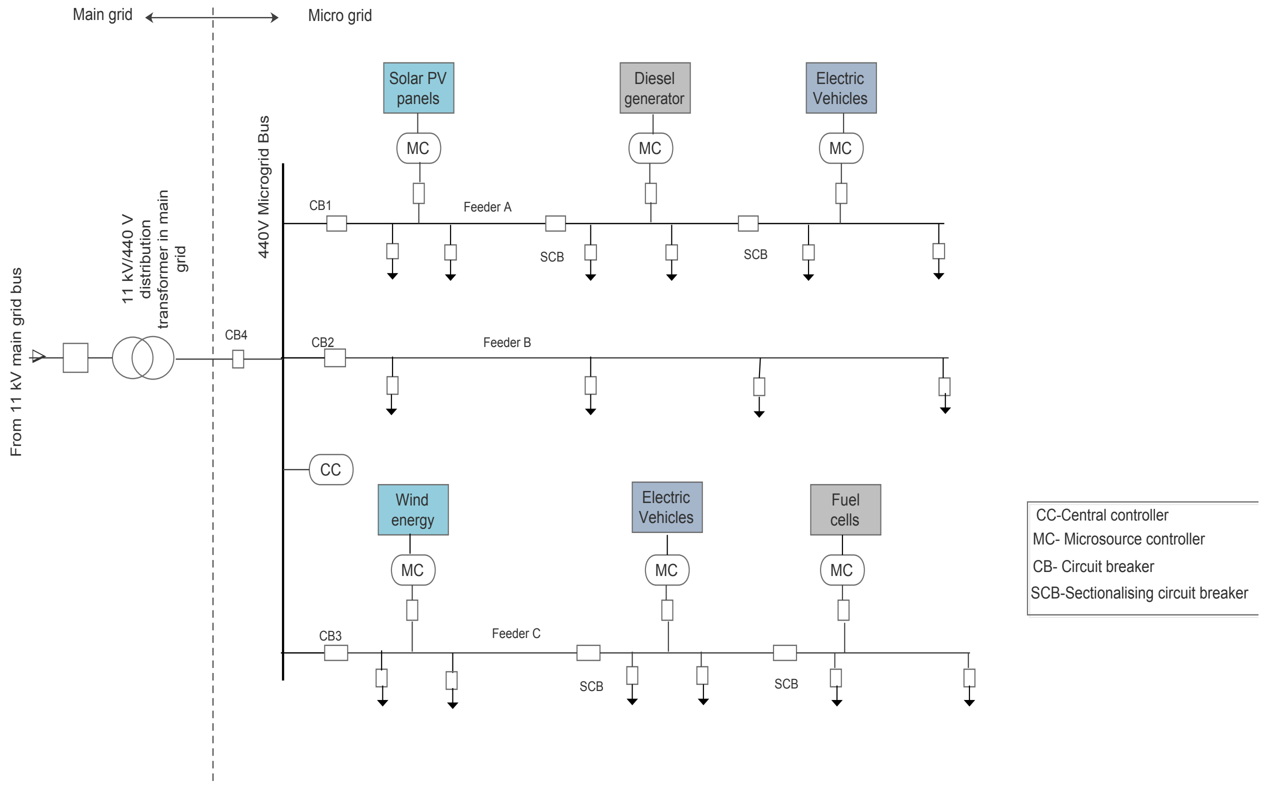

Figure 1.1: Microgrid

9 defines MG as low-voltage distribution power systems with voltage levels such as-400V for three phase and 230V for single phase. The MG can operate in two modes such as-grid connected or islanded mode [3]. As shown in the figure (1.1), CB_4 acts as switch which is used to disconnect and connect the MG with the main grid. In the grid connected mode MG is connected to main grid and most of the system kinetics such as-voltage and frequency fluctuations are handled by the main grid. However, in the islanded mode, MG is responsible for maintaining the desired voltage and frequency levels [4]. Nevertheless, the varying capacity of DES leads to higher frequency fluctuations in the islanded mode than grid connected mode. Thus, frequency regulation needs to be done for ensuring MG stability for maintaining the balance between demand and supply. For this purpose, various controllers are needed in MG, figure (1.1) depicts that the each microsource has its own controller named as microcontroller (MC). This controller will collect infromation from microsources and dispatch it to central controller (CC) .

1.2 Issues in Microgrid

Microgrid have several technical issues as mention below.

- Voltage and frequency control

  For an electric grid, active and reactive power component of generated power should be in balanced condition with the power consumed by the loads and losses in the lines. The unbalance condition arises when there is mismatch between power generated and power demanded. This condition causes deviation in system frequency from its nominal frequency i.e., (50 Hz). Thus, there arises need to control these deviations which is called frequency control. Hence, the task of voltage and frequency control is to mitigate the deviations and ensuring both voltage and frequency within their nominal values. This can be achieved by adjusting active and reactive power. However, in MG there are various distributed generation resources due to which active and reactive power control fails. Therefore, in order to regulate the voltage and frequency droop controller is preferable. Thus, each distributed generation is equipped with the power frequency and power voltage droop characteristic during islanded operation.

- Islanding

  Islanding is basically represented as a small scale unit of the future interconnected grid. It consists of combination of various distributed generation resources. In autonomous mode, control strategies for islanding plays a very important role for proper functioning of a MG. There are two kinds of strategies utilized to operate an inverter in islanding mode. The first one is PQ inverter control which is used to supply a given active and reactive power set point. The second one is voltage source inverter (VSI) control. In this control load is fed with predefined nominal values for voltage and frequency. Thus, in VSI real and active power output depends on load conditions. It is acting as a voltage source with respect to magnitude and it controls the frequency of the output voltage through droop.

- Protection

  Protection is the one of the important challenge being faced in the implementation of MGs. After the implementation of MG, next step is to ensure the protection of loads, lines and the distributed generation resources. In order to protect the MG and line currents the two current limiting algorithms exist. These algorithms are named as resistance-inductance feedforward and flux charge-model feedback algorithms. These are use with a voltage source inverter (VSI) connected in series between the MG and main grids.

However, the main technical issue that MGs faces is the active power balancing, which affects the system frequency. Frequency fluctuations arise due to supply and demand variations. These fluctuations if not regulated properly, may cause series of undesirable events leading to blackouts. Two blackouts on consecutive days (30th and 31st July, 2012) have occurred due to the increase in frequency which leads to over drawl of power, overloading the transmission lines and hence leads to severe contingencies. So, frequency can be visualized as the pulse of MG which helps in estimating its overall health conditions. Hence, in this work frequency regulation is explored.

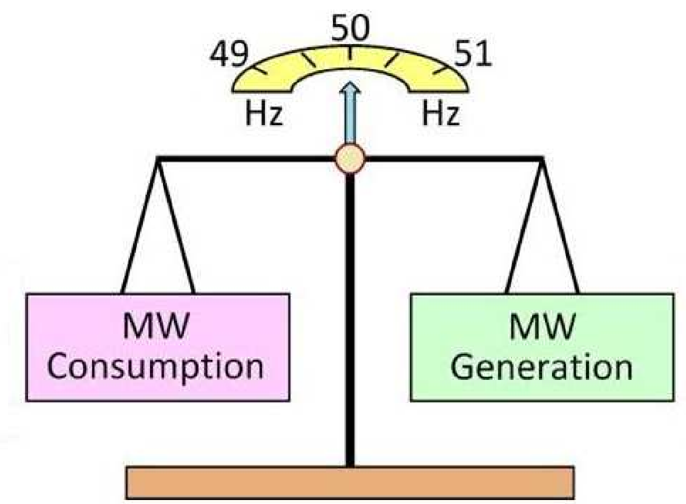

Figure 1.2: Frequency fluctuations

1.3 Background details

1.3.1 Electric Vehicles

Electric vehicles (EVs) referred to automobiles are driven by electric motors. The propulsion in EVs is provided by batteries which store electrical energy making them an important component. These vehicles are available in the market with different models and varying ranges and capabilities, and are recharged using electrical power. EVs can be of two types. One of them is vehicles which solely depend on electric power to recharge their batteries. These vehicles are referred as battery electric vehicles. Another is plug-in hybrid electric vehicles (PHEV) which can operate both on electric energy and internal combustion engine. For a certain distance it is driven on energy stored in battery and after then internal combustion engine is utilized to offer additional range. EVs batteries are recharged at a charging station through connection links called as Electric Vehicle Supply Equipment (EVSE). This equipment ensures safe charging by acting as a protective system by communicating with the vehicle and monitors electrical activity. There are two primary types of EVSE:

- Alternating current (AC) EVSE
  In AC EVSE, the transfer of AC power from the electric grid, takes place through the EVSE. Whereas, the transfer of electric power into the vehicle takes place through the industry standard J1772 port connector. In this type AC power is rectified within the vehicle to controlled direct current (DC) with the utilization of charger electronics.

- Direct current (DC) fast charging EVSE.
  Fast charging DC EVSE inverts AC to DC power off-board the vehicle and delivers high voltage direct current (typically over 400 V) straight to an electric vehicle's battery system.

Apart from this, charging power of EVSE is segregated into three levels:

- LEVEL 1- This type of level is the simplest form of charging. It uses a voltage level of 120V and it is connected to a standard residential/commercial outlet. The outlet is capable of supplying 15-20 amps of current. Moreover, it draws a power of around 1.4 kW when charging.

- LEVEL 2- This type of charging utilizes a 208/240V AC power connection. Here, charging time required by EVs batteries to charge themselves is very less. Either voltage works well for Level 2 charging. For this type of charging, J1772 standard connector is used by most EVs. It can theoretically provide up to 80 amps of current and 19.2 kW of power. However, out of 80 amps most EVs only use up to 30 amps for 3.3 to 6.6 kW charging.

- DC FAST CHARGING- This type of charging is also referred to as Level 3 charging. This type of DC EVSE is used when there is requirement of rapid charging. It basically delivers high power directly into an EV's battery system.

Various manufactures have developed connectors for fast charging equipment as mentioned below.

- CHAdeMO used by Nissan, Mitsubishi and Kia;
- SAE Combo used by American and European makes, such as Chevrolet, BMW and Mercedes-Benz; and
- Tesla's Supercharger is used exclusively on Tesla Model S. In addition to this, tesla has also manufactured an adapter. This adapter allows to use CHAdeMO equipment.

1.3.2 Vehicle to grid

EVs are treated as a highly flexible loads and their batteries can be used by the grid as an additional power source [10].

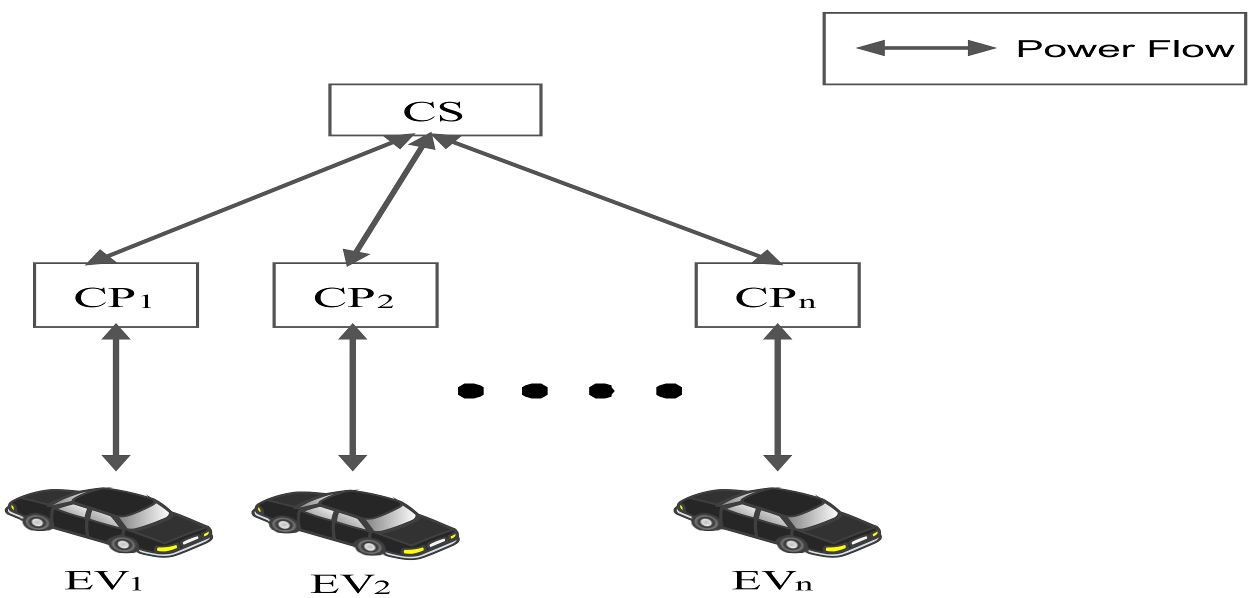

Figure 1.3: Power flow from EVs to CS

They can either deliver power to grid or withdraws power from it. Thus, allowing bidirectional flow of power with grid and leading to the concept of vehicle-to-grid (V2G). Fig. (1.3), clearly

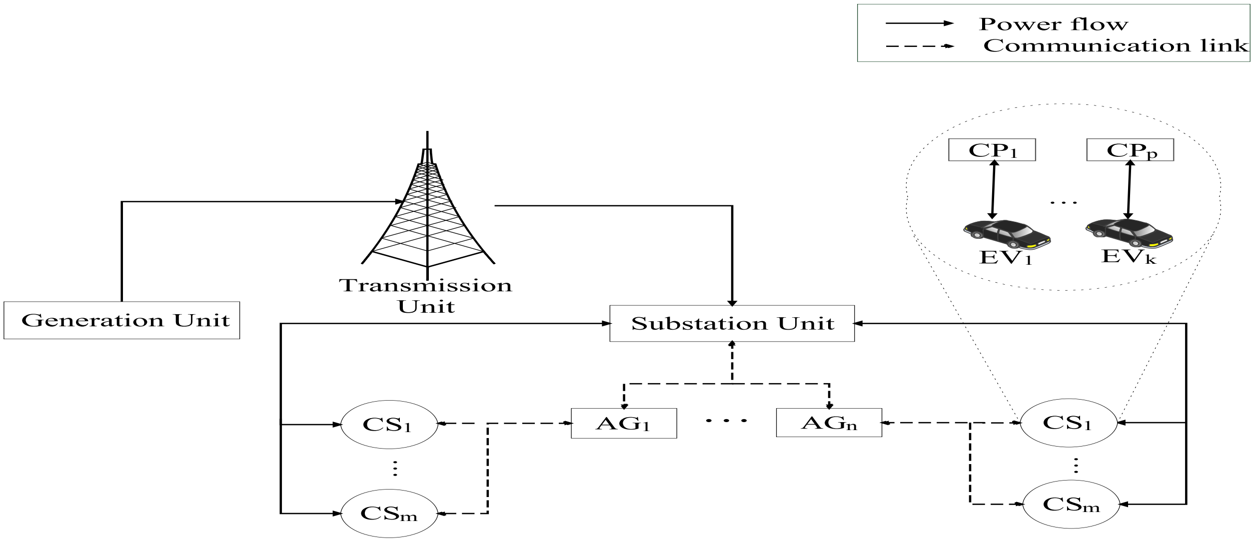

Figure 1.4: Power flow from CS to grid.

depicts the bidirectional flow of power from EVs to charging station (CS). It comprise of charging points (CPs) for charging, and discharging of EVs' batteries. Further the transfer of power form EVs batteries to grid is done at CS level. CS is connected to substation unit and aggregators (AGs) as shown in Fig. (1.4). These AGs play a crucial role in controlling the power exchange between the CSs, and the substation unit. Hence, AGs support bi-directional mode of communication, whereas, CSs provide bi-directional flow of power. This bidirectional flow of power and the future implementation of V2G is bound to support numerous services at grid level such as-peak shaving, valley filling, spinning reserve and regulation. Peak shaving is a strategy used for managing the high demand on grid, whereas valley filling deals with managing the low demand under high supply. In spinning reserve, EVs are not kept spinning unlike traditional generators. They can react fastly to contingencies and have capabilities to provide power within a fraction of seconds when requested. In regulation, EVs can actively participate and are best suited to provide regulation power because of the reasons mentioned below.

- EVs batteries response rate towards imbalances is much faster than conventional generators. Ihey can respond instantaneously to changes in the regulation request received form grid.

- EVs can participate in the regulation in various scenarios. For example, if grid do not allow back-feeding of power i.e., discharging the batteries and providing power back to the grid. In such case, EVs batteries charging rate is altered so as to manage the regulation request.

1.3.3 Frequency regulation

Frequency regulation is basically done in order to keep the frequency near to the nominal frequency i.e (50 Hz). If load exceeds generation then the frequency rises above the nominal frequency. If generation exceeds load then frequency drops below the nominal frequency. Hence to make the frequency same throughout the grid there should be balance between the load and generation. Frequency regulation is achieved at two levels primary regulation and secondary regulation. Primary regulation is not responsible for restoring frequency. It just captures frequency deviations based on generators governor response towards changes in rotor speed. Secondary regulation rely on automatic generation control to brings the system frequency back to the nominal.

Frequency regulations can be achieved using two strategies, i.e., regulation up (R_u) and regulation down (R_d). R_u is provided during deficit power supply and high demand. On the other hand, R_d is provided when, supply is more than the demand. Normally, R_u and R_d are achieved by employing generators, which increase or decrease their production in order to match with the demand [5]. Unfortunately, they have several inherent issues such as-prolonged start-up time, emission of harmful gases and inadequate response towards huge frequency deviations [6]. Due to these reasons, it becomes harder to manage frequency variations instantly and effectively.
Evolutions in MG domain have led to the emergence of another powerful technology, i.e., vehicle-to-grid (V2G). V2G refers to bi-directional flow of energy between electric vehicles (EVs) and MG. Decentralized and regulated energy exchanges with EVs at varying loads, may help MGs to regulate their frequency fluctuations to a great extent [7]. Moreover, V2G technology may support MGs in many ways such as-peak shaving, valley filling and several ancillary services [8]

Frequency regulation can also be achieved in MG environment using battery energy storage system (BESS) [9]. However, the major drawback of these systems is, they impose severe economic burden in terms of installation and maintenance costs [9, 10]. Hence, their utilization may not prove to be beneficial for the service providers in the long run. Thus, an alternative mechanism is required that not only supports frequency but is economical too. Therefore, use of EVs is one such solution which may cater these requirements, since they have re-chargeable batteries and act as distributed energy sources (DESs). Thus, EVs can instantly re-balance frequency deviations by either supplying, or withdrawing energy from the SG [7, 11]. Furthermore, use of EVs for supporting various ancillary services is more cost effective as the service providers need not to bear any installation and maintenance cost, unlike BESS and flywheels. In addition to this, EVs remain idle for almost 96% of their time which provides wider prospects to efficiently utilize them for frequency support [12].

1.3.4 Droop control

The droop control method is generally applied to generators to permit their parallel operations. It allows primary frequency, and voltage control of the generators by the control of active, and reactive powers.

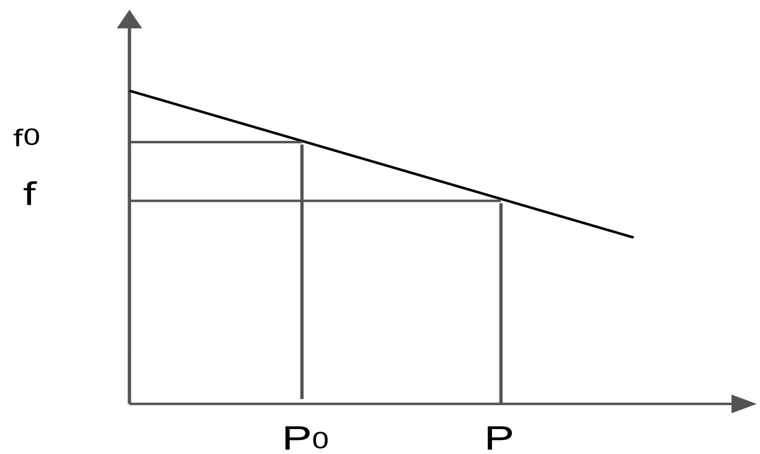

Figure 1.5: P-f droop characteristics

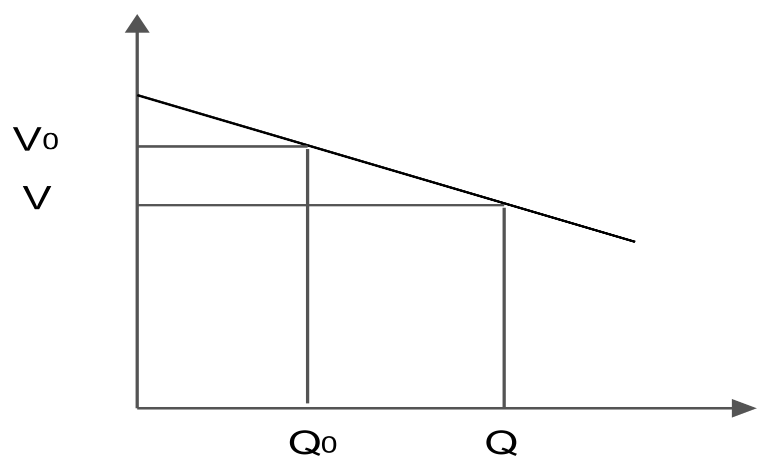

Figure 1.6: Q-V droop characteristics

$$P = V_1 * V_2 sin\delta \tag{1.1}$$

$$Q = (V_2/X)(V_2 - V_1 cos\delta) \tag{1.2}$$

where, P, and Q are the active, and reactive powers, respectively. V1, and V2 are the voltages at the sending, and receiving ends, respectively. X is the line reactance, and d is the power angle.

Since the power angle d is a very small quantity, thus, cosd=1 and sind=d. Thus, moreover, standard swing equation illustrates that frequency is proportional to the power angle.

$$\delta = PX/(V_1 * V_2) \tag{1.3}$$

$$V_2 - V_1 = QX/(V_1 * V_2) \tag{1.4}$$

Hence, by controlling the active, and reactive powers, the power angle or frequency, and the voltage, respectively can be controlled. Thus leading to the equations mentioned below.

$$f = f_0 - K_p(P - P_0) \tag{1.5}$$

$$v = v_0 - K_p(Q - Q_0) \tag{1.6}$$

The above equations and figures (1.5) and (1.6) illustrates the fact that when the frequency falls from f_0 to f , the generator's active power is allowed to increase from P_0 to P. Similarly, a drop in the voltage from V_0 to V increases the reactive power from Q_0 to Q.

1.4 Literature Survey

Various researchers have explored the frequency regulation using different types of DES. Watson and Jonathan [13] described a system which utilized solar power for voltage and frequency regulation. However, the intermittency linked with solar power makes this method inefficient in handling frequency and voltage fluctuations. Bunker and Weaver [14] proposed a control system which utilized wind energy for frequency regulation in islanded MG. Unfortunately, the intermittent and unpredictable nature of wind makes this scheme inefficient. Hence, weather dependent sources are not used alone for balancing frequency fluctuations.

Yoo and Kim [15] regulated frequency using battery storage system. Similarly, Guo *et al.* [16] utilizes batteries for regulating frequency of MG. Arghandeh *et al.* [17] developed a tool to demonstrate the use of flywheel storage units for serving loads in MG environment. However, the major disadvantage of these storage systems was their high installation and maintenance costs. Hence, the energy storage units must be economical so that they can be used extensively in MG.However, the major disadvantage of battery storage systems is their installation, and maintenance costs. Hence, considering the economic front they may put severe burden on utilities in the long run. Therefore, an alternative mechanism needs to be developed to re-balance the demand and supply gap, and restore MG's frequency to its nominal value. Thus, the use of EVs' batteries can be a promising solution to cater these frequency fluctuations instantly, since they provide fast response. EVs are treated as highly flexible loads, whose batteries can be used by the grid as an additional power source whenever required. Thereby, leading to the emergence of vehicle-to-grid (V2G) technology. The implementation of V2G may support many services of MG. However, one of the most important application of V2G is to support frequency regulation services. When there is drop in MG frequency, EVs supply power back to the MG thus stabilizing frequency of MG. On the other hand, when the frequency increases, EVs could absorb the power from the MG. This type of V2G control has been noted to be well suited for providing regulation services [18].

Number of researchers have explored frequency regulation in V2G environment. Kempton, and Tomic [11] suggested that EVs can be utilized in V2G infrastructure for frequency regulation, since they have fast battery response, thereby, stabilizing frequency instantly. Pilaai, and Jensen [19] developed an aggregated EV-based storage system for western Danish power system for regulating frequency fluctuations instantaneously. Unfortunately, their approach neglected the control of individual EVs. Dallinger *et al.* [20] evaluated the impact of EV's uncertain mobility patterns for providing regulation. Wu *et al.* [21] proposed a new game-theoretical model to interpret the correlations amongst EVs, and aggregators in a V2G infrastructure. Sortomme, and El-Sharkawi [22] proposed an algorithm to maximize aggregator's profit.

White, and Zhang [23] extended the Kempton's model [11], and proposed that EVs can be used for multiple purposes, i.e., frequency regulation, and peak load reduction simultaneously. The authors proposed that EVs could be used for frequency regulation on a daily basis, and can be used for peak reduction during high demands. Ota *et al*. [24] implemented an autonomous distributed V2G control scheme, which controlled EV's power with respect to frequency deviations detected at the time of EV's plug in. However, their work neglected dynamic characteristics of EV's battery, and considered the linear relationship between EV's power, and frequency fluctuations.

Han, and Han [25] suggested that prospective income is linked with EV's involvement in V2G frequency regulation. Moreover, the authors also estimated this income, and compared it with the battery's current price. Their results demonstrated EV's integration for frequency regulation is an economically perspective solution. Similarly, Brooks also suggested that integration of EVs with grid is feasible, and has potential to create income for the EV's users [26]. However, the author did not present the actual magnitude of regulation power that would be dispatched to EVs by grid. Sekyong *et al.* [27] proposed an aggregator that utilized EVs' distributed power. The authors also inspected optimal charging, and discharging strategies keeping into account battery's constraints.

Yang *et al.* [28] proposed a dynamic model for frequency regulation keeping into account battery's charging, and discharging characteristics. However, their model depicted limited communication between neighboring EVs, and distribution substations. Shimizu *et al.* [9] proposed a model for EV's integration in V2G scenario for frequency regulation. In this model, charging, and discharging of participating EVs was regulated based on load frequency control (LFC) signals. However, the major shortcoming of this model was, it did not cater simultaneously EVs' charging, and discharging needs. In other words, it neglected EVs' individual requirements, and was strictly a grid based approach. Kamboj *et al.* [29] presented an implementation of a multi-agent system that allowed EVs to participate in the frequency regulation market. Although, their system supported both charging, and discharging requirements of EVs but failed to regulate EV's charging, and discharging rates. Janfeshan *et al.* [30] designed a distributed fuzzy logic controller (FLC) for frequency regulation in V2G. This controller managed the EVs' discharging on the basis of regulation demand, and EVs' state of charge (SoC). However, it completely neglected EVs' charging activities for frequency regulation. Moreover, use of FLC seems to a bit inappropriate since fuzzy control methods was ideal for trivial problems which don't require high accuracy.

Frequency regulation is acknowledged significantly by many authors at grid level. Similarly, various control techniques have been proposed at MG level. Manjarres and Malik [31] proposed a fuzzy logic controller for frequency regulation by involving combined operation of wind generator, battery storage systems and dump load. However, fuzzy logic implementations have linguistic representation which may lead to uncertainties. Xia *et al.* [32] utilises master slave grid control method for MG in islanding mode. Unfortunately master-slave control has dependency on critical inter-communication lines which could reduce system reliability and expendability. Therefore, droop method comes out to be best alternative [33]. Katiraei and Iravani [34] proposed power management strategies for a MG based on droop characteristics. However, their strategy is only applicable to electronically interfaced fast acting, dispatchable sources. Bevrani and Shokoohi, [35] proposes adaptive neuro-fuzzy inference systems based on generalized droop controller. Clara *et al.* [36] utilized EV's battery for managing the frequency in MG using droop controller. However, it neglected the battery parameter such as- State of Charge (SoC), charging and discharging rates. Li *et al.* [37] proposed a dual droop based coordinated strategy in V2G scenario for regulating power fluctuations. This scheme considered both charging and discharging activities but it did not regulate EVs' charging and discharging rates. Liu *et al.* [38] proposed a V2G control scheme, which focuses on regulating EVs' power based on frequency deviations. However, this scheme did not consider the time required for meeting the expected SoC of the EVs. Thus, energy requirements of the EVs remain unfulfilled to a greater extent. Usunariz *et al.* [39] modified the existing droop control scheme by adding a proportional controller for efficient power sharing among DES. In addition to this, the authors utilized battery storage systems for managing the frequency deviations at MG. However, such approach fail to manage the SoC levels of battery storage units.

1.5 Research Gap

Residential, commercial, and industrial sector's dependency on electricity is increasing day by day. However, the generated electricity provided to them is limited which causes a gap between the supply, and the demand. This gap leads to frequency fluctuations.These fluctuations can be efficiently managed with the help of controllable DES. From the above discussions, the use of DES in MG for managing frequency is done extensively [13]- [17]. However, utilizing fleet of EVs as a DES in MG is less explored in the literature. EVs can be utilized as a flexible DES due to their expected penetration in upcoming future. Their batteries are regarded as mobile energy storage devices and can actively participate in frequency support.

Hence, in the proposed scheme, EVs along with other DES are utilized. In addition to this, various researchers have used droop controller scheme for managing the frequency at MG [33], [34], [36], [37]. Unfortunately, the droop controller is found to be suitable for DES whose maximum power rating is known. Due to this, utilization of fleet of EVs becomes a complex task. Since their uncertain arrival and departure patterns results in varying maximum capacity. Thus, need arises to feed back their instantaneous information to the controller so that they can be utilized in frequency support. Therefore, the conventional droop controller needs to be upgraded with a feedback mechanism so as to provide instantaneous system information for efficient frequency control at the MG.

Therefore, this work focuses on an efficient control scheme which would utilizes coordinated working of a modified droop controller (MDC) and aggregator (AG). MDC is basically a droop controller having a feedback mechanism which can continuously monitor and control the reference signals. Thus, it helps in achieving both primary and secondary frequency regulation. Moreover, the proposed AG controls the charging and discharging rates of EVs' batteries which is not considered so far for a MG.

1.6 Contributions

Hence, the major contributions of this work are summarized as follows.

- Unlike conventional droop controller, the proposed MDC takes instantaneous power available from the fleet of EVs and dispatch the reference signals to both diesel generator and EVs.

- An aggregator have been modeled, which coordinates the fleet of EVs thus ensuring frequency support at MG.

- The proposed scheme alters the charging and discharging rates of EVs utilized in MG unlike other schemes [39] thereby enhancing the flexibility of scheme.

- The proposed scheme takes care of users convenience by fulfilling EVs expected SoC requirement.

Chapter 2

SYSTEM FRAMEWORK

The proposed system depicted in Fig. 2.1 comprises of MG which integrates photovoltaic, diesel generator and wind power-based unit. Moreover, it also comprises of charging station and the proposed Modified droop controller (MDC). The proposed controller helps in proper coordination and synchronization of various units being considered here. Moreover, it helps in frequency stabilization of MG. The detailed description about the proposed system is given below.

2.0.1 Photovoltaic unit

This unit consists of photovoltaic array, and photovoltaic controller (PVC). This controller dispatches information regarding the status of a photovoltaic array to MDC. Moreover, it controls the device either by turning on and off or by restricting the amount of power it is producing. In addition to this, it can automatically disconnect and reconnect the photovoltaic array and inverter depending on the control strategy given by droop based controller. The inverter is used which converts the D.C power generated by the photovoltaic array into A.C power in order to fed the power directly to the MG.

2.0.2 Diesel Generator Unit

This unit consists of diesel generator and diesel generator (DG) controller. It is the generator control and monitoring system which provides information about the status of a prime-power generator to the MDC. Moreover, it can control the starting and stopping of the diesel generator. However,

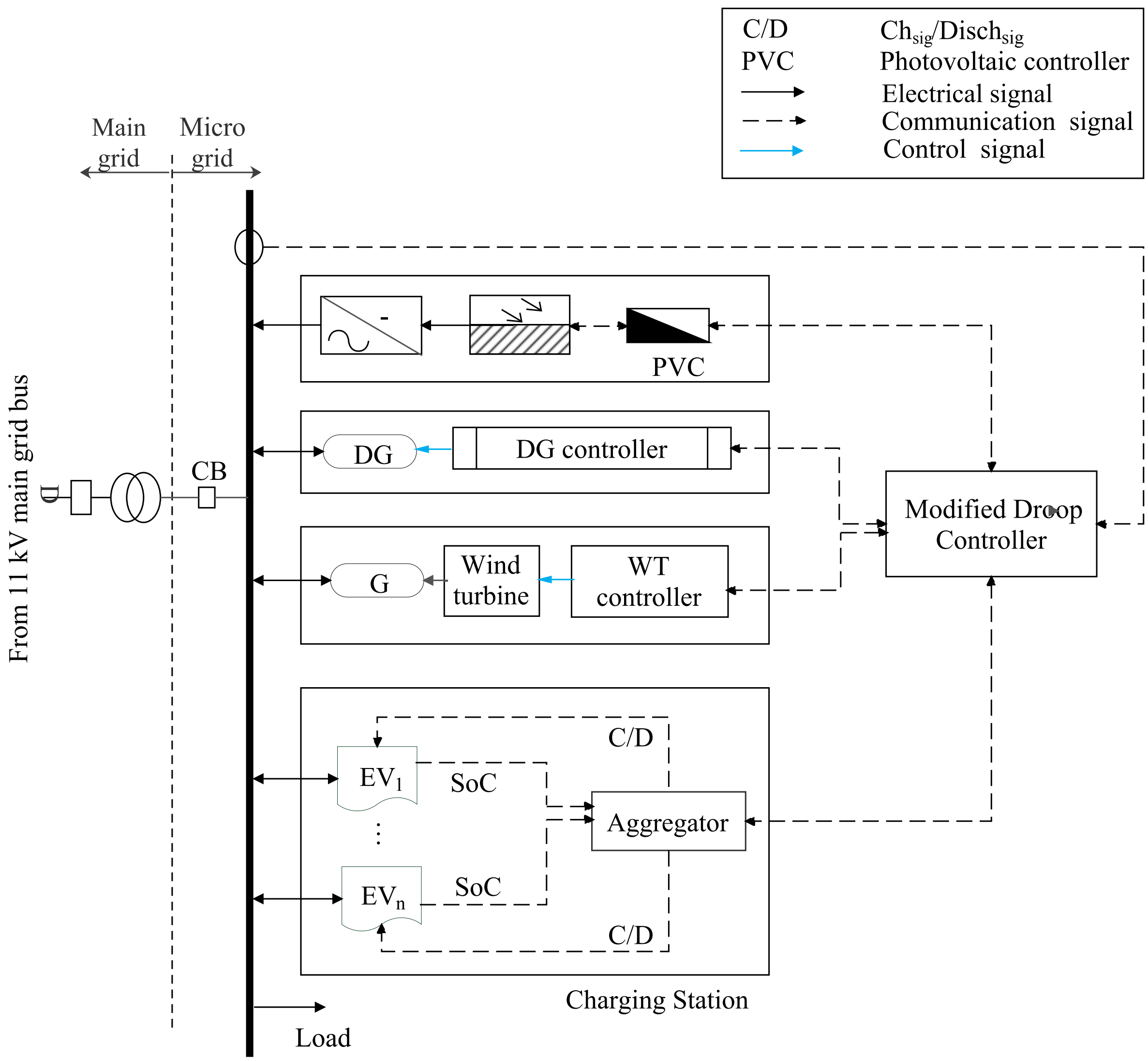

Figure 2.1: System framework of the proposed scheme.

this controller does not affect the speed and voltage setpoint of the generator. This task is primarily carried out by the MDC.

2.0.3 Wind power-based unit

This unit consists of wind turbine, wind generator and wind turbine (WT) controller. The controller is the wind turbine control and monitoring system which provides information about the status of a wind turbine to MDC.

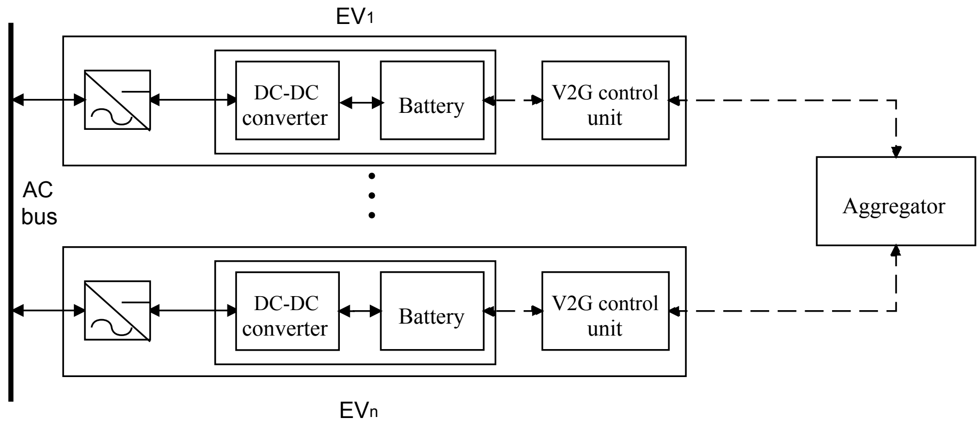

Figure 2.2: Interaction of EVs and aggregator at charging station.

2.0.4 Charging Station

As depicted in Fig. 2.2 charging station (CS) consists of electric vehicles (EVs), and aggregator (AG). Further, the AG is the main regulatory part of the unit which communicates with droop based controller and gives out charge and discharge control signals to the EVs via V2G control unit. A detailed description of individual components of CS in the proposed system is given below.

Electric Vehicles

The internal components of EV as shown in Fig. 2.2 consists of communication module V2G control unit and battery. The communication module allows communication with CP. It helps in communicating SoC, and charging and discharging rates among CP and EVs V2G control unit. This unit further helps in controlling charging and discharging rates of EV's battery.

Aggregator

The aggregator (AG) is responsible for communicating with both the droop based controller and EVs at charging stations. AG gives the information regarding maximum available power from EVs to droop based controller. The controller in turns gives the power reference signals to AG. Thus AG supports bi-directional mode of communication between EVs and controller. Moreover, AG monitors expected state of charge, initial state of charge, plug out and plug-in time of each EV. According to this information AG computes the available power from each EV at a particular instant of time. The AG Apart from this, also computes charging and discharging rates of EV.

2.0.5 Modified Droop Controller

The droop based controller monitors and controls the data obtained from MG local controllers such as- wind turbine controller (WTC), Photovoltaic controller (PVC), Diesel Generator controller (DGC) and AG. Additionally, controller keeps track of load and frequency deviations at Ac bus. According to these deviations and data obtained from local controllers, MDC give the reference power signal to DG controller and AG. The DG controller relay the corresponding reference power signal to Diesel generator. Nevertheless the AG divide the power reference signal dispatched by MDC to EVs available at charging station. Hence, AG is responsible for communicating with both the MDC and EVs at charging station. Hence the controller controls the integration of various energy sources thus helping grid to meet power requirements along with maintaining the overall grid stability.

2.1 Working of the proposed scheme

The proposed system is depicted in Fig. 2.1. It comprises of a MG integrated with photovoltaic, diesel generator and wind power based unit. These units consists of local controllers such as- photovoltaic controller (PVC), diesel generator (DG) controller and wind turbine (WT) controller respectively. These controllers gives the information regarding the power availability at its respective units to proposed MDC. In addition to it, the proposed system also comprises of charging station (CS). The information regarding State of Charge (SoC) of EVs at CS is given to aggregator (AG). It utilizes SoC to calculate power availability from EVs and consecutively gives it to MDC. Thus, MDC monitors and controls the data obtained from various local controllers and AG. It also keeps track of load and frequency data at the AC bus. However, if it senses any fluctuations at the bus it gives out reference power signal to both DG controller and AG.

AG utilizes this reference signal to compute charging and discharging rates for individual EVs. These charging and discharging rates are then given to V2G control unit as depicted in Fig. 2.2. This unit helps in relaying control signals to EVs' batteries by altering their charging and discharging rates. Further, according to these altered rates EVs' batteries either delivers power to MG or withdraws power from MG. Thus, allowing bi-directional flow of power through the inverter.

Chapter 3

PROBLEM FORMULATION

This section highlights the overall mathematical model for deducing the power required for stabilizing the frequency fluctuations. Frequency fluctuations possess significant problems for power systems and are primarily caused due to imbalances between load and generation. Standard swing equation is used to model these imbalances [5] as follows.

$$P_{mech} - P_{elec} = M\frac{\Delta\omega}{\Delta t} \tag{3.1}$$

where P_{mech} and P_{elec} represent mechanical power of the turbine and electrical power output of the generator respectively. M is an inertia constant and ω denotes the angular speed of generator's rotor as expressed in (3.2). Substituting the value of ω in (3.1) redefines it to (3.3).

$$\omega = 2\pi f \tag{3.2}$$

$$P_{mech} - P_{elec} = M2\pi\partial f/\partial t \tag{3.3}$$

Equation (3.3) relates power imbalances with frequency (f) variations. Hence, frequency can be considered as an actual measure for these imbalances. They can be managed by various frequency regulation techniques. Normally, frequency regulation is achieved with the help of generators at two levels, i.e., primary and secondary. Primary frequency regulation responds to frequency deviations by altering governor's speed and controlling the valves for steam flow. The regulated steam flow further controls P_{mech} with an intent of matching P_{elec} to load fluctuations (P_{load}). The following equation represents the correlation for the same.

$$\Delta P_{elec} = \Delta P_{load} \tag{3.4}$$

These imbalances are regulated by adjusting turbine's P_{mech}, which can be expressed using the below equation.

$$\Delta P_{mech} = \Delta P_{load} + \frac{dW_k}{dt} + P_{load}^{old} \tag{3.5}$$

W_k denotes the stored kinetic energy in generator's rotor and P_{load}^{old} is the old load on this generator. The rate of increase in W_k can be determined as follows.

$$W_k = W_{k_0} \left(\frac{f_0 + \Delta f}{f_0} \right)^2 \tag{3.6}$$

where W_{k_0} denotes rotor's kinetic energy at nominal frequency (f_0) and Δf represents frequency changes. The rate of change of W_k is given by,

$$\frac{dW_k}{dt} = \frac{2W_{k_0}}{f_0} \left(\frac{d\Delta f}{dt} \right) \tag{3.7}$$

P_{load}^{old} has a dependency on frequency and is mentioned using the given equation.

$$D = \frac{\partial P_{load}^{old}}{\partial f} \tag{3.8}$$

In the above equation, D represents the change in P_{load}^{old} with respect change in f. Now, rewriting (3.5) using (3.7) and (3.8) as follows.

$$\Delta P_{mech} - \Delta P_{load} = \frac{2W_{k_0}}{f_0} \frac{d\Delta f}{dt} + D.\Delta f \tag{3.9}$$

Converting the above equation into per unit format as mentioned below.

$$\Delta P_{mech} - \Delta P_{load} = \frac{2H}{f_0} \frac{d\Delta f}{dt} + D.\Delta f \tag{3.10}$$

where H is the per unit inertia constant and it is given by,

$$H = \frac{2W_{k_0}}{G_{rated}} \tag{3.11}$$

These deviations are very common in small and large power systems. In small power systems, the frequency deviations ranges from 2 to 3 % from the nominal frequency [40]. However, the large power system are adversely affected even due to minor frequency deviations. Hence, frequency fluctuations are significant problems in power systems and are primarily caused due to imbalances between load and generation. In the proposed scheme, these fluctuations are regulated by involving both diesel generator and fleet of EVs. In addition to this in the proposed scheme various DES are also used. Hence, in order to achieve effective coordination among DES and EVs, MDC and aggregator have been proposed.

3.1 Modified Droop Controller

The working of the proposed MDC is depicted in Fig. 3.1 and also elaborated in algorithm 1. Initially, MDC receives information regarding amount of power generated from PV (P_{PV}), wind (P_{wind}), diesel generator (P_{dg}), and cumulative power available from EVs (P_{EV}^{tot}) as computed in upcoming section 3.2. With this information, MDC calculates total power from all the sources (P_{tot}) as given by,

$$P_{tot} = P_{wind} + P_{PV} + P_{dg} + P_{EV}^{tot} \tag{3.12}$$

MDC keeps track of load (P_{load}) at MG and continuously compares it with P_{tot}. If P_{load} becomes greater than P_{tot}, then frequency drops below its nominal value (f_{nom}). Thus, giving rise to negative frequency deviations. On the other hand, if P_{load} becomes less than P_{tot}, then frequency rises above f_{nom} causing positive deviations. These deviations (Δf) can be determined using below mentioned equation.

$$\Delta f = -\left(\frac{P_{load} - P_{tot}}{\frac{P_{max}^{dg}}{k*f_{nom}} + \frac{P_{max}^{wind}}{k*f_{nom}} + \frac{P_{max}^{pv}}{k*f_{nom}} + \frac{P_{EV}^{tot}}{k*f_{nom}}}\right) \tag{3.13}$$

In the above equation, (k) is the droop coefficient, whereas (P_{max}^{dg}), (P_{max}^{wind}) and (P_{max}^{pv}) represents the maximum rated capacity of diesel generator, wind source and PV source respectively.

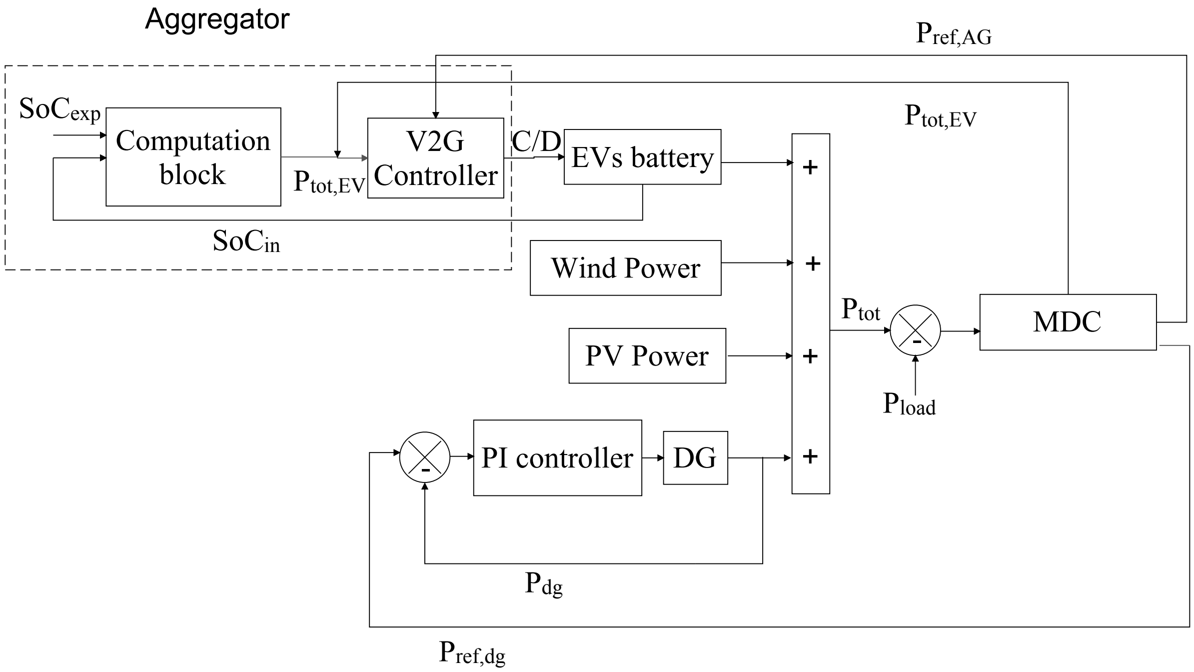

Figure 3.1: Block diagram of the proposed scheme.

In order to cater Δf, the MDC gives the individual reference power signal to both diesel generator controller and AG for a time duration (T). The reference power signal for AG (P_{ref}^{AG}) and for diesel generator (P_{ref}^{dg}) can be computed as below.

$$P_{ref}^{AG} = P_{EV}^{tot} - \frac{(P_{load} - P_{tot})P_{EV}^{tot}}{P_{max,dg} + P_{EV}^{tot}} \tag{3.14}$$

$$P_{ref}^{dg} = P_{dg} + (P_{load} - P_{tot}) - P_{ref}^{AG} \tag{3.15}$$

This P_{ref}^{dg} is given to PI controller as shown in Fig. 3.1. This controller ensures that the P_{ref}^{dg} is met at all the instances of time duration T. As a result, for next time duration T, diesel generator generates P_{ref}^{dg} as expressed in algorithm 1. Therefore, this additional PI control loop enhances the frequency regulation capabilities of the proposed scheme. In addition to this, P_{ref}^{AG} is given to AG which act as a control unit for the EVs. It also act as an interface between MDC and EVs. The detailed functionality of AGs is discussed in the next subsection.

Algorithm 1 Working of proposed controller for managing frequency deviations.

Input: $P_{wind}, P_{PV}, P_{load}, P_{EV}^{tot}$
Output: Computed P_{ref}^{AG}

1: Set P_{dg} = P at T=0
2: Set $P_{tot} = P_{wind} + P_{PV} + P_{dg} + P_{EV}^{tot}$
3: Compute Δf using (3.13)
4: Compute P_{ref}^{AG} using (3.14)
5: Compute P_{ref}^{dg} using (3.15)
6: Set $P_{dg} = P_{ref}^{dg}$
7: Update $P_{dg}$for step 1
8: Set $P_{EV}^{tot} = P_{ref}^{AG,met}$ as computed in algorithm 2

3.2 Working of Aggregator

The AG receives inputs such as-initial SoC (SoC_i^{in}) and expected SoC (SoC_i^{exp}) of the i^{th} EV battery as shown in Fig. 3.1. Using these inputs, it computes number of EVs available for charging (N_{char}) and discharging (N_{dis}) as elaborated in algorithm 2. Based on N_{char} and N_{dis}, AG computes cumulative power available from EVs (P_{EV}^{tot}) as shown below.

$$P_{EV}^{char} = -\sum_{i=1}^{N_{char}} P_{max} \tag{3.16}$$

$$P_{EV}^{dis} = \sum_{i=1}^{N_{dis}} P_{max} \tag{3.17}$$

$$P_{EV}^{tot} = P_{EV}^{char} + P_{EV}^{dis} \tag{3.18}$$

where, (P_{max}) is the maximum power utilized from EVs' battery, (P_{EV}^{char}) is the total amount of power required for EVs' charging and (P_{EV}^{dis}) is the total amount of power available from EVs' for discharging.

This value of P_{EV}^{tot} at each instance is shared with MDC via feedback loop between AG and MDC. In response to the P_{EV}^{tot} received from AG and Δf at MG, MDC computes P_{ref}^{AG} signal for AG for the time duration T. AG ensures that P_{ref}^{AG} received from MDC is met at all the times. This can be achieved by varying charging (C_i^{rate}) and discharging (D_i^{rate}) rates of the EVs' batteries. For charging scenario, energy requirement of i^{th} EV (E_i^{req}) to fulfill SoC_i^{exp} can be computed using (3.19), whereas, in case of discharging, is computed using (3.20).

$$E_i^{req} = E_{rated}(\frac{SoC_i^{exp} - SoC_i^{in}}{100}) \tag{3.19}$$

$$E_i^{req} = E_{rated}(\frac{SoC_i^{in} - SoC_i^{exp}}{100}) \tag{3.20}$$

where (E_{rated}) is the maximum rated capacity of EVs' battery.

In order to fulfill the E_i^{req}, while meeting the P_{ref}^{AG}, EVs' C_i^{rate} and D_i^{rate} are altered using below mentioned equations.

$$C_i^{rate} = \frac{P_{ref}^{AG}}{P_{EV}^{tot}} \tag{3.21}$$

$$D_i^{rate} = \frac{P_{ref}^{AG}}{P_{EV}^{tot}} \tag{3.22}$$

Thus, power drawn by i^{th} EV (P_i^{char}) and total net power drawn (P_{net}^{char}) by all EVs seeking charging can be computed as follows.

$$P_i^{char} = -P_{max} C_i^{rate} \tag{3.23}$$

$$P_{net}^{char} = \sum_{i=1}^{N_{char}} P_i^{char} \tag{3.24}$$

Similarly, power deliver (P_i^{dis}) by i^{th} EV and total net power deliver by all EVs (P_{net}^{dis}) to discharge their batteries at regulated D_i^{rate} can be computed as follows.

$$P_i^{dis} = P_{max} D_i^{rate} \tag{3.25}$$

$$P_{net}^{dis} = \sum_{i=1}^{N_{dis}} P_i^{dis} \tag{3.26}$$

Thus, the amount of reference signal met $P_{ref}^{AG,met}$ and unmet $P_{ref}^{AG,unmet}$ during frequency support is given as follows.

$$P_{ref}^{AG,met} = P_{net}^{char} + P_{net}^{dis} \tag{3.27}$$

$$P_{ref}^{AG,unmet} = P_{ref}^{AG} - P_{ref}^{AG,met} \tag{3.28}$$

Apart from managing P_{ref}^{AG}, the proposed AG also fulfills energy requirements of EVs. This can be achieved by calculating time required by individual EVs to meet their SoC_i^{exp}.

The time duration (T_i^{char}) for charging and discharging (T_i^{dis}) can be computed using the below mentioned equations.

$$T_i^{char} = -\frac{E_i^{req}}{P_i^{char}} \tag{3.29}$$

$$T_i^{dis} = \frac{E_i^{req}}{P_i^{dis}} \tag{3.30}$$

These T_i^{char} and T_i^{dis} are the important parameters which determines whether the E_i^{req} and SoC_i^{exp} will be met or not within time duration T. Therefore, in order to compute energy met (E_i^{met}) and SoC met (SoC_i^{met}), four cases are considered by AG as discussed below.

- **First Case**: This case is chosen when T_i^{char} is equal to or less than T i.e., time required by an EV to get charged to its SoC_i^{exp} is less than or equal to the time for which P_{ref}^{AG} will be available.

$$E_i^{current} = -(P_i^{char} T_i^{char}) \tag{3.31}$$

$$SoC_i^{current} = SoC_i^{in} + \frac{100(E_i^{current})}{E_{rated}} \tag{3.32}$$

Hence, level of energy met E_i^{met} and unmet (E_i^{unmet}) can be computed as expressed in algorithm 2 (Lines 12-13). Similarly, SoC met SoC_i^{met} and unmet (SoC_i^{unmet}) are calculated using lines (14-15) of algorithm 2.

$$E_i^{met} = E_i^{current} = E_i^{req} \tag{3.33}$$

$$E_i^{unmet} = E_i^{req} - E_i^{current} \tag{3.34}$$

Similarly, SoC met SoC_i^{met} and unmet SoC_i^{unmet} can be determined using below mention equations.

$$SoC_i^{met} = SoC_i^{current} = SoC_i^{exp} \tag{3.35}$$

$$SoC_i^{unmet} = SoC_i^{exp} - SoC_i^{current} \tag{3.36}$$

From the equations given in (Lines 12-15) it can be concluded that E_i^{unmet} and SoC_i^{unmet} will be zero as SoC_i^{exp} becomes equal to $SoC_i^{current}$. Thus, for this case the EVs fulfill their energy requirements within the stipulated time duration T.

- **Second Case**: This case is chosen when T_i^{char} is greater than T. Here, $E_i^{current}$ and $SoC_i^{current}$ of i^{th} EV can be computed as mentioned below.

$$E_i^{current} = -(P_i^{char}T) \tag{3.37}$$

$$SoC_i^{current} = SoC_i^{in} + \frac{100(E_i^{current})}{E_{rated}} \tag{3.38}$$

The equations regarding E_i^{met}, E_i^{unmet}, SoC_i^{met} and SoC_i^{unmet} are elaborated in lines (23-26). These equations

$$E_i^{met} = E_i^{current} \tag{3.39}$$

$$E_i^{unmet} = E_i^{req} - E_i^{current} \tag{3.40}$$

Similarly SoC_i^{met} and SoC_i^{unmet} can be determined using below mentioned equations.

$$SoC_i^{met} = SoC_i^{current} - SoC_i^{in} \tag{3.41}$$

$$SoC_i^{unmet} = SoC_i^{exp} - SoC_i^{current} \tag{3.42}$$

depicts that the same EV is utilized for next time duration T and this process will continue until T_i^{char} becomes equal to or less than T.

- **Third Case**: This case is chosen when (T_i^{dis}) is equal to or less than T i.e, time duration required by EV battery to get discharged to its SoC_i^{exp} is equal to or less than time duration upto which P_{ref}^{AG} is received. In such cases, the computation of $E_i^{current}$ and $SoC_i^{current}$ is expressed as,

$$E_i^{current} = (P_i^{dis}T_i^{dis}) \tag{3.43}$$

$$SoC_i^{current} = SoC_i^{in} - \frac{100(E_i^{current})}{E_{rated}} \tag{3.44}$$

For such cases the level of energy met E_i^{met} and SoC met SoC_i^{met} can be computed as expressed in line (42 and 45) respectively. Similarly, the level of energy unmet E_i^{unmet} and SoC unmet SoC_i^{unmet} can be determined as given in line (43 and 46). Similar to the first case, E_i^{unmet} and SoC_i^{unmet} will be zero and EVs requirements are completely fulfilled within time duration T.

$$E_i^{met} = E_i^{current} = E_i^{req} \tag{3.45}$$

$$SoC_i^{met} = SoC_i^{current} = SoC_i^{exp} \tag{3.46}$$

$$E_i^{unmet} = E_i^{req} - E_i^{current} \tag{3.47}$$

$$SoC_i^{unmet} = SoC_i^{current} - SoC_i^{exp} \tag{3.48}$$

- **Fourth Case**:This case is chosen when T_i^{dis} is greater than T. Here, the value of $E_i^{current}$ and $SoC_i^{current}$ are obtained as follows.

$$E_i^{current} = (P_i^{dis} T) \tag{3.49}$$

$$SoC_i^{current} = SoC_i^{in} - \frac{100(E_i^{current})}{E_{rated}} \tag{3.50}$$

The equations regarding E_i^{met}, E_i^{unmet}, SoC_i^{met} and SoC_i^{unmet} are elaborated in lines (53-56). Therefore, energy met E_i^{met} and unmet E_i^{unmet} can be calculated as follows.

$$E_i^{met} = E_i^{current} \tag{3.51}$$

$$E_i^{unmet} = E_i^{req} - E_i^{current} \tag{3.52}$$

Similarly SoC met SoC_i^{met} and unmet SoC_i^{unmet} can be determined using below mentioned equations.

$$SoC_i^{met} = SoC_i^{current} - SoC_i^{in} \tag{3.53}$$

$$SoC_i^{unmet} = SoC_i^{current} - SoC_i^{exp} \tag{3.54}$$

Algorithm 2 Working of proposed aggregator for managing frequency deviations and EVs energy requirements.

Input: SoC_i^{exp}, SoC_i^{in}, T

Output: Computed C_i^{rate}, D_i^{rate}, E_i^{met} and SoC_i^{met} of EVs.

Set $P_{EV}^{char} = -\sum_{i=1}^{N_{char}} P_{max}$

Set $P_{EV}^{dis} = \sum_{i=1}^{N_{dis}} P_{max}$

Compute P_{EV}^{tot} using (3.18)

Set $Met_{char} = 0, Met_{dischar} = 0$

Compute E_i^{req} using (3.19)

Compute $C_i^{rate} = \frac{P_{ref}^{AG}}{P_{EV}^{tot}}$

Compute P_i^{char} using (3.23)

Set $T_i^{char} = \frac{E_i^{req}}{P_i^{char}}$

if $(T_i^{char}) \leq$ (T) **then**

  Compute $E_i^{current}$ using (3.31)

  Compute $SoC_i^{current}$ using (3.32)

  Set $E_i^{met} = E_i^{current} = E_i^{req}$

  Set $E_i^{unmet} = E_i^{req} - E_i^{current}$

  Set $SoC_i^{met} = SoC_i^{current} = SoC_i^{exp}$

  Set $SoC_i^{unmet} = SoC_i^{exp} - SoC_i^{current}$

  if $SoC_i^{unmet} \neq 0$ **then**

    Set $Met_{char} = Met_{char}+1$

  end if

end if

if $(T_i^{char}) > (T)$ **then**

  Compute $E_i^{current}$ using (3.37)

  Compute $SoC_i^{current}$ using (3.38)

  Set $E_i^{met} = E_i^{current}$

  Set $E_i^{unmet} = E_i^{req} - E_i^{current}$

  Set $SoC_i^{met} = SoC_i^{current} - SoC_i^{in}$

  Set $SoC_i^{unmet} = SoC_i^{exp} - SoC_i^{current}$

  if $SoC_i^{unmet} \neq 0$ **then**

    $SoC_i^{in} = SoC_i^{current}$

Set $Met_{char} = Met_{char}$+1
end if
end if
if $Met_{char} \neq 0$ **then**
Set $N_{char} = Met_{char}$
end if
Compute E_i^{req} using (3.20)
Compute $D_i^{rate} = \frac{P_{net\_ref}^{AG}}{P_{EV}^{tot}}$
Compute P_i^{dis} using (3.25)
Set $T_i^{dis} = \frac{E_i^{req}}{P_i^{dis}}$
if $(T_i^{dis}) \leq (\mathrm{T})$ **then**
Compute $E_i^{current}$ using (3.43)
Compute $SoC_i^{current}$ using (3.44)
Set $E_i^{met} = E_i^{current} = E_i^{req}$
Set E_i^{unmet}=0
Set $SoC_i^{met} = SoC_i^{current} = SoC_i^{exp}$
Set $SoC_i^{unmet} = SoC_i^{current} - SoC_i^{exp}$
if $SoC_i^{unmet} \neq 0$ **then**
Set $Met_{dischar} = Met_{dischar}$+1
end if
end if
if $(T_i^{dis}) > (T)$ **then**
Compute $E_i^{current}$ using (3.49)
Compute $SoC_i^{current}$ using (3.50)
Set $E_i^{met} = E_i^{current}$
Set $E_i^{unmet} = E_i^{req} - E_i^{current}$
Set $SoC_i^{met} = SoC_i^{current} - SoC_i^{in}$
Set $SoC_i^{unmet} = SoC_i^{current} - SoC_i^{exp}$
if $SoC_i^{unmet} \neq 0$ **then**
$SoC_i^{in} = SoC_i^{current}$
Set $Met_{dischar} = Met_{dischar}$+1
end if
if $Met_{dischar} \neq 0$ **then**
Set $N_{dis} = Met_{dischar}$
end if
Update N_{dis} and N_{dis} for Step 1 and Step 2
Compute $P_{ref}^{AG,met}$ and $P_{ref}^{AG,unmet}$ using (3.27) and (3.28)
end if

Chapter 4

SIMULATION AND RESULTS

This section emphasizes the simulation and results applicable to the proposed scheme. For implementing this scheme, Santa Rita Jail's (SRJ) MG is considered. This MG comprises of various generation sources such as-wind, solar, diesel generator, fuel cell and battery storage systems. However, in this work, fuel cell is not considered and battery storage systems are replaced by CS with maximum capacity of 40 EVs.These EVs are assumed to be Chevrolet volt EVs having battery capacity of 16 kWh.The minimum and maximum SoC limit of EV's battery is assumed to be 20% and 100% respectively. Extensive simulations have been performed on actual power data acquired from SRJ MG. The simulation parameters used here are presented in Table 4.1.

Table 4.1: Parameters used for simulation

Parameters	**Values**
P_{max}^{pv}	1.2 MW
P_{max}^{dg}	2.4 MW
P_{max}^{wind}	11.2 kW
P_{max}	16 kW
E_{rated}	16 KWh
EV's default C_i^{rate}	1
EV's default D_i^{rate}	1
T	3.48 minutes
k	0.05

4.1 Case Study

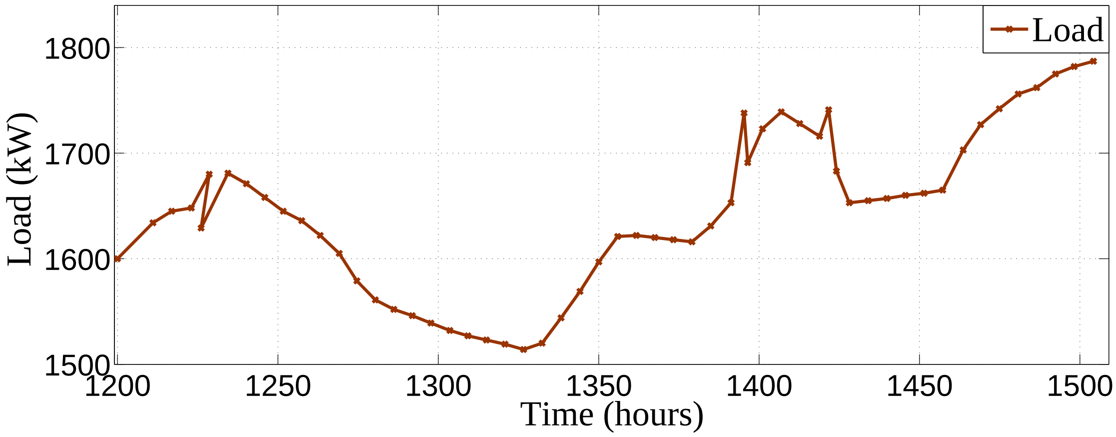

Figure 4.1: Santa Rita Jail MG load across 3 hours.

In order to implement the proposed MDC and AG, various simulations have been performed on SRJ's MG data obtained for 17^{th} July, 2012. The total load on SRJ's facility for a duration of 3 hours is shown in Fig. 4.1.

Two diesel generators with maximum capacity of 1.2 MW are taken along with above mentioned renewable energy sources which are collectively utilized to meet this load. Fig. 4.2 and 4.3 shows SRJ's MG power generation from 1200 to 1500 hours utilizing wind and solar energy sources respectively. In the proposed work CS with maximum 40 EVs are being used in place of

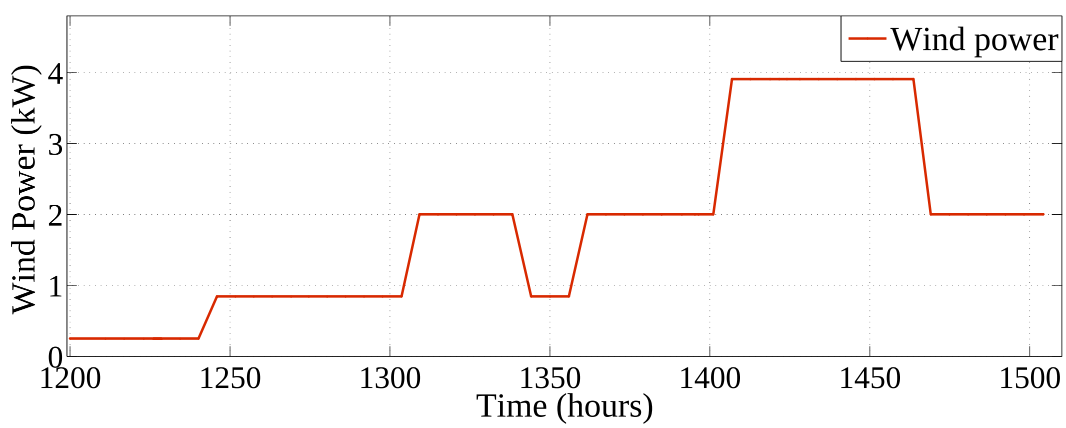

Figure 4.2: Wind power across 3 hours.

battery storage system. Fig. 4.4 shows number of EVs available at CS for charging and discharging

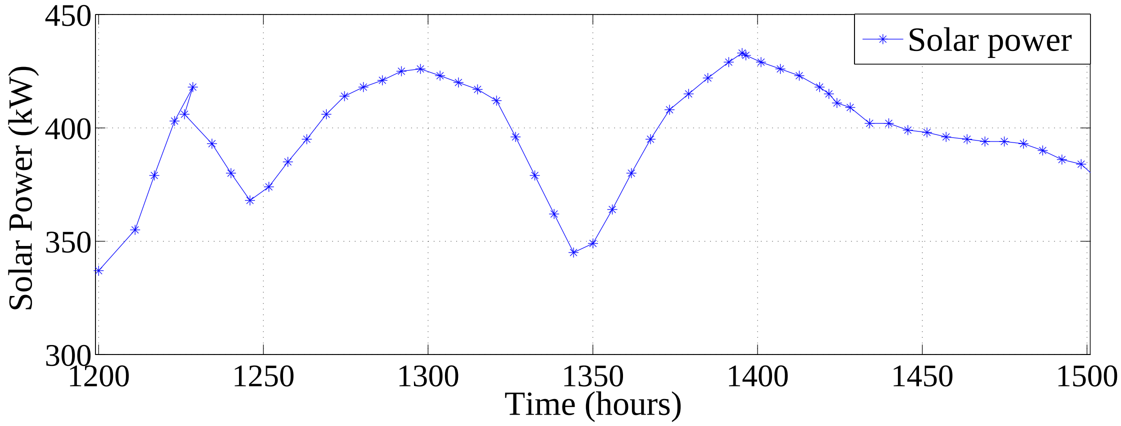

Figure 4.3: Solar power across 3 hours.

their batteries. The proposed scheme also manages the dynamics of the number of EVs as depicted in Fig. 4.4. These EVs have been segregated into 3 broad types, i.e., newly arrived, departing and operative. The EVs which participate in frequency support mechanism since the previous slots are considered as operative EVs.

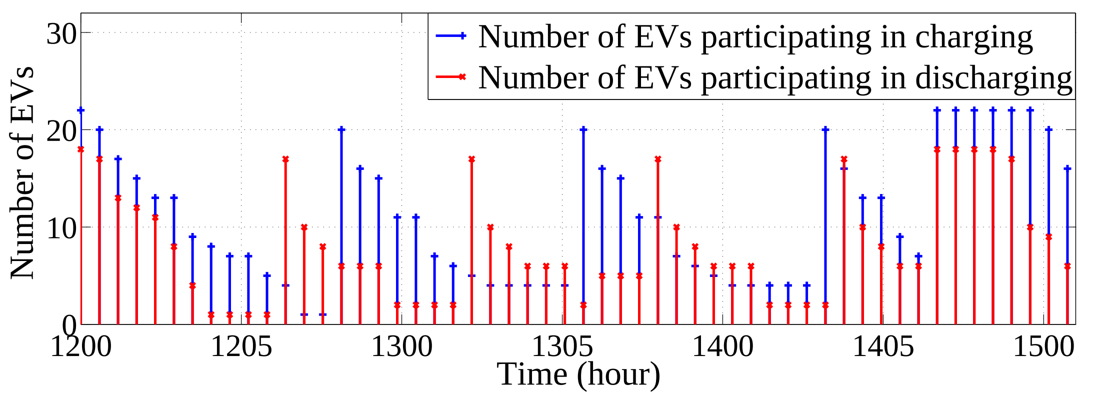

Figure 4.4: Number of EVs available at CS.

On the basis of this categorization of EVs, their availability in a particular time slot is computed and are considered by the controller for rendering frequency support. For instance, at 1200 hours, 22 EVs arrived at the CS for charging and exactly 18 EVs arrives for discharging. At 1203 hour one EV both from charging and discharging category departed from the CS after charging and discharging their respective batteries. On the other hand, no further EVs arrived in the CS for charging and discharging purposes. This simply implies to the fact that, the controller manages the frequency support by dynamically considering the number of EVs willing to participate in the frequency support mechanism. Further, P_{EV}^{tot} available from all these EVs is computed using (3.18) and is depicted in Fig. 4.5.

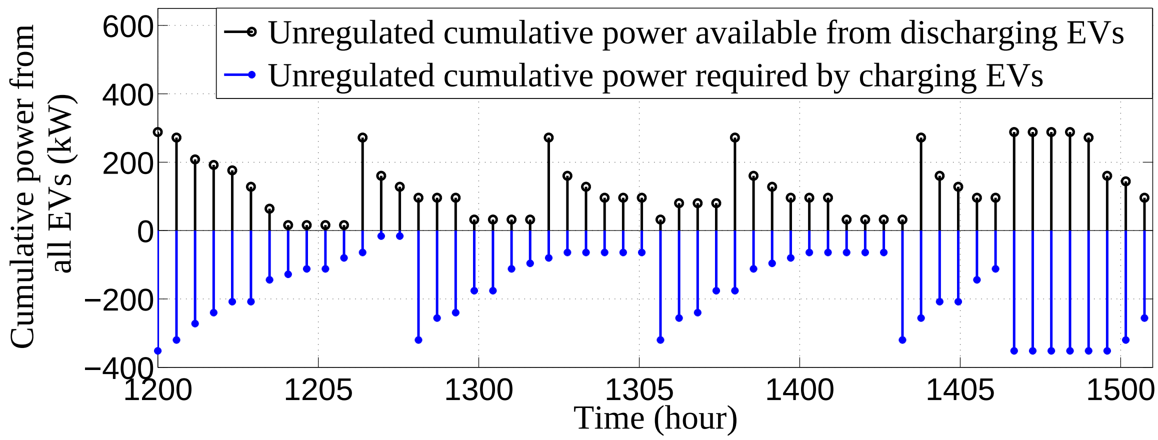

Figure 4.5: Cumulative power from EVs.

The MDC monitors above data and computes P_{tot} using (3.12). Fig. 4.6 represents the P_{tot} and total load at MG. From the figure, it can be seen that the load does not follow P_{tot} for most of the instances. For example at 1200 hours, load is 1600 kW, whereas P_{tot} is 1313 kW, thus there exists a wide gap between the load and supply. This gap leads to frequency deviations at MG as computed

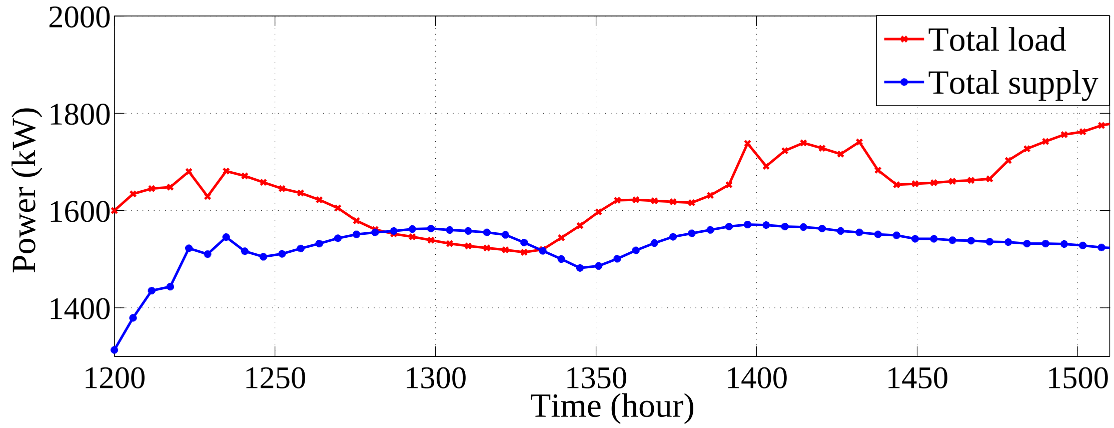

Figure 4.6: Total load and total supply.

using (3.13). In order to minimize these deviations, MDC computes reference signals, i.e., P_{ref}^{AG} and P_{ref}^{dg} using (3.14) and (3.15). The reference signals are shown w.r.t time as shown in Fig. 4.7 and 4.8 respectively. These reference signals are further given to diesel generator and AG as shown in Fig. 3.1. The proposed AG meets P_{ref}^{AG} and SoC_i^{exp} while managing the frequency deviations by altering the EV's respective C_i^{rate} and D_i^{rate}.

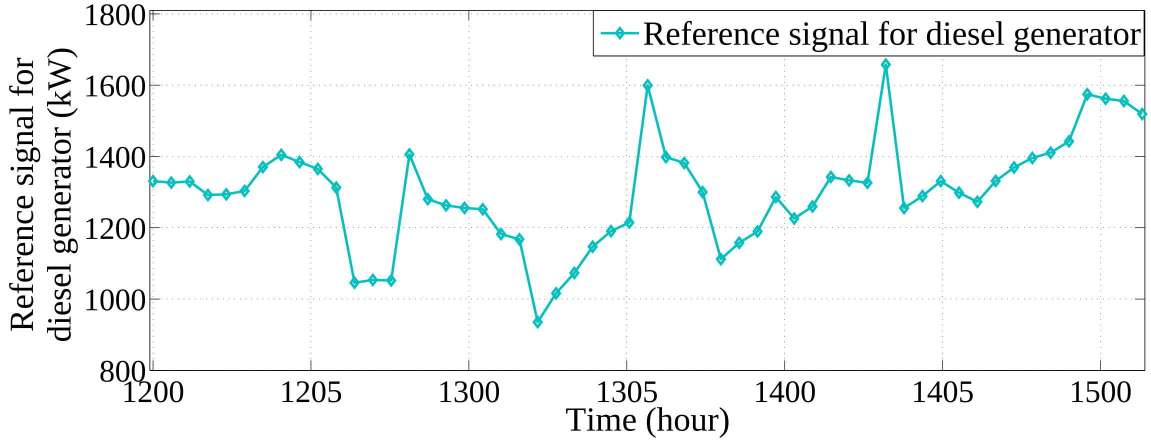

Figure 4.7: Reference signal for diesel generator.

Fig. 4.9 depicts EV's altered C_i^{rate} and D_i^{rate}. On account of alterations, the corresponding P_{net}^{char} and P_{net}^{dis} also changes as per (3.24) and (3.26). These alterations are depicted in Fig. 4.10 whereas

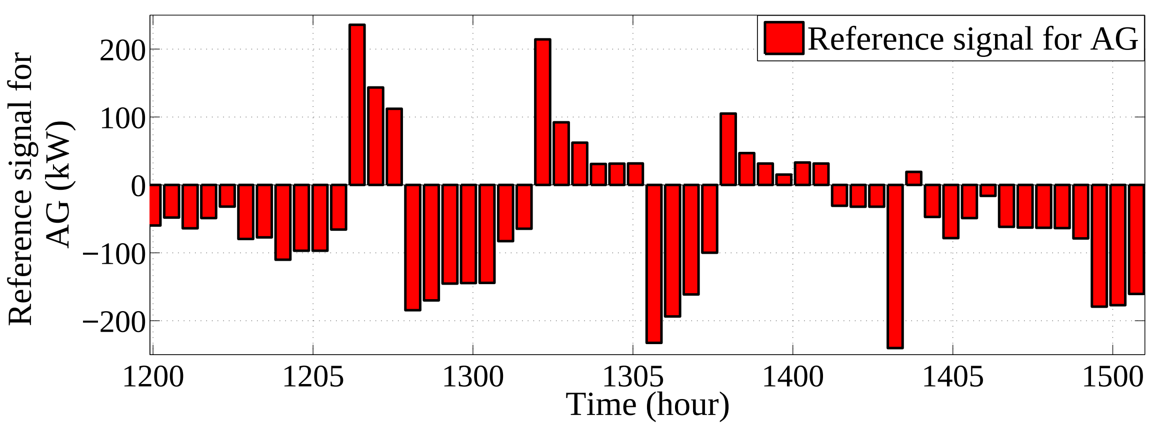

Figure 4.8: Reference signal for AG.

unregulated cumulative power is shown in Fig. 4.5. For example, at 1200 hours, the unregulated powers for charging and discharging were -352 and 128 kW respectively. Thus, the cumulative power drawn by EVs was -124 kW (-352 + 228 = -124 kW). Simultaneously, the reference signal P_{ref}^{AG} received was -59.81 kW. In order to meet this signal, the C_i^{rate} and D_i^{rate} of participating EVs are altered to 0.93453 by proposed AG. Due to this, the value of regulated P_{net}^{char} becomes -328.95

kW and P_{net}^{dis} turned out to be 269.14 kW respectively. These values of P_{net}^{char} and P_{net}^{dis} are depicted with the help of Fig. 4.10. The power met and unmet is depicted in Fig. 4.11 which depicts that

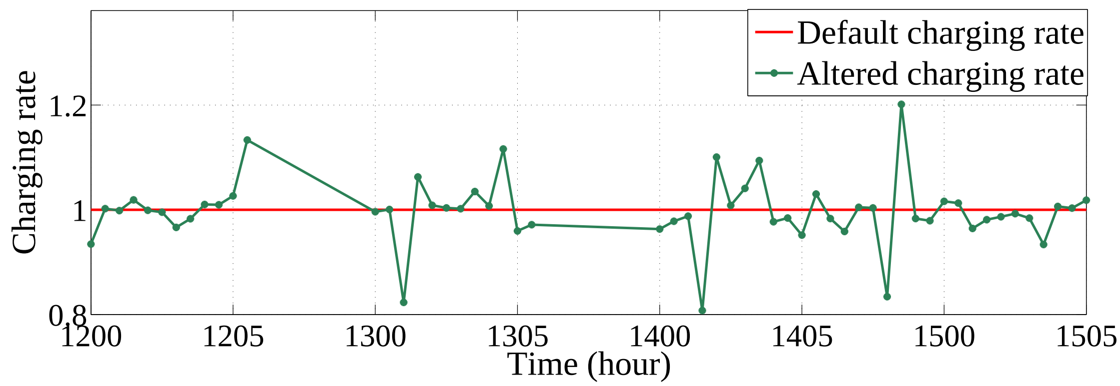

Figure 4.9: Charging and discharging rates of EVs.

P_{ref}^{AG} was nearly met by the controlled fleet of EVs throughout the considered time frame.

Thus, the proposed scheme with AG reduces Δf to a larger extent as shown in Fig. 4.12. For example, at 1200 hour Δf initially was -0.10068 Hz. However, after applying the regulation scheme the value of Δf is reduced significantly to 0.006648 Hz. In addition to providing efficient frequency control, the proposed scheme also caters the energy and SoC requirements of EVs. To cater the expected SoCs of the EVs they are categorized into charging and discharging vehicles based on the values of SoC_i^{exp} and SoC_i^{in}.

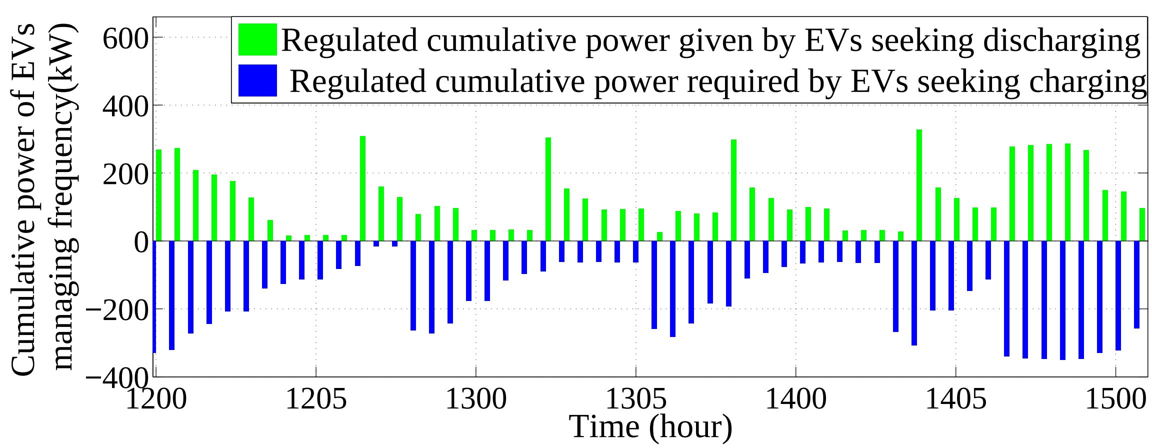

Figure 4.10: Regulated power from EVs for meeting reference signal.

Fig. 4.13 shows a discharging scenario of an EV. The SoC_i^{in} and SoC_i^{exp} of this EV are 70% and 20% respectively. In order to meet the desired SoC_i^{exp}, the two most important parameters are

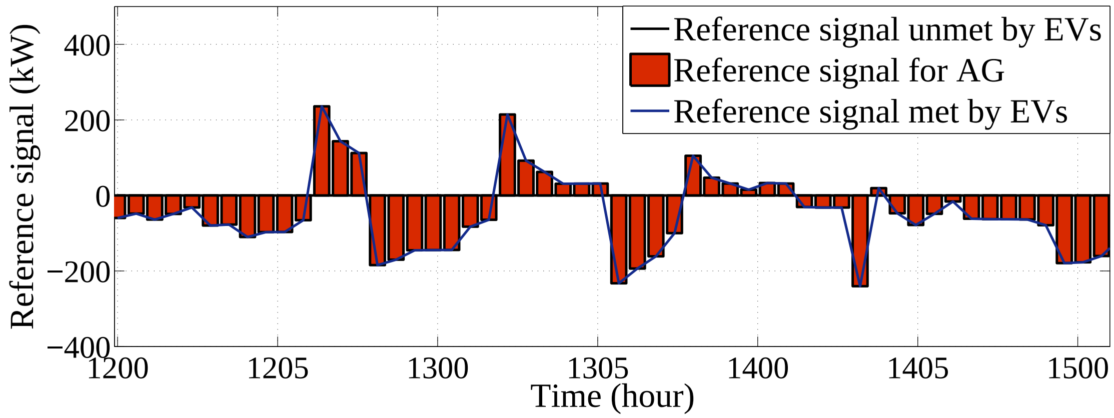

Figure 4.11: Reference signal met and unmet.

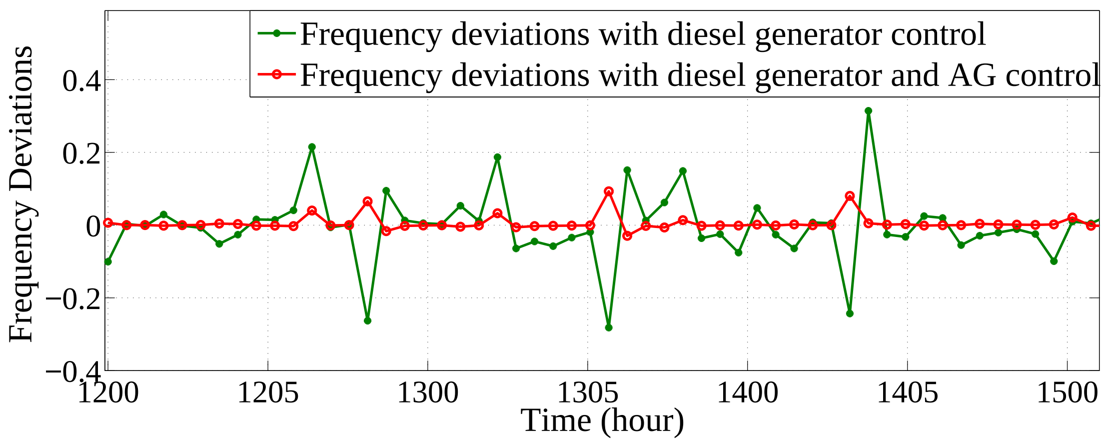

Figure 4.12: Output of MDC with and without AG control.

T_i^{dis} and T. The value of T is considered to be 3.48 minutes in the proposed scheme. Initially, for the first duration of time T, T_i^{dis} comes out to be 29.22 minutes using (3.30) which is greater than T. At this instance, when T_i^{dis} is 29.22 minutes, the values for $SoC_i^{current}$, SoC_i^{met} and SoC_i^{unmet} are 64.047%, 5.9531% and 44.047% respectively. Since, T_i^{dis} is greater than T, the corresponding EV is again utilized for the next instance of T and the process continues until T_i^{dis} becomes equal to or less than T. Therefore, when T_i^{dis} is 1.96 minutes, $SoC_i^{current}$ becomes equal to SoC_i^{exp} i.e., 20% as shown in Fig. 4.13.

Similar to the above scenario, Fig. 4.14 depicts charging scenario. The values for SoC_i^{in} and SoC_i^{exp} are 30% and 100% respectively. For the first duration of time T, T_i^{char} comes out to be 44.94 minutes using (3.29). At this instance when T_i^{char} is 44.94 minutes, the values for $SoC_i^{current}$, SoC_i^{met} and SoC_i^{unmet} are 35.42%, 5.4203% and 64.58% respectively. Moreover, at first instance

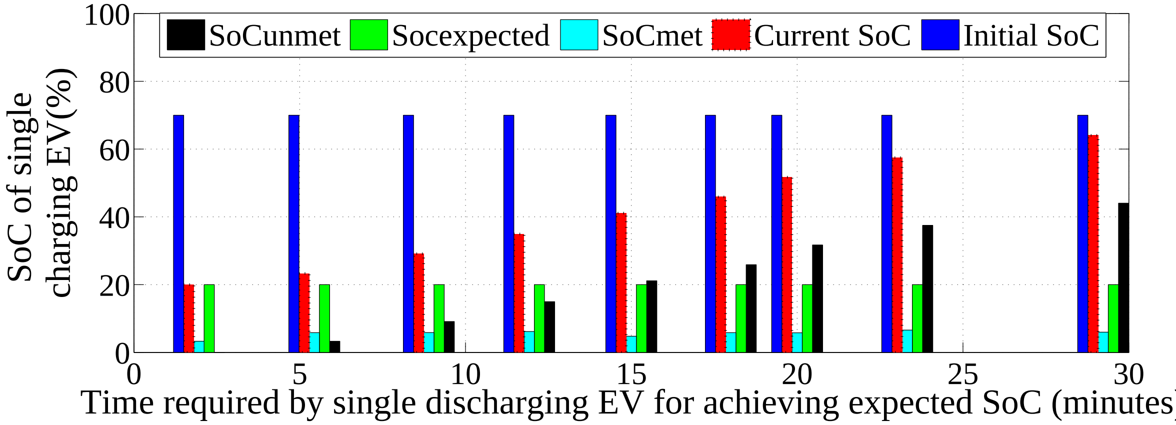

Figure 4.13: SoC variations of an EV seeking discharging.

T_i^{char} is greater than T thus EV's battery is utilized until T_i^{char} either approaches to T or becomes less than T. Finally, when T_i^{char} is 3.45 minutes, $SoC_i^{current}$ becomes equal to SoC_i^{exp} as shown in Fig. 4.14.

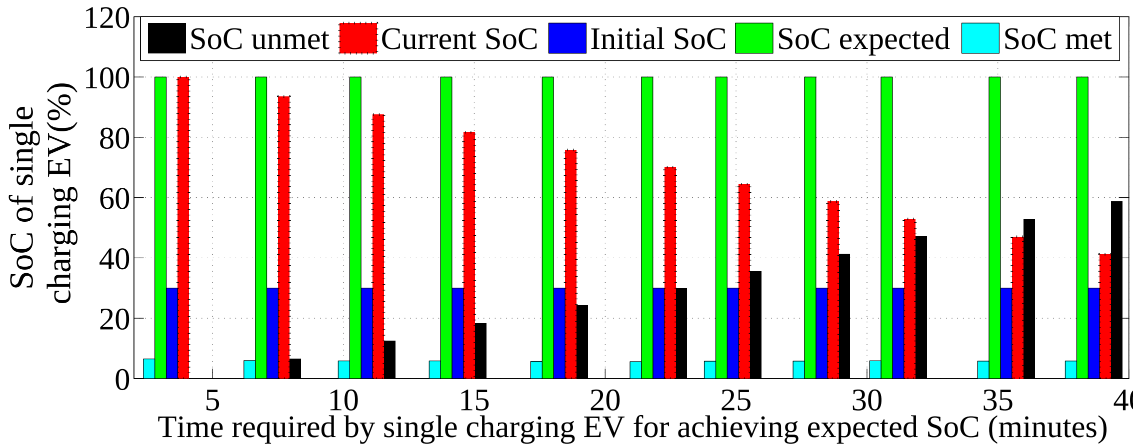

Figure 4.14: SoC variations of an EV seeking charging.

Chapter 5

COMPARISON

In this section, the proposed scheme is compared with one of the existing scheme of Liu *et al's* in [38] so as to get more vivid picture of the proposed scheme. For the comparison purpose, the number of EVs considered and P_{ref}^{AG} for 1200 hours are shown in Fig. 4.4 and Fig. 4.8. At 1200

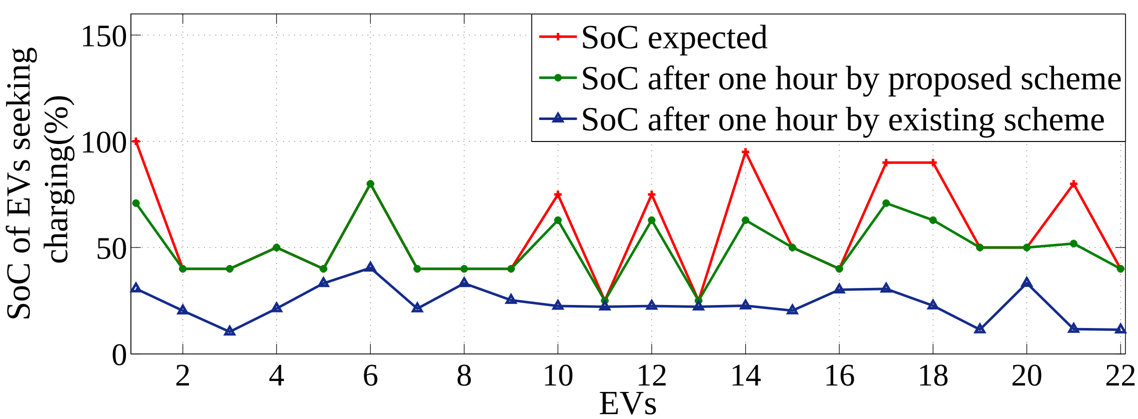

Figure 5.1: SoC comparison for EVs seeking charging.

hours, number of EVs for charging and discharging were 22 and 18 respectively. In addition to this, the value of P_{ref}^{AG} was -59.81 kW. However, for comparing both the schemes this P_{ref}^{AG} is received for time duration T=1 hour. In accordance to this, in the existing scheme, the net power fetched by EVs is 105.58 kW which is higher than P_{ref}^{AG} thus results in even more frequency fluctuations at MG. Table 5.1 depicts the comparison between the two schemes with respect to reference request met during the frequency support mechanism. As shown in Table 5.1 the proposed scheme successfully met the desired reference signal.

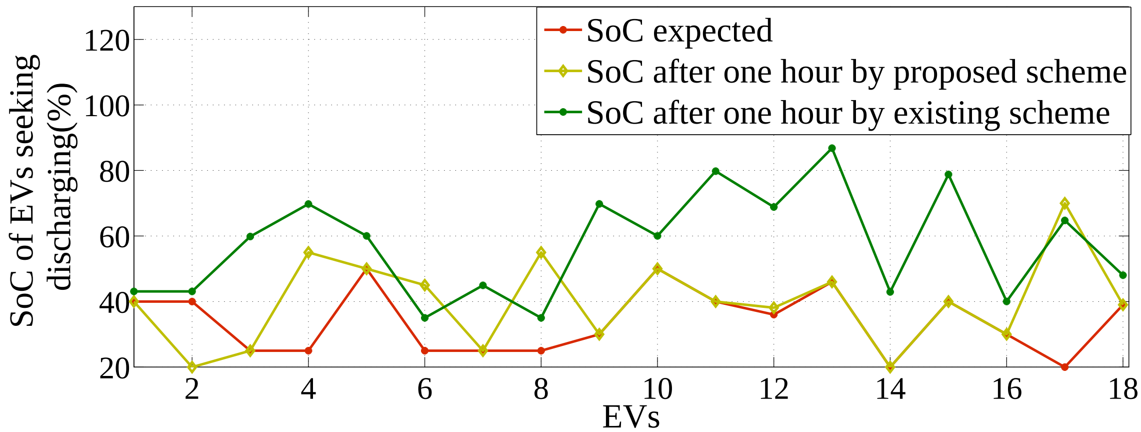

Figure 5.2: SoC comparison for EVs seeking discharging.

In addition to this, the SoC comparisons between existing and proposed scheme for charging and discharging EVs are shown in Fig. 5.1 and 5.2 respectively. Figures clearly depicts the difference in levels of SoC met by both the schemes. After one hour Liu *et al's* scheme is not able to meet the expected SoC of individual EVs. On the other hand, proposed scheme proves to be more successful in meeting the expected SoC for individual EVs. The reason behind this fulfillment is that the proposed scheme considers the time required for achieving expected SoC unlike Liu *et al* scheme.

Table 5.1: Comparison of proposed scheme with existing scheme based on reference signal met and unmet.

Existing Scheme		***Proposed scheme***	
$P_{ref}^{AG,met}$	$P_{ref}^{AG,unmet}$	$P_{ref}^{AG,met}$	$P_{ref}^{AG,unmet}$
105.58 kW($> P_{ref}^{AG}$)	-45.77 kW	59.81 kW ($= P_{ref}^{AG}$)	0

Chapter 6

CONCLUSION

In this work, frequency deviations at MG level have been managed using controllable DES such as-diesel generator and EVs. Batteries of EVs are regarded as mobile energy storage devices and have ability to actively participate in frequency support. In order to enable fleet of EVs participation in frequency support at MG, conventional droop controller have been modified and referred as MDC. Moreover for coordinating fleet of EVs an AG has been proposed. It computes available power from EVs batteries and control their charging and discharging rates. The simulation results clearly depicted that the MDC along with the AG can not only meet the energy requirements of EVs but can stabilize the frequency at MG. In addition to this, comparison with one of the existing technique clearly depicts the effectiveness of proposed scheme in terms of managing frequency while meeting EVs energy requirements.

LIST OF PUBLICATIONS

- K. Kaur, R. Rana, N. Kumar, M. Singh and S. Mishra, ”A Colored Petri-Net Based Frequency Support Scheme using Fleet of Electric Vehicles in Smart Grid Environment,”*IEEE Transactions on Power Systems, DOI-10.1109/TPWRS.2016.2518743*

- R. Rana, K. Kaur, M. Singh, N. Kumar and P. Kumar, "Integrated fleet of electric vehicles as a frequency regulation agent in the grid," Transportation Electrification Conference (ITEC), 2015 IEEE International, Chennai, 2015, pp. 1-7. doi: 10.1109/ITEC-India.2015.7386953

- R. Rana, M. Singh, S.Mishra,”Design of Modified Droop Controller for Frequency Support in Microgrid using Fleet of Electric Vehicles,” *IEEE Transactions on Power Systems* (manuscript under revision)

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