CHAPTER 1

INTRODUCTION

1.1 General

India is one of the fastest growing nations in the field of wind energy and it has exploited the same with an installed capacity of 26,769 MW as on March 2016. In terms of wind power installed capacity India is ranked fifth in the world. This emerging competence in the wind arena is due to the depletion of the conventional resources of energy. The focus of the power generation sector is slowly turning towards the renewable energy resources which are strong alternatives for energy production from fossil fuels. Also amongst the non-conventional resources wind is a promising source of power. The statistics of the installed capacity clearly tells the need for harnessing wind power in a more effective way so as to utilize wind resources in an optimal manner and thereby contribute to the country’s quest for affordable, clean energy.

Today the growth of wind energy technologies has extended even into the seas through off-shore systems with sophisticated control systems. But the need of the hour is to design small scale wind turbines for use in household applications. Active control is becoming more and more important for the wind energy community. However, new advances in wind turbine modeling and control are required to push turbines to the next level of performance. More advanced control concepts and methodologies should help the wind industry surpass current limitations, resulting in even more reliable wind turbines. The technology and science of control of wind turbines are, therefore, an important subject for industry and research institutes.

Apart from wind energy, solar resources are also used extensively as an alternative source of energy. Photovoltaic is a method of generating electric power by converting solar radiation into direct current using semiconductors that exhibit photovoltaic effect. In this
manner, the energy output of the sun is converted into a useful form which is used in many applications like rooftop installations, transport, standalone devices, rural electrification etc. Due to the demand for renewable energy resources, the advancement in solar technology is also progressing at a faster pace. As technology advances, the cost of solar PVs also reduces, which in turn enhances the scope and feasibility of the PV applications.

The main limitation of the wind and solar power is its intermittent nature. The power generated from wind farms varies with the wind speed. If the wind speed is low, generally the maximum possible power is extracted from the wind turbine corresponding to that wind speed. If the wind speed is high, the pitch control is active to limit the power generated from the wind turbine. If the wind farm is connected to the grid, this kind of fluctuation in generated power from the wind farm may cause stability problems in the system. Similarly, clouds affect the instantaneous energy output from the photovoltaic resources even during the day hours. One way to solve this problem is to use additional storage devices. Generally, energy storage devices like batteries or ultracapacitors are used for this purpose. But storage devices always add to the cost and sometimes make the project economically unfeasible. An alternative solution is to use the plug-in-electric vehicles (PEV) as an external storage device and thus mitigate the intermittency of the wind and solar resources.

Due to depleting fossil fuel resources, the importance of plug-in-electric vehicles is rapidly increasing. Some plug-in vehicles are considered ‘battery electric vehicles’, since they entirely rely on electricity, while others are called ‘plug-in hybrid electric vehicles’ since they still rely partly on conventional fuels. Both the category of vehicles are called ‘plug-in electric vehicles’ because they are designed to be recharged by plugging into the power grid. Powering vehicles with electricity is of significant interest because innovation in battery technology, if dramatic enough, could constitute a breakthrough in the search for ways to reduce petroleum use. But again the generation of electricity depends on the depleting fossil fuels. Though contradictory, it has an appealing solution. The wind and solar energy can be used to charge the batteries of the plug-in electric vehicles. When intelligent control technique is incorporated, the performance of the system is enhanced visibly and hence proposed in this work.
1.2 Microgrid Concepts

Electricity is the most versatile and widely used form of energy in the world, developed over the past one hundred years. More than 5 billion people have access to electrical energy. The electrical system ranges from power generation and transport to final consumption. Its evolution is ongoing but we urgently need to speed up the development. To mitigate global climate change the electrical system needs to change quickly. A much better system is needed. Hence there is a shift towards smart grid technology and microgrid plays a major role in it. The microgrid can be defined as a power system which has limited geographic extent and contains embedded generation or storage resources or both which may operate parallel to the grid or in isolation mode (Kondanda Ram and Venu Gopala Rao Mannanm 2014; Joydeep Mitra et al. 2011). The future electrical systems will be different from those of the past, where power from all types of generations varying in size and type is tuned to cope with the environmental challenges.

For better understanding of the concept of microgrid an example is taken from the CERTS microgrid. The main points or issues to be noted in building a microgrid are interface, control and protection for each distributed generation, as well as Microgrid voltage control, power flow control, load sharing during islanding, protection, stability, and overall operation. The ability of the Microgrid to operate when connected to the grid as well as smooth transition to and from the island mode is another important function (CERTS microgrid whitepaper).

The Microgrid assumes three critical functions that are unique to this architecture.

- **Microsource Controller** - The Power and Voltage Controller coupled with the microsource provides fast response to disturbances and load changes without relying on communications.
- **Energy Manager** - Provides operational control through the dispatch of power and voltage set points to each microsource Controller. The time response of this function is measured in minutes.
- **Protection** - Protection of a Microgrid in which the sources are interfaced using Power
Electronics requires unique solutions to provide the required functionality (CERTS Microgrid Whitepaper). The microgrid architecture is shown in Fig. 1.1.

![Microgrid Architecture](image)

**Fig. 1.1 Microgrid Architecture, Courtesy CERTS Microgrid**

Balancing power is a major issue for utilities and especially critical with large amounts of intermittent wind and solar energy in the supply mix. If the wind farm is connected to the grid, this kind of fluctuation in generated power from the wind farm may cause stability problems in the system. Similarly, clouds affect the instantaneous energy output from the photovoltaic resources even in the day hours. Bulk storage of electrical energy helps to bridge the time of reduced or missing power to activate reserves. One way to solve this problem is to use additional storage devices. (Energy storage devices like batteries or ultra capacitors are used for this purpose). Battery systems with DC-AC converters are one way of coping with the problem. But storage devices always add to the cost and in effect sometimes make the project economically infeasible. An alternative solution is to use the plug-in-electric vehicles (PEV) as an external storage device and thus mitigate the intermittency of wind and solar resources.
1.2.1 Distributed Generation

In the recent years there has been an increase in the emphasis on utilizing renewable DGs like wind, solar etc. The important motivation behind the bloom in this technology is the sustainability of the resources and environment friendly nature of the same when compared with the coal based generation which is polluting and limited for power generation. In the literature works relating to the possibilities of generating power using wind and solar energy application is extensively abound (Jiayi et al. 2008). It is evident that, as the mentioned sources are variable in nature; optimal operation would be possible by tracking the maximum power point. In this research work, the MPPT for tracking solar is controlled by the incremental conductance method. For optimum control of real and reactive powers in the wind farm, decoupled d-q control is used and PI-type speed controller uses the reference value $i_{qr}^*$ for maximum wind power extraction. The speed command is determined from the maximum wind speed tracking power tracking algorithm. Initially the performance of the microgrid using reconfigured PI controller is studied in two different simulation platforms and the microgrid is controlled in a satisfactory manner. On the other hand, in order to improve the control architecture, a fuzzy logic based control is proposed.

1.2.2 Power Electronic Interface

Power Electronic Interface plays a major role in the control of DGs as well as interconnecting them to the grid and also for cooperative control. It not only enhances the power quality as harmonics are improved due to fast switching of the switches but also offers reactive power support in the grid connected mode of operation. PEI provides flexibility and reduces the potential effects due to the flow of fault current (Sina Parhizi et al. 2015). Microgrids that contain renewable energy DGs like wind and solar PV do not produce constant power as there are fluctuations which results in complex control of microgrid. There are two main control methods for microgrids: master-slave control and peer-to-peer control. The former associates with a voltage-frequency (V-f) control while other DGs associate with P-Q control, to control the active and reactive power to be reached to the planned ones (Che and Chen 2012). The research prospective presented in this work includes a master controller
which follows the peer-to-peer approach and helps in optimal energy management of the hybrid microgrid. Also the coordinated control strategy is adopted so that all entities operate in such a way that constant or a stiff power is supplied to the grid at any point of time irrespective of the variations in climatic conditions. However the fuzzy logic controller improves the system performance which is evaluated based on the total harmonic distortion level.

1.2.3. Standalone and Grid-Connected Mode

When DGs are deployed in practice, there are two modes of operation. One is the standalone mode and the other is grid-connected mode. In grid connected mode of operation the role of the microgrid is to meet the load demand at all the time and offer grid support. When the main grid is gone, the priority is to schedule power to critical loads and also to reduce the cost of operation with maximum satisfaction. The microgrids can be operated in any of the above mentioned modes using simple controllers for seamless transfer of power between different working conditions.

1.3 Power Scenario in India

India is a developing nation wherein there is a never ending chasing game between the electric energy generated and the consumed. There are conventional sources of generation which contribute to the major part of generation. However, this has led to several environmental hazards and there is a growing need to produce electricity in an alternative manner. The concept of microgrid is an excellent option when considering remote locations and also in places where expansion of the main grid is a practical constraint. Not only that, if proper coordinated control is achieved in a microgrid consisting of various distributed energy resources and distributed energy storage systems, it becomes more efficient and optimum. The proposed microgrid can be a futuristic approach which in turn improves the socio-economic status of the country on the whole. To support the idea of self-sustained microgrid, in this work two microgrid configurations using PI controllers are extensively studied. Then an intelligent controller is proposed for optimizing the performance.
The renewable energy scenario in India is shown in Fig. 1.2. History shows that India has shown steady progression in renewable energy generation. It also shows installation of various energy resources as in the year 2009 and projected installed capacity in the year 2032. This steady growth is due to the combined efforts of the government organizations like regional renewable energy development agencies, Ministry of New and Renewable Energy (MNRE) and the participation of private players (Murthy Balijepalli et al. 2010).

Almost 250 million people living in remote locations in developing countries like India are not able to utilize the benefits of the rural electrification scheme. Huge investment is required to connect these isolated places to the central or the respective state electricity grid. Hence electrifying rural areas using DGs may be considered as a viable option. Not only this, semi-urban areas suffer load shedding problems and serious power quality issues. Therefore in India there is huge scope for the deployment of self-sustained microgrids.

In this scenario the Microgrid technology is taking its turn in India through small startups and enterprises. However the viable options of a combined Microgrid where wind and PV resources are connected and coordinated to achieve power quality taking into account their intermittency with the support of an Electric Vehicle have not been extensively explored.
In the proposed work a coordinated control of the master controllers of the DERs is presented which is an appealing and economically a feasible solution for providing reliable power to the remote locations.

There is high potential for the generation of renewable energy from various sources – wind, solar, biomass, small hydro and co-generation bagasse. As on 31-03-14, the total potential for renewable power generation in the country is estimated at 147615 MW. This includes wind potential of 102772 MW (69.9%), SHP (small hydro power) potential of 19749 MW (13.38%), Biomass power potential of 17538 MW (11.88%) and 5000MW (3.39%) from bagasse based cogeneration in sugar mills (http://mospi.nic.in/Mospi_New/upload/Energy_stats_2015_26mar15.pdf). This is shown in Fig. 1.3.

![Sourcewise Estimated Potential of Renewable Power in India as on 31.03.14](http://mospi.nic.in/Mospi_New/upload/Energy_stats_2015_26mar15.pdf)

**Fig. 1.3 Renewable Power in India**

*Courtesy (http://mospi.nic.in/Mospi_New/upload/Energy_stats_2015_26mar15.pdf)*

From the statistics given by the ministry of power, the geographic distribution of the estimated potential of renewable power as on 31.03.2014 clearly shows that Gujarat has the highest share of about 25.04% (36,956 MW), followed by Karnataka with 13.08% share (19,315 MW) and Tamil Nadu with 11.17% share (16,483 MW), mainly on account of wind
power potential (http://mospi.nic.in/Mospi_New/upload/Energy_stats_2015_26mar15.pdf). This statistics is depicted in Fig. 1.4.

![Statewise Estimated Potential of Renewable Power in India as on 31.03.14](http://mospi.nic.in/Mospi_New/upload/Energy_stats_2015_26mar15.pdf)

From the statistical data it is evident that there is enormous potential for microgrids in India and deployment of the same using hybrid combination of wind, solar and electric vehicle has not been explored widely, which is one of the key reasons for undertaking this research work.

### 1.4 Energy Management in Microgrid

Energy management is the term related to the control mechanism in a microgrid which comprises multiple DGs and ESS for optimal operation. It includes various aspects like Predictions of renewable resources, Intelligent scheduling for charging and discharging of the vehicles, Bi-directional power flows (vehicle to grid and grid to vehicle), State of charge (SOC) estimation for vehicle batteries, Forecasting and intelligent scheduling of loads, Dynamic dispatch and Handling uncertainties and variability. In this work, to analyze the performance of the microgrid, the simple PI controller is reconfigured such that most of the points stated above are taken care of effectively. Real field data for solar irradiation and
temperature have been obtained from CWET (Centre for Wind Energy Technology, Tamilnadu, India) for various studies. Taking a deeper look into the control part, an intelligent controller is expected to be capable of enhancing the coordinating control of the microgrid. A comparison is drawn between the PI based controls and fuzzy based control to establish the effectiveness of the proposed controller. Multiple EV configuration is also simulated and the possibility to use a fleet of EVs is proposed.

1.5 Motivation and Problem Statement

Rural India is a potential target for the development of microgrids as there are nearly 250 million people who are still not connected to the grid. In many places even though they are connected to the grid they have limited access to power as they face 16 hours of power outages every day. In this scenario, the Microgrid technology is taking its turn in India through small startups and enterprises. However, the viable options of a combined Microgrid where wind and PV resources are connected and coordinated to achieve power quality taking into account their intermittency with the support of an Electric Vehicle have not been extensively explored.

Nowadays, a Power System that does not fail is the goal of the Electric Utility Service providers. One of the cutting edge technologies which enable a perfect power system is the master controller. To improve the efficiency of a microgrid the master controller coordinates intelligently with the generation and storage depending upon various factors like state-of-charge (SOC) of batteries and schedules the power to be perfect power.

The foremost idea behind the proposed work is to develop a Master Controller which is capable of Energy Management in a photovoltaic (PV), Electric Vehicle (EV) and the wind energy conversion system combined microgrid. The effects of cloud transients and intermittency due to passing clouds are taken into account and the PI controller intelligently schedules the Electric Vehicles depending upon the State-of-Charge of the Ni-MH battery and hence the power utility receives constant power irrespective of the intermittent nature of the Distributed Energy Resources. A coordinated control of the Distributed Energy Resources and
Distributed Storage is achieved using a simple Master Controller. Then an intelligent controller is proposed and the performance of the microgrid is evaluated based on the IEEE 1547 standard.

The comprehensive literature survey revealed that there are many challenges present in coordinating the wind and solar resources with the plug-in electric vehicles, which are listed below.

- Predictions of the wind and solar energy
- Intelligent scheduling for charging and discharging of the vehicles
- Bi-directional power flows (vehicle to grid and grid to vehicle)
- State of charge (SOC) estimation for vehicle batteries
- Forecasting and intelligent scheduling of loads
- Dynamic dispatch and
- Handling uncertainties and variability

In the proposed work a simple coordinated control of the master controllers of the DER’s is presented which is an appealing and economically a feasible solution for providing reliable power to remote locations. The master controller is capable of scheduling the usage of the DER’s and ESS in an intelligent fashion which in turn smoothes the intermittency due to cloud cover and wind speed fluctuations. Another important feature is, the intelligent controller is using fuzzy logic and fault analysis deploying UPFC for support during fault conditions. PSCAD/EMTDC and MATLAB/Simulink platform have been used for simulation studies and hence the results obtained hence will help in the deployment of intelligent and efficient microgrids. The proposed Microgrid power system has been modeled with fuzzy logic controller based battery management system in MATLAB/Simulink environment and the results have been evaluated. The UPFC has been designed in the proposed Microgrid simulated under various fault conditions and its simulation results have also been presented. The simulation results have been evaluated with IEEE 1547 standard and compared with the existing system to prove the effectiveness of the proposed intelligent control system.
1.6 Organization of the Thesis

The thesis has been organized as four chapters. Chapter 1 introduces the concept of microgrid, power scenario in India, Energy management and the motivation and problem statement. The rest of the thesis is organized as follows.

- **Chapter 2** presents the review of literature which provides the background and significance of this research work under various points such as Distributed Energy Resources, Energy Storage Systems, Coordinated Control Strategy, Active and Reactive Power Control and Power Quality.

- **Chapter 3** describes the methodology using which the system is designed. It is discussed in detail under various sub-headings like Design of Wind Energy Conversion System, Modeling and Control of Grid-Connected PV System, Modeling and Control of Grid-Connected Electric Vehicle, Coordinated Control of PV-EV Combined Microgrid, Design and Supervisory Control of Hybrid Microgrid and finally Realistic Modeling and Control of Multiple EV Microgrid, Battery management system and UPFC using fuzzy controller.

- **Chapter 4** explores the results obtained from simulation using PSCAD/EMTDC and MATLAB/Simulink platform and presents the conclusion, major contributions of the work and open the path for future scope of research.
CHAPTER 2

REVIEW OF LITERATURE

2.1 General

The energy crisis is an ongoing social issue which needs to be addressed worldwide. Recently many developing countries have even decommissioned the nuclear power plants after the Fukushima disaster. This has led to the growing need for generating energy in an alternative manner and microgrid technology started becoming more popular. The microgrid can be defined as a power system which has limited geographic extent and contains embedded generation or storage resources or both which may operate parallel to the grid or in isolation mode (Kondanda Ram and Venu Gopala Rao Mannanm 2014; Joydeep Mitra et al. 2011). Microgrid technology is one of the viable solutions for electrification where the expansion of the main grid is either not possible or has no economic justification. The microgrid offers decentralized operation and control which helps to reduce the transmission burden on power utility systems.

Distributed energy resources (DER) are a part of the microgrid which includes photovoltaic (PV), small wind turbines (WT), heat or electricity storage, combined heat and power (CHP), and controllable loads. Among the various DERs, the PV resource is more appealing as it is not having any moving parts and the losses associated with motion are nonexistent. Also, solar power systems are used in applications similar to a generator to supply remote loads. But the main disadvantage of solar power is its intermittent nature. Energy storage is generally recommended in the case of an intermittent source (Pinaki Mitra and Ganesh Venayagamoorthy 2010; Alam et al. 2014).
2.2 Distributed Energy Resources

Distributed energy resources (DER) are nothing but power sources which are down sized and can be operated in clusters to provide adequate power so as to strike a balance between the supply and demand. As renewable energy resources provide excellent economic, environmental and technical benefits, they have attracted the attention of many researchers. Due to these advantages there is rapid growth in the penetration of DGs into the existing conventional grid (Sima Seidi Khorramabadi and Alireza Bakhshai 2012). Normally DGs are connected to the distribution grid rather than the transmission network. There are many types of DGs such as wind, solar PV, micro turbines, fuel cell etc. available in various sizes. Also in many countries due to deregulation of power market, the penetration of DGs has increased tremendously. However, as the number keeps increasing, it is mandatory to have better control techniques for energy management (Edris Pouresmaeil et al. 2013).

In the literature presented by Phatiphat Thounthong et al. 2012, a hybrid microgrid fed by photovoltaic and fuel cell supported by a super capacitor is discussed. Here an intelligent fuzzy logic control is used to estimate the PV/SC/FC. Even though this system is capable of compensating the uncertainties, the cost of the ES is comparatively high. The research work presented in this study overcomes this as cost is considerably reduced. Also there is a huge growth in the usage of PVs on rooftops of residential buildings which in turn has a greater impact on the smart grid scenario where there is a possibility of trading power (Julio Romero Aguero et al. 2012; Ali Elrayyah et al. 2012).

Another important issue to be addressed at this point is the reduction of carbon dioxide footprint in the atmosphere which is mainly contributed by the power grid and transportation industry due to emission of green house gases. Distributed energy resources like wind and solar play a major role in reducing emissions by the above mentioned sectors as the renewables are capable of meeting such targets at attractive prices due to technological advancements (Ahmed Yousuf Saber and Ganesh Kumar Venayagamoorthy 2012). The research work presented in this thesis is focused on the same inclination.
Distributed energy resources can also be termed inverter-based DG units which are further classified as high frequency such as micro-turbine generator, variable frequency such as wind turbine and direct energy such as photovoltaic and fuel cell. In all these cases an interconnected PEI is needed to convert the energy produced from DC to a constant voltage and frequency AC power source (Waleed Abood Baddai Al-Saedi 2013). In this work for the control of wind turbine back-to-back VSCs are used and for the PV and EV, again the controls include VSC. Therefore real and reactive power flow is regulated and energy management is also optimized. The switching frequency is controlled by PLL technique.

2.3 Energy Storage System

It has been shown before that plug-in vehicle parking lots (SmartParks) can be used to absorb the variations caused due to the intermittency of wind power (Venayagamoorthy and Mitra 2011; Xiangjun Li et al. 2013). The idea of using an electric vehicle (EV) as external energy storage can be extended to a solar powered system also. In the near future the rising penetration of PV system may also lead to important impacts on power distribution systems, particularly due to the intermittent nature of its output caused by cloud cover (Aguero et al. 2012; Guishi Wang et al. 2014). Therefore, a coordinated use of the solar powered system with EVs will be a possible solution which can help to maintain a flat power profile to the grid (Sugihara et al. 2013; Alam et al. 2013).

EVs can be coordinated with PV systems in many ways. For example, a dc-dc converter inserted between an EV and the dc bus voltage of a PV system can improve grid integration of PV systems by reducing the ramp rate of the PV inverter output power (Traube et al. 2013; Foster et al. 2013). To reduce the fluctuations in the grid, only slowly changing power can be exported by the use of a high pass filter in the network, which directs rapid power fluctuations to the EV battery. Not only that, to regulate the energy imbalance in the system, the daytime solar-generated power can effectively be converted into night time consumption using the vehicle to grid and grid to vehicle concept (Clement Nyns et al. 2010; Ling Xu et al. 2012a). Also as more and more PV generation is pumped into the existing
power system, the need for an energy storage which is cost effective is emphasized (Changsong Chen et al. 2014; Patterson et al. 2015).

The need of energy storage is emphasized and also before the role of energy storage for the future grid systems is studied, the technical and economic feasibility incorporating the same has to be considered (Qiang Fu et al. 2012; Ling Xu et al. 2012a). In the present power scenario, more than one energy storage devices are used. Hence optimally operating them is one criterion that needs to be justified in order to implement this technology into practice. The penetration of wind power can be maximized with the support of EVs. When large numbers of Evs are connected in a parking lot, it helps to deliver power to the grid and it can be called a smartpark (Ganesh Kumar Venayagamoorthy 2012). In this work the concept of using EV and multiple EV configurations is used in coordination with a hybrid microgrid.

It is also possible to have a vehicle to grid and grid to a vehicle (bidirectional) configuration which helps to improve grid efficiency and reliability. Nevertheless, the automobile industries have increased the production of hybridized vehicles and it is anticipated to increase (Ahmed Yousuf Saber and Ganesh Kumar Venayagamoorthy 2011). Hence a controller for supervising the charging and the discharging becomes the need of the day. There is an agent-based control system available which helps to coordinate the EV’s such that charging is possible when the electricity prices reduce. When idle these electric vehicles are capable of supplying power to the grid which helps in overcoming the effects of intermittency of the renewable energy resources which are widely injected into the grid and this also paves the way for revenue (Wang et al. 2015).

2.4 Coordinated Control Strategy

Control techniques play a major role in the successful operation of a combined microgrid. Many controls need to be addressed depending upon the mode of operation of the microgrid. In grid-connected mode, real and reactive power control is very essential while in autonomous mode control of voltage and frequency becomes a priority. Only when these controls are executed properly the microgrid can act as a reliable source of generation. Proper
control ensures system stability. In this work reference signals are generated and the controllers are tuned to follow the same which enables to obtain perfect power.

It was proposed by the author, that a proper control system using multi-agent based control helps in optimized energy management in both grid connected and islanded modes (Aung et al. 2010). Even though it is shown that real-time control is achieved, the control strategy is quite complex. The concept of microgrid offers competent solution for combining advanced components and enabling technologies which helps in meeting load demand. A decentralized control architecture based on agent-based decision making is proposed. It takes care of on grid market price, resources available to the DERs and environmental perspectives (Colson et al. 2013). In another literature, a real-time simulation platform for analyzing the smart grid is suggested. It is capable of simulating complex structures like integration of communication systems and electric power systems (Feng Guo et al. 2013).

Another control method is a pseudo droop control structure where DGs operated in islanded mode are streamlined for harvesting maximum energy. The overcharging of battery is also monitored in this algorithm in order to avoid damage consequences (Emanuel Serban and Helmine Serban 2010). Seamless transfer of power for smoothing fluctuations in a microgrid will help in islanding operation with improved reliability and reduced disturbance levels. Here the DGs are segregated as master and slave wherein the masters control the fluctuations and the slaves act as a current source, thus regulating power in islanded mode (Zeng Liu and Jinjun Liu 2012).

Protection of the microgrid is another issue which calls for attention. Protection needs to be addressed in terms of grid-connected as well as autonomous mode of operation. The scheme of protection includes fault identification in both modes and fault clearing. In some cases admittance relays are used, which has inverse time characteristics based on the measured admittance of the line (Manjula Dewadasa et al. 2009). Protection can also be defined in the customer-driven microgrid which features embedding the scheme into the DGs converter control scheme. This is a novel feature which needs more research exploration for implementation (Fang Peng et al. 2009).
The increase in penetration of DGs paves the way for cooperative control schemes where micro sources and energy storage systems are operated in coordination for better power quality (Jong Yul Kim et al. 2010; Guo Li et al. 2012). A simple coordinated control algorithm developed to coordinate different DGs like photovoltaic PV, fuel cell and Li-ion battery is taken into consideration. A predictive control algorithm is used which enables faster computational time wherein steady-state and transient problems are analyzed separately. However, to incorporate this in a smart grid peak shaving and load shedding needs to be addressed (Tan et al. 2013). Another combination discussed in coordinated control method is PV and battery where PV array operates in power control mode (Ling Xu et al. 2012b).

2.5 Active and Reactive Power Control

Smart Parks is a term that is used in smart grid environment which is closely related to the control of active and reactive powers in a microgrid. When a fleet of electric vehicles are parked in a parking space, it will enable vehicle to grid transaction. Hence it is referred to as Smart Park, as it offers grid support. The advantage of using this technique is that reactive power can be injected to the grid without reducing the state of charge of the battery. In the process only a small amount of real power will be lost which is compensated by the vehicle itself (Ganesh Kumar Venayagamoorthy 2012). The main benefit of using electric vehicles is, it is a cost effective solution for smoothing variations due to intermittent sources and offers grid support as mentioned earlier (Ahmad Zahedi 2012). In the present research work, a simple logic for the PI controller is introduced which helps in power sharing between multiple EVs and flattens the fluctuations caused by varying renewable DGs. Hence the usage of FACTs devices can be eliminated for reactive power compensation.

2.6 Power Quality

The Institute of Electrical and Electronics Engineers (IEEE) is a standard body which has defined power quality in its Authoritative Dictionary as "the concept of powering and grounding electronic equipment in a manner that is suitable to the operation of that equipment and compatible with the premise wiring system and other connected equipment." Utilities may want to define power quality as reliability. This is a standard definition for power quality. PQ
is an important issue for electricity consumers at all levels of usage, particularly industries and the services sector. As sensitive power electronic equipments are used extensively and the usage of non-linear loads in industries for commercial purpose and domestic applications, power quality is becoming an issue. In such an environment, problems like power surges/sags, poor voltage and frequency regulation, harmonics, switching transients, electrical noise and the Electro-Magnetic Interference effect are frequently encountered. This leads to damage of capital-intensive appliances, safety concerns, loss of reliability and above all a huge economic loss (http://www.apqi.org/about-us/power.php).

To improve power quality, converter based systems are used for control (Jeffrey Bloemink and Reza Iravani 2012). Decoupled control i.e., a virtual ω-E frame droop method is very effective in power control and organizing the flow of real and reactive powers (Yan Li and Yun Wei 2009; Yan Li and Yun Wei 2011). It is becoming more and more important to maintain the power quality of the system to which DGs are connected without using auxiliary equipment. When coordinated control in combination with energy storage is implemented better quality of power is ensured (Phatiphat Thounthong et al. 2012). This research work focuses on meeting this objective to provide stiff power at advantageous price incorporating decoupled d-q control strategy for converter.

2.7 Vehicle to Grid Transaction

As the number of electric vehicles keeps increasing worldwide, they have started to become more predominant in the power sector. These vehicles participate in vehicle to grid (V2G) transaction which enhances some key points like regulating the spinning reserve, voltage support for reactive power compensation, revenue generation and contingency support (Mitra et al. 2010). Plug-in electric vehicles are provided with larger battery to offer grid support and also help to decrease the carbon emission by the transportation sector. Bi-directional power conversion capability with the incorporation of PEI is a boon for modernizing existing power grids (Linni Jian et al. 2013).
PEVs can act as a load or a distributed energy resource providing power due to the V2G transaction concept. It can improve the performance of the conventional grid in various aspects such as efficiency, stability and reliability. As discussed earlier it offers excellent reactive power compensation (Murat Yilmaz and Philip Krein 2013; Lanka Udawatta et al. 2012). In this work the hybrid microgrid is supported by EVs to provide a stiff source to the grid.

2.8 Intelligent Control

Even though the reconfigured PI based control gives satisfactory output parameters, a fuzzy logic based MPPT controller can enhance the overall performance of the microgrid under partial shading conditions (Alajmi et al. 2013). In another literature a fuzzy logic based SEPIC converter is modeled for MPPT (El Khateb et al. 2014). When non-linear loads are predominant in a power network, there exists a mismatch between the voltage and frequency especially if the penetration of solar PV is huge. Hence to obtain regulation of voltage a D-STATCOM is incorporated. When FACTS devices are used, the system effectiveness improves (Indumathi et al. 2012). Fuzzy based battery management system also proves to be efficient where charging and discharging is controlled by fuzzy rules and power deficiency is taken care of (Venkateshkumar 2016). Recently hierarchical control in microgrid is becoming more important as it is flexible and ensures reliability. In this literature quoted, battery storage is used for power back-up. The interfacing of PV resources is studied under various conditions like, variation in irradiation level, MPPT, centralized control of real and reactive powers and coordinated control (Wandhare et al. 2014). However, intelligent techniques are not applied.

In this work, the IEEE 1547 standard is adopted for modeling the intelligent hybrid microgrid. This standard is defined basically to meet out the technical requirements which can be adopted globally. It focuses on the technical specifications for, and testing of, the interconnection itself, and not on the types of the DR technologies. This standard aims to be technology-neutral, although cognizant that the technical attributes of DR and the types of EPSs do have a bearing on the interconnection requirements. The addition of DR to an EPS will change the system and its response in some manner (Basso and Friedman 2003). Now-a-days, since fossil fuel based power generation does not meet the consumer power demand due
to its availability and pollution, researchers are focused on alternative ways for power generation with reduced environmental pollution and carbon footprint. The proposed intelligent microgrid which is self-sustained will definitely pave the path for exploiting the technological advancements in the field of renewable generation and making the grid better and better.

2.9 Inference and Major Contributions

In this section the inference from the literature survey and the major contributions of this research work is discussed.

2.9.1 Inference

From the brief review of literature presented in the foregoing pages, it is clear that the electric energy sector is constantly evolving in new dimensions across the globe. There is a gradual changeover in the energy generation technologies from the centralized to the decentralized, especially in the case of microgrid technology. As mentioned earlier, remote microgrids are becoming popular since such systems are enormously potential to electrify places which are still not connected to the grid via transmission and distribution networks (Sheeba Percis, et al. 2015c). In the near future, the relevance of microgrids is expected to open new platforms in developing countries which in turn will create a turnover in the utilization of renewable energy resources like wind, solar, biomass, water and energy storage systems.

Some of the microgrid models reviewed above have not taken into consideration the needs of the user (on field specifications) into account (Adhikari and Fangzing Li 2014). A field-based study will help in realizing the technology in a better way. Also, any renewable energy microgrid basically is designed considering the technical and economic problems. A proper energy management system will definitely reduce the cost of the system on the whole with added technical benefits (Tummuru et al. 2015).

However, in order to generate more confidence in this technology, the system has to be exposed to realistic field data. This is one of the most important objectives of this work,
where, a grid connected combined PV and EV system is thoroughly modeled and studied by incorporating the real field data in PSCAD/EMTDC environment. In order to verify the performance of the PV-EV combined microgrid, field data (solar irradiance and temperature) obtained from Centre for Wind Energy Technology (CWET), Chennai, Tamilnadu, India, have been used. The results obtained shows that this Electric Vehicle technology in coordination with the solar PV generating unit gives a smooth power output to the grid (Sheeba Percis et al. 2015a).

A coordinated control strategy by reconfiguring the PI controller is achieved in this work and hence the cost of the microgrid is obviously reduced. The master controller is capable of state-of-charge estimation, intelligent scheduling of EVs, dynamic dispatch, bi-directional power flow and also handling uncertainties. It is capable of scheduling the usage of the DER’s and ESS in an intelligent fashion which in turn smoothes the intermittency due to cloud cover and wind speed fluctuations. PSCAD/EMTDC has been used for simulation studies and the results obtained hence will help in the deployment of efficient microgrids (Sheeba Percis et al. 2015b).

Another case study has been done in MATLAB/Simulink platform where UPFC is included in the hybrid microgrid model and the system has been studied under various fault conditions. The proposed intelligent controller is capable of providing uninterrupted power and the FACTS device helps to improve the power quality of the system.

2.9.2 Major Contributions of the Thesis

The major contributions of this work titled “Modeling and Control of Wind Energy Conversion System Coordinated with other Distributed Energy Resources” is listed as follows,

- Incorporation of real field data to support the V2G and G2V transactions in the PV-EV combined Microgrid
- Multiple Electric Vehicle Configuration for grid support
• Intelligent Master Controller by reconfiguring the PI Controller for controlling the voltage and frequency of the microgrid
• Decoupled d-q control of the DFIG based WECS with Current Controlled PWM and Hysteresis Control
• Coordinated control of the DER and DES using the master controller
• To enhance the energy management and hence the reliability of the system using fuzzy logic controller
• To improve the power quality of the microgrid (stiff power source) by incorporating UPFC
• Study of the system effectiveness by comparing reconfigured PI and fuzzy logic controllers
• Fault analysis to evaluate the performance of the unified power flow controller
• Intelligent battery management system and PLL for synchronizing PV and wind power
• The intelligent controller has been used for MPPT of Photovoltaic power system and improves PV system generation level as much close to maximum power generation range
CHAPTER 3

METHODOLOGY

3.1 System Design

This thesis deals with the detailed modeling and intelligent control of wind energy conversion system coordinated with other distributed energy resources like solar PV and energy storage system which in this case is an electric vehicle. The simulation is carried out in both PSCAD/EMTDC and MATLAB/Simulink software platform. Also in order to validate the operation of the microgrid under study, real field data for solar irradiation and temperature obtained from the Centre for Wind Energy Technology (CWET) were incorporated. A comparative study between the reconfigured PI controller and intelligent fuzzy controller was done in order to prove the effectiveness of the proposed intelligent model. Another idea is proposed, where multiple EVs can be operated in parallel using the reconfigured PI control. The response of the hybrid microgrid is discussed in the following chapter while the methodology adopted for design is elaborated in this chapter. The simulation of the hybrid microgrid was carried out under various subtitles as follows:

- Microgrid model in PSCAD/EMTDC
  - Design of Wind Energy Conversion System
  - Modeling and Control of Grid-Connected PV System
  - Modeling and Control of Grid-Connected Electric Vehicle
  - Coordinated Control of the PV-EV Combined Microgrid
  - Design & Supervisory Control of the Hybrid Microgrid
  - Realistic Modeling & Control of PV and Multiple EV Microgrid

- Microgrid model in MATLAB/Simulink
  - Wind Turbine model
  - Solar PV model
• PI controller based PLL
• Proposed model of Intelligent Controller using fuzzy logic
• Intelligent battery management system
• Modeling of UPFC and study under various fault conditions

3.2 Case Study 1 - Microgrid Model in PSCAD/EMTDC

The detailed design of wind energy conversion system is illustrated in this section under various titles like Doubly Fed Induction Generator, decoupled d-q control, rotor side converter control and grid side converter control. In this work a Doubly Fed Induction Generator (DFIG) is used in coordination with IGBT based PWM voltage source converters.

3.2.1 Doubly Fed Induction Generator

Since there is enormous scope for generating power using wind turbines, it is one of the most exploited technologies from the microgrid point of view. Generally wind turbine generator (WTG) systems employ Squirrel cage Induction machines to capture wind energy. The main limitation of this system is that it does not allow control of speed and hence voltage and frequency cannot be controlled too. Therefore a better option would be to opt for Doubly Fed Induction Generators (DFIGs) due to its undisputed advantages. DFIGs are variable speed machines which are capable of providing active and reactive power control, enhanced power quality and also fault ride-through capability.

DFIG control can be classified into two modes. If the wind speed is below the rated value, the wind turbine is operated in variable speed mode. On the other hand, if the wind speed is above the rated value, the pitch control is activated to increase the wind turbine pitch angle to reduce the mechanical speed of the machine.

The general block diagram of a DFIG is depicted in Fig. 3.1. It shows the grid side converter and the rotor side converter connected through a DC link capacitor. Since vector
control is used the power quality of the active power supplied to the system is improved. The control of DFIG is achieved in two stages,

- Rotor side converter control
- Grid side converter control

The main objectives of the rotor side converter are to regulate the DFIG rotor speed for maximum wind power capture, maintaining the DFIG stator output voltage frequency constant and controlling the DFIG reactive power. These objectives can be achieved by adopting rotor current regulation in the stator flux oriented reference frame. In this work the control system is designed in such a way that the maximum possible wind power is extracted by employing decoupled control of real and reactive powers employing current regulated control. Vector control is incorporated as it is capable of effectively controlling the real power without affecting the reactive power and perfect decoupled control is achieved. The desired values of the real and the reactive powers are determined by the power electronic interface. Therefore, the DFIG and the converter behave similar to those of a current-regulated VSC.

![Fig. 3.1 Structure of a DFIG (Courtesy Andreas Peterson 2005)](image-url)
In general the configuration of the DFIG has a wind turbine which is connected through a set of mechanical shafts consisting of a low speed and a high speed shafts which are interconnected through a gearbox. In this work the induction machine used is a wound rotor induction generator (WRIG). The stator is directly connected to the grid while the rotor is fed through a variable frequency converter (VFC), which only needs to handle a fraction (25-30%) of the total power to achieve full control of the generator. The flow of power between the rotor circuit and the grid should be controlled in magnitude and direction. In this case the voltage fed converter consists of two back-to-back connected PWM controlled IGBT based PEIs. Both the converters are connected through a DC link capacitor.

The power output of the DFIG is a combination of the power coming out of the machine’s stator and that from the rotor through the converter to the grid. Since back-to-back converter is connected to the rotor, it has to handle only power rating of the maximum operating slip times rated power of the machine. The air gap power for an induction motor is \( P_{ag} = sP_{input} \). Thus, if slip ‘s’ is negative, the direction of power flow would be from rotor to stator. As the rotor is connected to a converter, the slip power flows out of the converter to the grid. As a result, the induction generator operates at super-synchronous speed and power is fed from both stator and rotor sides to the grid. When the unit is operating at sub-synchronous speed, real power is absorbed by the rotor from the grid through the converter. At synchronous speed, the voltage at the rotor is essentially DC and there is no significant exchange of power from the rotor to grid. In this work, a 0.9 MVA wound rotor induction generator operated at a frequency of 50 Hz is connected to the wind turbine. The Wound Rotor Induction Generator is equipped with back-to-back connected IGBT based converters which are controlled using current reference hysteresis control PWM technique. The machine parameters used are shown in Fig. 3.2. The actual model simulated in PSCSD/EMTDC is shown in Fig. 3.3.
Fig. 3.2 Machine parameters

Fig. 3.3 Simulated Wind turbine in PSCAD/EMTDC
3.2.2 Design of Wind Farm

The detailed model of the wind turbine is discussed in this section. The various subsystems are individually modeled and assembled to form the final wind farm. The wind turbine is modeled based on equation 1. The power extraction from wind turbine is governed by the given equation. The rotor diameter taken for this work is 40 meters. The wind power extracted from the turbine is given in Fig. 3.4.

\[ P = \frac{1}{2} \rho v^3 \pi r^2 C_p \]  

(1)

where,

‘P’ is Mechanical power in watts
‘\rho’ is air density in kg/m\(^3\)
‘v’ is wind speed in m/sec
‘r’ is wind turbine rotor radius in meter
‘\(C_p\)’ is Coefficient of efficiency or power coefficient

![Diagram](image.png)

**Fig. 3.4 1MW Wind farm**

3.2.3 Control of DFIG

As the rotor and grid side converters handle AC quantities of slip and grid frequencies respectively, they are controlled utilizing vector control techniques. As discussed before,
vector control is based on the concept of developing a rotating reference frame based on AC flux or voltage, and project stator and rotor currents on such a reference frame. Such projections are usually referred to $d$-$q$ axis components of their respective currents; with a suitable choice of reference frames, AC currents appear as DC currents in steady state. For flux based rotating reference frame (applicable for rotor side converter) the $d$-axis rotor current component controls the reactive power of the generator, whereas $q$-axis rotor current component controls the active power or torque.

In voltage based reference frame (and thus $90^0$ ahead of flux based reference frame) the effect is opposite, i.e., $d$-axis current component controls the active power, whereas $q$-axis component controls the reactive power. This is applicable for grid side converter shown in Fig. 3.5. In the DFIG designed in this work, the reference levels are in turn typically set by controllers such as,

- An electrical torque controller driving the rotor-side converter $i_q$ current component (flux based controller);
- A capacitor voltage controller driving the grid-side converter $i_d$ current component (voltage based controller);
- Power factor and/or AC voltage controllers driving the $i_d$ and $i_q$ current components on either (or both) rotor side or grid side converters respectively.

### 3.2.4 Rotor Side Converter Control

In d-q reference frame, the sinusoidal command tracking problem is converted into a DC command tracking problem. Therefore, the PI controller can be used effectively as the PI controller finds it difficult to track the command if it is a continuously varying signal. The objectives of the rotor side control are as follows,

- Regulating the DFIG rotor speed for maximum wind power capture
- Maintaining the DFIG stator output voltage frequency constant
- Controlling the DFIG reactive power
The above mentioned objectives are achieved in this work by incorporating rotor current regulation in the stator-flux oriented reference frame. In stator flux oriented reference frame, the d-axis is aligned with the stator flux linkage vector \( \lambda_s \), which means \( \lambda_{ds} = \lambda_s \) and \( \lambda_{qs} = 0 \). Therefore according to the two axis-equations of the DFIG, the following relationships can be obtained.

\[
\begin{align*}
    i_{qs} &= \frac{-L_m i_{qr}}{L_s} \\
    i_{ds} &= L_m \left( i_{ms} - i_{dr} \right)/L_s \\
    T_e &= -\frac{3}{2} \frac{p}{2} L_m^2 i_{ms} i_{qr}/L_s \\
    Q_s &= \frac{3}{2} \omega_s L_m^2 i_{ms} \left( i_{ms} - i_{dr} \right)/L_s \\
    v_{dr} &= r_r i_{dr} + \sigma L_r \frac{d i_{dr}}{dt} - s \omega_s \sigma L_r i_{qr} \\
    v_{qr} &= r_r i_{qr} + \sigma L_r \frac{d i_{dr}}{dt} + s \omega_s \left( \sigma L_r i_{dr} + L_m^2 i_{ms}/L_s \right)
\end{align*}
\]

where,

\[
i_{ms} = \frac{v_{qs} - r_r i_{qs}}{\omega_s L_m} \quad \text{and} \quad \sigma = 1 - \frac{L_m^2}{L_s L_r}
\]

It is understood that,

\[
\begin{align*}
    v_{dr} &= r_r i_{dr} + \sigma L_r \frac{d i_{dr}}{dt} - s \omega_s \sigma L_i i_{qr} \\
    v_{qr} &= r_r i_{qr} + \sigma L_r \frac{d i_{dr}}{dt} + s \omega_s \left( \sigma L_r i_{dr} + L_m^2 i_{ms}/L_s \right)
\end{align*}
\]

Here, \( v_{dr} \) and \( v_{qr} \) depend on both \( i_{dr} \) and \( i_{qr} \) but the main aim is to decouple them. Hence the following equations hold good.

Let

\[
v_{dr1} = r_r i_{dr} + \sigma L_r \frac{d}{dt} i_{dr} \quad (10)
\]
\[ v_{qr1} = r_r i_{qr} + \sigma L_r \frac{d}{dt} i_{qr} \]  

(11)

Since the above equations are perfectly decoupled, it is set as follows:

\[ v_{dr1} = \left( k_{pr} + \frac{k_{lr}}{s} \right) (i_{dr}^* - i_{dr}) \]  

(12)

\[ v_{qr1} = \left( k_{pr} + \frac{k_{lr}}{s} \right) (i_{qr}^* - i_{qr}) \]  

(13)

Therefore the reference voltages now become,

\[ v_{dr} = \left( k_{pr} + \frac{k_{lr}}{s} \right) (i_{dr}^* - i_{dr}) - s \omega_s \sigma L_r i_{qr} \]  

(14)

\[ v_{qr} = \left( k_{pr} + \frac{k_{lr}}{s} \right) (i_{qr}^* - i_{qr}) + s \omega_s \left[ \sigma L_r i_{dr} + \frac{L_m^2}{L_s} i_{ms} \right] \]  

(15)

The equations and Fig. 3.5 indicate that the DFIG rotor speed \( \omega_r \) can be controlled by regulating the q-axis rotor current components, \( i_{qr} \). It is also indicated that the stator reactive power \( Q_s \) can be controlled by regulating the d-axis rotor current component, \( i_{dr} \). Consequently, the reference values of \( i_{dr} \) and \( i_{qr} \) can be determined directly from the stator reactive power (\( Q_s \)) and DFIG rotor speed (\( \omega_r \)) commands. In this work a PI controller generates the reference value \( i_{qr}^* \) for maximum wind power extraction. The speed command \( \omega_r^* \) is determined from the maximum wind power tracking algorithm.
In order to align the d-axis of the rotating frame of the stator magnetic flux, the instantaneous angular position of the stator magnetic flux has to be determined. The angular position is determined from the three phase voltages \( v_a \), \( v_b \), and \( v_c \) respectively. Initially the three phase voltage is converted or transformed so that \( v_{alpha} \) and \( v_{beta} \) are obtained. Then it is passed through the filter circuit to get rid of any transients present. The PSCAD/EMTDC simulation of the above is shown in Fig. 3.6. Since the magnitude of the stator flux and angular position is determined in a precise way using the above circuit, the d-axis of the synchronous rotating frame can be aligned as required.

Fig. 3.5 Rotor side Converter Control

Fig. 3.6 Calculation of stator flux magnitude and phase angle
Once the stator flux magnitude and phase angle is determined, the three-phase current source in the stationary a-b-c frame can now be controlled using reference currents specified by the power electronic control system in the d-q frame. After the desired current values are obtained it is again transformed into stationary a-b-c frame which is then injected into the grid. The controls exhibited are shown in Fig. 3.7 and 3.8. The Fig. 3.8 shows the control which integrates the rotor speed in order to obtain position of the rotor.

![Diagram](image)

**Fig. 3.7 Calculation of slip angle**

Thus with a reference frame attached to the rotor, the position of the stator’s magnetic field vector can be determined from slip angle referred in Fig. 3.7. The desired or the commanded rotor currents are obtained from the inverse d-q transformation by using the slip angle as shown in Fig. 3.8.

![Diagram](image)

**Fig. 3.8 Calculation of reference currents**

Here the switch is used so that the PI controller will work only after $t = 0.5$ seconds. Now the PI controller is used to eliminate the error in actual speed $W_{pu}$ and speed reference $W_{ref}$. The output of PI will be the current that is required to maintain rotor speed as required. S
to T mode means speed to torque mode. Initially the machine is run in constant speed mode for a few seconds and then it is converted to torque mode, where the torque input is coming from Wind Park.

### 3.2.5 Current Reference PWM Control with Hysteresis Band Control

The instantaneous value of the stator’s rotating magnetic field is given by $\lambda_s$. It is also seen that the rotor is rotating at the rotor angle $\lambda_r$ which is again an instantaneous value. Using the inverse d-q transformation, the commanded values of rotor currents, $I_{r\text{ref}}$, $I_{b\text{ref}}$ and $I_{c\text{ref}}$ are calculated using slip angle which is the difference between the stator and the rotor fluxes, the PWM signals can be generated for the IGBT based Voltage Source Converter using the circuit shown in Fig. 3.9. One of the important features of the current regulated PWM technique is hysteresis control method.

The main task of the control system in current regulated PWM inverters is to force the current vector in the three phase load according to a reference trajectory. The hysteresis band current control is one of the simplest methods of control and hence applied in this work. The basic implementation is based on deriving the switching signals from the comparison of the current error with a fixed tolerance band.

![Fig. 3.9 Generation of triggering pulses for RSC](image)

Another important requirement of the rotor side converter is a stiff DC source at its input which is provided by the grid side converter. The objective of the grid side converter is to maintain the value of the DC link capacitor constant and it is discussed in the next section.
3.2.6 Grid Side Converter Control

The other control in the back-to-back connected converter circuit is the grid side controller whose objectives are listed as follows,

- One is to keep the dc-link voltage constant regardless of the magnitude and direction of the rotor power
- Also, the grid side converter supplies reactive power to the grid and controls the stator terminal voltage. The control block diagram is shown in Fig. 3.10

The equations governing the grid connected voltage source converter are depicted in the following section.

\[ v_{dg} = r_g i_{dg} + L_g \frac{d}{dt} i_{dg} - \omega_s L_g i_{qg} + v_s \]  
\[ v_{qg} = r_g i_{qg} + L_g \frac{d}{dt} i_{qg} - \omega_s L_g i_{dg} \]

In a synchronously rotating frame, with the d-axis aligned to the grid voltage vector \( v_s \) (\( v_s = v_{ds}, v_{qs} = 0 \)), the grid side converter can now be commanded as given below.
\[ v_{dg} = \left[ k_{pg} + \frac{k_{ig}}{s} \right] (i_{dg}^* - i_{dg}) - \omega_s L_g i_{ag} + v_s \]  \hspace{1cm} (18)

\[ v_{ag} = \left[ k_{pg} + \frac{k_{ig}}{s} \right] (i_{ag}^* - i_{ag}) - \omega_s L_g i_{dg} \]  \hspace{1cm} (19)

In the above equation \( i_{dg}^* \) is generated from the DC voltage controller and \( i_{ag}^* \) is generated from the reactive power or AC voltage controller. It is also evident that the DC voltage across the DC link capacitor can be controlled by controlling \( i_{dg} \).

The decoupled d-q control which is established in this work using PSCAD/EMTDC is shown in Fig. 3.11. It is also possible to control the \( d \)-axis current by controlling the \( d \)-component of the PWM output waveform and the \( q \)-axis current via the \( q \)-component. However, the control response is very poor as any change in \( i_d \) will cause a corresponding change in \( i_q \) (Farhad Shania and Mohammad Sharifian 2008). Therefore the PI controller is reconfigured such that a change in \( i_d \) will in turn not change \( i_q \).

By adjusting the value of real power, the voltage across the DC link capacitor is maintained at rated value by choosing proper \( I_{dref} \). As shown in Fig. 3.12, the actual voltage across the DC link capacitor \( E_{cap} \) is compared with the desired voltage \( E_{capref} \) and passed through a PI controller to generate the value of \( I_{dref} \). The \( q \)-component is set to zero and therefore decoupled control is achieved. Once \( i_{dref} \) and \( i_{qref} \) are generated, it is converted to the
stationary reference frame using inverse transformation and then the current references are used to generate the PWM pulses for the grid side converter, thereby fulfilling the purpose of the grid side converter circuit in maintaining a stiff DC voltage and also providing reactive power compensation.

Fig. 3.12 Generation of triggering pulses for GSC

The control of the wind turbine using current regulated PWM is discussed in detail, where the grid side converter control and the rotor side converter control established through decoupled d-q control are effective in producing a constant power output from the turbine system which is also used in the hybrid microgrid model to offer grid support. The output power extracted from the wind turbine is 0.86 per unit which is shown in Fig. 4.2. The active power output shows that the wind turbine system is operating successfully.

3.2.7 Modeling and Control of Grid-Connected PV System

In general a grid-connected photovoltaic system is helpful in converting the energy from the sun light into electrical energy, which can be used to give grid support. Therefore, a photovoltaic PV system normally consists of a Maximum Power Point Tracking (MPPT) unit, PV modules, an inverter and controls for the same. In the existing techniques for modeling the
components mentioned, it takes quite a long processing time. Due to unlimited time constraints, the testing is also difficult and all components might not be covered. Sometimes predictive algorithms may not give accurate results. The typical grid-connected PV system is depicted in Fig. 3.13 (Daniel Riley and Ganesh Venayagamoorthy 2011).

![Typical Grid Connected PV System (Daniel Riley et al. 2011)](image)

**Fig. 3.13 Typical Grid Connected PV system (Daniel Riley et al. 2011)**

Nowadays since high penetration of solar PVs is seen across the electricity grids, the effect of intermittency due to moving clouds which causes significant fluctuations in the voltage is a serious problem. One of the solutions is to use the photovoltaic PV system not only to generate active power but also provide ancillary services like reactive power compensation. However, it is not economical and also complexity in implementation is a major drawback (Wenxin Peng et al. 2012). As an alternative in this study, the real field data is fed as the input to the PV arrays and an electric vehicle is connected to provide compensation during cloud transients thus improving power quality. The block diagram of the grid-connected PV system designed in this work is shown in Fig. 3.14.
In this work, a 100 kW solar farm (Fig. 3.14) is modeled in PSCAD/EMTDC platform. The parameter values of all the passive components are obtained from the MATLAB demo model of a 100 kW solar PV system. Ten numbers of modules are connected in series and eight numbers of modules are connected in parallel. There are 216 cells connected in series per module and eight cells in each string per module in series. The series resistance per cell is 0.02 ohm and the shunt resistance is 1000 ohm. The input to the PV module is nothing but the solar irradiance and the temperature. The DC-DC converter is used to boost the output of the PV module. The firing pulse of the DC-DC converter is generated through the MPPT control logic. The output of the converter is connected to the grid through a three phase current controlled PWM inverter. The actual simulated model is shown in Fig. 3.15.

All the simulations were carried out with a 100 minutes data set. However, in PSCAD, it was quite time consuming to actually run a 100 minute data set when the simulation time-step was 50 μs. Such a small time-step had to be used in order to achieve the high frequency switching of the power electronic converters which were modeled in quite detail in this work. In order to obtain a realistic solution to this problem, the 100 minute data set was used with one second interval in the PSCAD model. Fig. 4.8 shows, how the irradiance and temperature varied during the time interval mentioned before. Due to that variation, the output of the solar PV system changed, which is shown in Fig. 4.9. The output of the PV array varies within the
range of 80 kW to 130 kW. This power was captured using the MPPT algorithm and it is discussed in the next section. The parameters of the solar PV array is given in Fig. 3.16.

Fig. 3.15 Actual simulation in PSCAD/EMTDC

Fig. 3.16 Parameters of Solar PV array

3.2.7.1 Modeling of the Boost Converter

In the curve plotted between power and voltage of the PV array, it is noticed that a point exists where maximum power is produced. In other words, peak power is generated at a particular value of voltage and current which is defined as the maximum power point. Since the efficiency of the solar PV array is less (around 13%), it is desirable to operate the PV module at the MPPT such that maximum power can be delivered even under varying climatic
conditions. Therefore, an MPPT controller is used in coordination with a DC-DC converter such that the system achieves the targeted power output from the PV array.

When varying resources like wind, PV etc are used, it is always better to use a Maximum Power Point Tracking system that is mandatory for operating the entity with maximum efficiency. The MPPT is based on irradiation and temperature which keeps varying with respect to time. Though there are many techniques used for this purpose, the incremental conductance method gives accurate results. The flow chart for incremental conductance is given in Fig. 3.17 (Ratna Ika Putri et al. 2014).

![Flow Chart](image-url)

**Fig. 3.17 Example Flow Chart – Incremental Conductance**
From the above flow chart it is understood that after measuring the PV panel voltage and current, the changes in those of values $dV$ and $dI$ are calculated. The algorithm is based on the fact that the slope of the PV array power curve is zero at the Maximum Power Point (MPP), positive on the left of the MPP, and negative on the right. The MPP can thus be tracked by comparing the instantaneous conductance ($I/V$) to the incremental conductance ($\Delta I/\Delta V$).

![Flowchart](image)

**Fig. 3.18 MPPT and Control of Boost Converter**

As discussed earlier, it is very important to extract the maximum possible power from the panel using Maximum Power Point Tracking (MPPT) algorithm. The algorithm is embedded inside the control of the boost converter. The implementation of MPPT based boost converter control in this work is presented in Fig. 3.18 which shows that the output current ($I_{pv}$) and output voltage ($V_{pv}$) of the PV module are passed through a first order low pass filter. The MPPT block uses the Incremental Conductance Algorithm for tracking the required point. The algorithm is based on the fact that the slope of the PV array power curve is zero at the Maximum Power Point (MPP), positive on the left of the MPP, and negative on the right. The MPP can thus be tracked by comparing the instantaneous conductance ($I/V$) to the incremental conductance ($\Delta I/\Delta V$).

The output of the MPPT block is the MPP voltage ($V_{mpp}$). This is the voltage at which the PV module has to operate to extract maximum power. The algorithm decrements or increments $V_{mpp}$ to track the maximum power point when operating under varying climatic conditions and passing clouds. This voltage ($V_{mpp}$) is then compared with the measured PV
panel output voltage ($V_{pv}$) and is fed as the input to PI controller. The output of the PI controller is used to generate the switching pulses for the boost converter. The MPPT control realized in PSCAD/EMTDC environment is shown in Fig. 3.19.

Fig. 3.19 PSCAD/EMTDC model of MPPT and the control of boost converter

A capacitor used in the DC link as shown in Fig. 3.15 helps to minimize the ripples produced by the PV resource current. The DC-DC converter is used in order to maintain the voltage across the same. Here a reference voltage is generated and fed to the PI controller which forces the voltage across the PV array to follow the same without any deviation. The output from the solar PV resource, namely $I_{pv}$ and $V_{pv}$ which are the output current and voltage being initially passed through a first order filter which has magnitude of $G=2$ and time constant $T=0.01$ second. This enables in filtering the harmonics and any other disturbances like high frequency components from the input signals.

As seen in Fig. 3.19, the output from the filter circuit is given to the MPPT block where incremental conductance algorithm is applied to track the point where maximum power is generated. Hence the circuit tends to trace the MPP from the varying of solar data (irradiation and temperature) which has been obtained from Centre for Wind Energy Technology (CWET) for research purpose, in order to incorporate real field values and obtain a realistic model. The boost converter combined with the MPPT block is capable of effectively extracting maximum power from the given solar data and thus better control is obtained.
The duty cycle of the boost converter is generated by a comparison between the solar voltage $V_{pv}$ and the reference voltage $V_{mpp}$. This is fed as input to the PI controller which in turn controls the duty cycle of the converter based on the difference. The output of the PI controller is then compared with a saw-tooth wave which has a range of 0 to 1. The comparator defines the output as 1 if A is greater than B and 0 otherwise, which produces pulses with magnitude 1 and pulse width of the same depends on the duty cycle. From this logic the PWM signal is generated successfully.

When the PWM signal $T_1$ is given to the IGBT’s gate terminal, the converter is either switched ON or OFF depending on the width of the pulse. When the converter is ON, the diode which is connected with it and is reverse biased. Since the circuit is now open, the inductor is charged and the maximum rate of change of output voltage is limited or in other words controlled. The ripples in the voltage are reduced by the capacitor which acts as a filter. On the other hand, if the converter is in OFF position, the diode is forward biased, therefore, a path is established for the current to be discharged by the inductor. Also the capacitor now forces the PV output voltage to follow the reference voltage in order to work at the maximum power point. This also enables the PV voltage to effectively track the reference even under varying irradiance and temperature.

3.2.7.2 Control of the Inverter

Since the output obtained from the PV resource is DC, it needs to be converted into three phase AC such that it can be facilitated to tie up with the utility grid. Therefore, an inverter is necessary and also a crucial part of the system. In this work a simple modified real and reactive power regulatory circuit is designed along with the IGBT based bridge inverter and control circuits. The control circuits are shown in Fig. 3.20. Here the DC bus voltage which is the input to the inverter circuit is derived from the PI controller which is set to produce a voltage of 0.5 kV. The controller output $I_{dordered}$ is further used to generate triggering pulses for the IGBTs. Another PI controller is used to set the reactive power $Q$ of the utility grid as zero. This enables the inverter to operate at unity power factor and the output $I_{qordered}$ is again used in generating triggering pulses.
The circuit used for generating the triggering pulses for the operation of the three phase inverter is obtained from the circuit shown in Fig. 3.21 and 3.22. The value of theta is obtained initially using the PLL logic and then the signals are converted from a-b-c to d-q reference frame. The role of theta is very crucial as it controls the real and reactive power flow in the circuit. It is used to turn on and off the IGBTs. The values $I_{d_{\text{ordered}}}$ and $I_{q_{\text{ordered}}}$ are the reference values with which the actual $I_d$ and $I_q$ are compared. The error signal is passed through the PI controller which generates $V_{d_{\text{ordered}}}$ and $V_{q_{\text{ordered}}}$; they in turn act as the commanded converter voltages.

When the control is exercised in the d-q reference frame, a sinusoidal tracking problem is transformed to an equivalent DC command tracking problem. Therefore, PI compensators can be effectively used for control. Also in a-b-c frame, models of specific types of electric machine exhibit time-varying, mutually coupled inductions. If the model is expressed in d-q reference frame as in this work, time-varying inductions are transformed to constant parameters. Therefore the complexity in control architecture is reduced. The mathematical model of the inverter control is discussed in the next section.
Fig. 3.21 Generating d-q components

Fig. 3.22 Generation of commanded converter voltages
Once the commanded converter voltages are generated, it is again expressed in the a-b-c reference frame such that the switching pulses can be generated as seen in Fig. 3.23. The three sinusoidal modulating waves are compared with a carrier wave generated using the angle resolver and non-linear block. Since the upper leg and the lower leg of the inverter operate in a complimentary fashion, the switching signals are inverted for $g_{14}$, $g_{16}$ and $g_{12}$.

![Diagram of Triggering Pulses]

**Fig. 3.23 Generation of Triggering Pulses**

By applying the triggering pulses to the IGBT switches, it is clearly seen that the DC voltage is maintained at a constant value of 0.5 kV irrespective of the variation in solar irradiation and temperature as simulated in Fig. 4.8. Thus the DC voltage level is kept constant which is a mandatory requirement for the successful operation of the circuit.
3.2.7.3 Dynamic Model of Inverter Control

The inverter is nothing but the point where DC is converted to AC for grid-tied applications. The dynamic modeling of the inverter resembles, to some extent, the controls exhibited in the grid side converter of the DFIG circuit. It actually decouples the PV system from the grid; therefore the faults on the grid side will not affect them.

The output of the DC-DC converter is connected to the inverter, which converts it into AC and then connects it to the utility grid. Current controlled PWM technique is used to generate the switching order for the IGBTs. In order to explain the control of the grid-connected VSC, a simplified diagram is shown in Fig. 3.24. The phasor representation of the same is shown in Fig. 3.25. The PLL is used to generate the value of theta (θ). This theta is used to turn on and off the IGBT’s which in turn controls the flow of real and reactive powers.

![Fig. 3.24 Schematic diagram of a grid-connected VSC](image)

![Fig. 3.25 Complex phasor representation of grid connected VSC](image)

Here, $e^s$ is the converter voltage, $v^s$ is the grid voltage and $i^s$ is the current flowing from the converter to the grid. All these variables are represented in the stationary reference frame. Converting them into synchronous (d-q) reference frame yields
\[ e^{-j\theta}e^s = e^{-j\theta}Ri^s + e^{-j\theta}L\frac{di^s}{dt} + e^{-j\theta}v^s \]

\[ \Rightarrow e = Ri + e^{-j\theta}L\{e^{j\theta}(j\omega + \frac{di^s}{dt})\} + v \]

\[ \Rightarrow e = Ri + L(j\omega + \frac{di^s}{dt}) + v \]

The PLL is used to generate the value of theta (\( \theta \)), which is used to turn on and off the IGBT’s which in turn controls the flow of real and reactive powers.

Putting \( e = e_d + je_q, v = v_d + jv_q, i = i_d + ji_q \) and separating real and imaginary parts

Representing the Fig. 3.25 in stationary reference frame,

\[
\begin{bmatrix}
    e_d \\
    e_q
\end{bmatrix} =
R
\begin{bmatrix}
    i_d \\
    i_q
\end{bmatrix} +
L\frac{d}{dt}
\begin{bmatrix}
    i_d \\
    i_q
\end{bmatrix} +
\begin{bmatrix}
    -\omega Li_q \\
    \omega Li_d
\end{bmatrix} +
\begin{bmatrix}
    v_d \\
    0
\end{bmatrix} \tag{21}
\]

In equation (21), the terms \( \omega Li_q \) and \( \omega Li_d \) are the speed/frequency induced terms that give rise to the cross coupling between the two axes. These terms are considered as disturbances in the system and hence eliminating them will yield better results. If we define our commanded converter \( d \) and \( q \) voltages as \( e_d^* \) and \( e_q^* \) and commanded currents to be \( i_{d(ref)} \) and \( i_{q(ref)} \), then with a PI type current controller along with cross-coupling compensation, following equations hold good.

\[
e_d^* = L\left(K_p + \frac{K_i}{s}\right)(i_{d(ref)} - i_d) - \omega Li_q + v_d \tag{22}
\]

\[
e_q^* = L\left(K_p + \frac{K_i}{s}\right)(i_{q(ref)} - i_q) + \omega Li_d \tag{23}
\]

Here, since \( i_d \) is directly proportional to the active power, it is reasonable to control the DC voltage by controlling the \( i_d \). Therefore, \( i_{d(ref)} \) can be generated as an output of the DC voltage controller.
The overall control of the inverter for the grid-connected PV system is shown in Fig. 3.26.

![Overall control schematic of the grid-connected PV inverter](image)

**Fig. 3.26** Overall control schematic of the grid-connected PV inverter

### 3.2.8 Modeling and Control of Grid Connected Electric Vehicle

In general, when intermittent sources like solar or wind are connected for grid support, an energy storage system is used in order to meet out the variations in power produced by these distributed generation units. But the main limitation of such systems is the cost associated with them. As an alternative solution, an electric vehicle can be used such that the purpose is solved at a reasonable cost. In this work an electric vehicle is modeled at a rating of 0.5MW where a Ni-MH (Nickel metal Hydride) battery is used. The PI controller is again used such that effective energy management is ensured. Stability and reliability of the microgrid is ensured as the EV provides the required support such that quality power is supplied to the grid. The detailed model of the electric vehicle modeled in this work is given in the following sections.
3.2.8.1 Electric Vehicle Technology

The electric mobility is getting popular these days due to factors like environmental concerns, energy security, oil price concerns and technological progress. There are four types of electric vehicles.

- Hybrid Electric Vehicles (HEV)
- Fuel Cell Electric Cars
- Plug-in Electric Vehicles (PHEV)
- Battery Electric Vehicles

The hybrid electric vehicle uses both internal combustion engine and electric motor to propel the vehicle. A series or parallel connection is used. In series set-up, the engine powers the battery, not the electric motor directly. A fuel cell combines hydrogen fuel and oxygen to produce electricity used to power an electric motor. On the other hand, plug-in electric vehicles use only electricity for operation. Batteries are charged from a combination of grid electricity, regenerative braking and other onboard sources. The final type uses battery solely to power the motor and they are in turn charged from the electric grid and regenerative braking.

3.2.8.2 Model of Ni-MH Battery

The main component of electric vehicles (EV) and of more electric systems in general is the battery. The battery is capable of storing a huge amount of energy according to the defined capacity and can release the same when necessary. Electric vehicles have become more popular in the transportation as fuel is not based on fossil resources and green energy is used. Not only that, in the microgrid the intermittent resources like wind and solar energy need an energy storage system to produce best results with enhanced power quality.

A battery management system ensures that the state of charge (SOC) of the EV is monitored continuously and depending upon the input power from the PV array the battery
charges or discharges accordingly. For this purpose a detailed description of the battery model is mandatory. In this work a Nickel Metal Hydride (Ni-MH) battery is used. The components of the Ni-MH battery are harmless to the environment and the batteries can be recycled. Fig. 3.27 and 3.28 shows the typical discharge characteristics of a Ni-MH battery and hysteresis phenomenon. Once the battery reaches the full charge the voltage decreases slowly depending on the amplitude of current. The Battery Management system has to be efficient in order to estimate the state-of-charge and enable V2G or G2V transactions of power depending upon the solar irradiation.

![Typical discharge curve of battery](image1)

**Fig. 3.27 Typical discharge curve of battery**

![Hysteresis phenomenon](image2)

**Fig. 3.28 Hysteresis phenomenon**
The discharge model is similar to the Shepherd model but can represent accurately the voltage dynamics when the current varies and takes into account the open circuit voltage (OCV) as a function of SOC (Locment et al. 2012). The battery model uses a controlled voltage source in series with a constant resistance. The discharge model of the battery is shown in Fig. 3.29 and Fig. 3.30 shows the battery model in PSCAD (Olivier Tremblay and Louis Dessaint 2009).

![Fig. 3.29 Discharge model of the battery](image)

The open circuit voltage is calculated depending upon the state of charge of the battery.

Discharge:

\[
V_{\text{batt}} = E_0 - Ri - K \frac{Q}{Q - i t} (i_t + i^*) + \exp(t) \quad (25)
\]

Charge:

\[
V_{\text{batt}} = E_0 - Ri - K \frac{Q}{|i_t| - 0.1Q} i^* \quad (26)
\]

where,

‘\(V_{\text{batt}}\)’ is the battery voltage (V)
‘\(E_0\)’ is the battery constant voltage (V)
‘\(K\)’ is the polarization constant (V = (Ah))
‘Q’ is the battery capacity (Ah)

\[ i_t = \int idt = \text{actual battery charge (Ah)} \]

‘R’ is the internal resistance (Ω)

‘i’ is the battery current (A)

‘i*’ is the filtered current (A)

### 3.2.8.3 Grid Connected Electric Vehicle

EVs can be coordinated with PV systems in many ways. For example, a dc-dc converter inserted between an EV and the dc bus voltage of a PV system can improve grid integration of PV systems by reducing the ramp rate of the PV inverter output power. To reduce the fluctuations in the grid, only slowly changing power can be exported by the use of a high pass filter in the network, which directs rapid power fluctuations to the EV battery. Not only that, to regulate the energy imbalance in the system, the day time solar generated power can effectively be converted into night time consumption using the vehicle to grid and grid to vehicle concept. Also as more and more PV generation is pumped into the existing power system, the need for an energy storage which is cost effective is emphasized.

However, in order to generate more confidence on this technology, the system has to be exposed to realistic field data. This is the most important objective of this work, wherein, a grid connected combined PV and EV system is thoroughly modeled and studied by incorporating the real field data in PSCAD/EMTDC environment. In order to verify the performance of the PV-EV combined microgrid, field data (solar irradiance and temperature) obtained from Centre for Wind Energy Technology (CWET), Chennai, Tamilnadu, India have been used (Sheeba Percis et al. 2015b).

The electric vehicle is modeled as a DC voltage source with a three-phase two-level inverter through which it connects to the grid as shown in Fig. 3.30. The control of the electric vehicle inverter system is almost the same as the PV inverter. The only difference between the two is that since it is connected to a constant DC voltage source, the DC voltage control is not
necessary. Instead, it can directly control the active power commanded ($P_{EV}^*$) from the electric vehicle. However, here the active power order comes from the coordinating controller which controls the overall power injection (PV+EV) into the utility grid. Then, the reference current for the current controller is calculated directly from the following equation

$$i_{d(ref)}_{EV} = \frac{P_{EV}^*}{v_d}$$  \hspace{1cm} (27)

Following the above equation, the reference current is tracked by the actual d-axis current of the electric vehicle successfully.

![Fig. 3.30 Grid Connected EV](image)

3.2.9 Coordinated Control of the PV-EV Combined Microgrid

Advancement of energy exploitation, accelerates the demand of various alternative and efficient production and utilization systems which paved the way for increase in renewable energy systems exploitation. Photovoltaic (PV) systems are affected by various conditions like the position of the sun, change in temperature and irradiance due to passing clouds etc. In order to improve the intermittency of solar power a supplementary source of power is required. The foremost idea behind this study is to develop a battery model to suit the electric vehicle used in the solar power system which enhances the performance of the system by absorbing the variations in the power produced. In this work the real field data obtained from
Centre for Wind Energy Technology has been used to show the variation in temperature and irradiance along with a Ni-MH battery coordinating to regulate the intermittency. The Maximum Power Point Tracking (MPPT) algorithm is used to track the maximum power point of the PV array. It is proposed in this work that an Electric Vehicle (EV) can be used as energy storage to stabilize the power supplied to the grid from the photovoltaic resources. A coordinated control incorporating the State-of-Charge (SOC) of the battery is necessary for the EV to obtain desired outcome. The modeling has been done in PSCAD/EMTDC and the results have been verified through simulation.

The concept of ‘Vehicle-to-Grid’ (V2G) was first proposed in 1997 by Professor Willet Kempton of the University of Delaware in his article “Electric Vehicles as a New Power Source for Electric Utilities” Kempton’s concept of V2G is based on the vehicles with remotely controlled, bidirectional chargers providing services to the electric power grid. The services will have a value that may result in payments back to vehicle drivers, resulting in lower vehicle operating costs.

Electric grid needs something to bridge the gap between altering demand or supply and the response of the generally slow large generation units. Renewable energy sources such as solar and wind power, as well as heat-driven micro-generation (building-based CHP) increase the demand for reserves and regulation due to their intermittent nature. This reserve/balancing capacity is generally referred to as ‘ancillary services’.

The V2G transaction would allow using electrical vehicle batteries as storage for the grid where cars would be loaded at off-peak times and partially unloaded at peak times. Smart Grid functionalities play a major role in this complex set-up. Depending on the business model, batteries can be owned and maintained by utilities or by car owners for whom this energy trading would be a profit source.

In this work, in order to smooth out the power fluctuations from the PV inverter and to make sure that the power injection to the utility grid is absolutely constant, a coordinating controller is deemed necessary. The desired power to the utility grid is given as an input to the
coordinating controller. It also tracks the output power from the PV system. Then the difference between these two powers, which is the output of the coordinating controller, can be used as the commanded power for the EV system. Mathematically,

\[ P_{\text{utility}}^* - P_{PV} = P_{EV}^* \] (28)

where, \( P_{\text{utility}}^* \) represents the desired power output of the utility grid, \( P_{PV} \) represents the output power from the solar generating plant and \( P_{EV}^* \) represents the commanded power to the electric vehicle. Fig. 3.31 shows the simulated model of the combined PV-EV microgrid. The electric vehicle is supplied with the commanded power as input after passing through a first order filter. The EV also has an inverter with IGBTs and controlled similar to that of the solar PV inverter using PI controllers. The control achieved is validated through the simulation results which are discussed in chapter 4. It is seen that the idle time of the EV can be effectively used for vehicle-to-grid and grid-to-vehicle transactions, thus providing quality power to the utility grid.

Fig. 3.31 PV-EV combined microgrid
In this work the electric vehicle was used to absorb the power variations caused due to the variation in irradiation and temperature as seen in Fig. 4.8. The variations were simulated using the real time field data obtained from Centre for Wind Energy Technology, Chennai, Tamilnadu, India. The Control circuit of the electric vehicle tracks the $P_{ord}$ and the vehicle power follows the same satisfactorily. The vehicle power varies in the range of +/- 30kW. The vehicle power tracks the reference power which is shown in Fig. 4.12.

![Diagram of commanded values of $I_d$ and $I_q$](image)

**Fig. 3.32 Commanded values of $I_d$ and $I_q$**

The generation of triggering pulses for the voltage source inverter in the EV is quite similar to the control used in solar PV inverter. Fig. 3.32 shows the generation of the commanded values of d-axis and q-axis currents for the control of EV. The difference in commanded power and the power from the solar PV is given as the input to the electric vehicle which is capable of either V2G or G2V transactions. The presence of EV allows for a higher share of intermittent energy sources (wind, solar), since there is more regulating capacity to even out wind fluctuations and allows for a longer ramp-up time for larger generating units.

The parameters of the battery used in electric vehicle are given in Fig. 3.33 where the fully charged voltage is 3.45 kV.
The main idea of using the electric vehicle, as discussed earlier, is for grid support during its idle parking time. From the simulation studies it is evident that for effective vehicle to grid transactions or vice versa it needs to satisfy certain criteria like a proper grid connectivity, a control system to regulate the power depending on the state-of-charge of the battery and a signal from the grid which in this case is the $P_{ref}$, that is specified as the requirement from the utility grid. The use of power electronic converters makes the control less complex and more effective. The PI controller is capable of intelligently regulating the power flow, thus maintaining a constant value of power to the connected utility grid.

**3.2.10 Design & Supervisory Control of the Hybrid Microgrid**

The fluctuation of wind and solar power produces stress on the electric grid. There exists a possibility of congestion in transmission lines. Hence some areas experience shortage of power. Smart parking lots can actually act as shock absorbers for such kind of situations. In India since the concept of smart parking lots is still emerging, a stop gap can be the extensive usage of electric vehicles rather than pumped storage systems which adds on to the cost of the
entire system enormously. In this work a solar and wind combined hybrid system is designed in coordination with the electric vehicles, which enables the microgrid to be self sustained and delivers quality power with reduced harmonics, thus taking care of the intermittency due to cloud cover.

In order to smooth out the power fluctuations from the PV inverter and to make sure that the power injection to the utility grid is absolutely constant, a coordinating controller is necessary. The desired power to the utility grid is given as an input to the coordinating controller. It also tracks the output power from the PV system. Then the difference between these two powers, which is the output of the coordinating controller, can be used as the commanded power for the EV system. In this case shown in Fig. 3.34, the mean wind velocity is set at a value of 10m/s.

![Fig. 3.34 Hybrid Microgrid Model](image)
Nowadays, since electrification in rural India has gained momentum, the results in the proposed work may lead to deployment of energy efficient microgrids in the near future incorporating the Electric Vehicle technology. In remote locations where grid connectivity is a challenge, electric vehicles in the form of ambulances may be used as ESS and the vehicles idle parking time may be utilized for effective V2G and G2V transactions. Thus the intermittency due to cloud cover will be taken care of and the economics of using a separate energy storage system or super capacitors will be ruled out, thus providing quality power at affordable cost.

3.2.11 Realistic Modeling & Control of PV and Multiple EV Microgrid

Now, with an objective to obtain a flat power profile injected to the utility grid, a power reference of 100 kW is set in the coordinating controller. It means that, if the PV system is capable of producing power more than 100 kW, then the EV will absorb excess power. Similarly, if the PV system produces less power than 100 kW, the EV system will supply the deficit. Obviously, the EV system cannot supply or absorb power for an indefinitely long period. It will be determined by the available state of charge of the EV batteries which are taking part in this V2G and G2V transactions.

In this case, to maintain the power fed into the grid when two EV’s are connected in parallel as shown in Fig. 3.35, it is assumed that 50% of power is shared by both electric vehicles. From the simulation result shown in Fig.4.16, when the time is 5 minutes, the solar power \( P_s \) varies and the power is 0.089 MW. At the same time, it is clearly evident that the combination of two EV’s injects 0.035MW each into the grid such that the grid power or the commanded power is maintained at 0.1MW in total irrespective of the variations in solar irradiation and temperature.
Fig. 3.35 Multiple EV configuration

When a fleet of electric vehicles or multiple EVs are connected, by establishing a proper control mechanism, optimal energy management can be achieved. In doing so integrating the microgrid with the main utility grid leads to various advantages like enhancement in power quality, increase in reliability, protection of the system becoming easier and also reduction in losses. The microgrid developed in this work is capable of providing perfect power to the utility which is evident from the simulation results obtained.

From the above discussions and various case studies on the designed microgrid configuration it is seen that the master controller operates within the specification of the utility grid in operating as a stiff power source. It also provides interface between various entities of the microgrid like the wind power system, solar PV system, battery management system and the supply system. In cooperative or coordinated mode of operation these entities assure continual quality power to critical loads when connected while achieving economic operation. The basic function of the master controller which is decision making is effectively carried out by the PI controllers as seen.
3.3 Case Study 2 - Hybrid Microgrid Model in MATLAB/Simulink

In this section of the research work, the main focus is on developing an intelligent control system based grid integration of hybrid PV-Wind power system along with an electric vehicle which is represented as a battery. The mathematical model of PV-wind system has been developed and simulated in MATLAB environment and its performance is analyzed under various working conditions. The MPPT controller for PV system has been designed using fuzzy logic and the simulation results have been analyzed under different climatic conditions. The grid integration of hybrid PV and wind along with an intelligent controller based battery management system [BMS] has been developed and the system performance has been studied under normal operating conditions. The same system has been simulated with UPFC and analyzed under different fault conditions. Finally the proposed system’s simulation results have been analyzed and evaluated with IEEE 1547 standard to prove the system’s effectiveness.

3.3.1 Wind Turbine Design

In the previous case study, the model of the wind energy conversion system is designed using a doubly fed induction generator. A back-to-back connected converter system is used for control incorporating the hysteresis current PWM technique. The regulation of the system voltage is achieved and the power sharing between the various DERs and the DES is presented successfully. Therefore the microgrid is able to provide a stiff power supply to the utility grid taking into account the intermittency of the distributed energy resources.

In this case, however, a synchronous wind generator is used. The speed of the wind turbine is monitored. The PLL is used to control the system and it is operated using the reconfigured PI controller. The output of the wind system is converted into a DC quantity and fed to a DC bus. The PQ scheme of control is achieved using the simple controller. The simulated model of the wind system is shown in Fig. 3.36.
The PLL technique incorporated using the PI controller is modeled in MATLAB/Simulink platform and is depicted in Fig. 3.37.
3.3.2 Solar PV Model

The electrical characteristics of the solar PV cell which includes open circuit voltage, light generated current, reverse saturation current, short circuit current and irradiation are discussed in this section.

Open circuit voltage

This corresponds to the voltage drop across the diode (p-n junction), when it is transversed by the photocurrent $I_{ph}$, (ie.) when the generated current $I = 0$. It reflects the voltage of the cell in the night and it can be mathematically expressed as follows.

\[
V = \left(\frac{NKT}{Q}\right) \ln \left(\frac{(I_L-I_o)/I_o+1}{1}\right) \tag{29}
\]

where,

‘$V$’ is the open circuit voltage
‘$N$’ is diode ideality constant
‘$K$’ is the Boltzmann constant ($1.381 \times 10^{-23}$ J/K)
‘$T$’ is temperature in Kelvin
‘$Q$’ is electron charge ($1.602 \times 10^{-19}$ c)
‘$I_L$’ is the light generated current same as $I_{ph}$ (A)
‘$I_o$’ is the saturation diode current (A)

Light generated current (Radiation)

\[
I_L = \left(\frac{G}{G_{ref}}\right) \times (I_{L_{ref}} + \alpha_{ISC}(T_C - T_{Cref})) \tag{30}
\]

where,

‘$G$’ is the radiation (W/m²)
‘$G_{ref}$’ is the radiation under standard condition
‘$I_{L_{ref}}$’ is the Photoelectric current under standard condition 0.15 A
‘$T_{Cref}$’ is the module temperature under standard condition 298 K
‘α_{ISC}’ is the temperature co-efficient of the short circuit current (A/K)=0.0065/K

‘I_{L}’ is the Light generated current (Radiation)

**Reverse saturation current**

\[
I_0 = I_{or}(T/T_r)^3\exp((QE_G)/(K*N)(1/T_r)-(1/T)) \tag{31}
\]

\[
I_{or} = I_{scn} / \exp \left( \frac{V_{ocn}}{N*V_{in}} \right) \tag{32}
\]

where,

‘I_{o}’ is the Reverse saturated current

‘I_{or}’ is the saturation current

‘N’ is the ideality factor 1.5;

‘E_G’ is the band gap for silicon 1.10ev

**Short circuit current**

It is the greatest value of the current generated by a cell. It is produced during the short circuit conditions \( V = 0 \).

\[
I_{sh} = I_L - I_0 \left( \exp \left( \frac{Q \left( V - I_R_s \right)}{NKT} \right) - 1 \right) \tag{33}
\]

In this case the solar PV is simulated at 370 W in MATLAB under a temperature of 25°C and irradiance of 1000 W/m² and shown in the Fig. 3.38. The V-I and P-V characteristics are shown in Fig. 3.44 under various weather conditions.
The renewable energy sources play a significant role in meeting consumer power demand due to their ample availability and minimum impact on the environment. The main difficulty in PV energy expansion is the investment cost of the PV power system implementation. PV energy generation is not constant throughout the day due to the change of weather (Alajmi et al. 2013). The efficiency of power generation is very low (the range of efficiency is only 9-17% in low irradiation regions). Therefore, MPPT technologies have an important role in PV power generation to operate at the maximum power generation point at various weather conditions. The various MPPT methods established are discussed and the proposed method is presented below.

- **Feedback voltage and current method**

  This method is mostly used in a Photovoltaic power system without storage. The PV panel observed output current and voltage values are matched with reference current and voltage values to calculate error. Based on error value the DC/DC converter duty cycle is designed and operates the PV panel close to the MPP.

- **Voltage and Frequency (P-Q) method**

  In this method two different controllers are available to control inverter side and battery power management. Duty cycle for DC-DC converter is generated by PI controller, with respect to change in PV power generation.
• **Perturbation and Observation (P&O)**

In P&O method PV panel voltage and currents are measured during present climate condition, and then calculate PV power $P_1$. After small changes in the duty cycle PV panel power $P_2$ is measured. The PV power $P_2$ is compared with $P_1$. The perturbation is taken as correct when $P_2$ is more than $P_1$. The main limitation of this method is the infrequent deviations from the extreme.

• **Incremental conductance method**

In this method the voltage and current values are measured from PV cell. The above values are compared with a reference value and based on error signal; the controller generates the duty cycle and feeds the PWM control of the inverter.

### 3.3.3 Intelligent Control Model for MPPT

In the proposed method shown in Fig. 3.39, the fuzzy logic controller has two inputs, namely actual irradiation and PV voltage as designed and presented in Fig. 3.40. Trapezoidal method was used to convert these parameters to fuzzy set (Anandhakumar et al. 2013). Knowledge based system has the reference voltage and compares the observed value. Based on the error IF-THEN rules were adopted for selecting duty cycle as shown in Fig. 3.41. Finally, the fuzzy set value is converted into a crisp set using the centre of gravity method, and then the signal is fed into a PWM generator to generate the pulse for DC-DC converter (El Khatib et al. 2014). The simulated output of the Maximum Power Point Tracking of the 370 W PV panel is presented in Fig. 3.42 under different weather conditions.
Fig. 3.39 DC-DC boost converter with Fuzzy logic based PV MPPT controller

Figure 3.40 Fuzzy logic controller for PV MPPT

Fig 3.41 Input membership function of irradiation
Fig 3.42 Input membership function of voltage

Fig 3.43 Output membership function of duty cycle

Fig. 3.43 shows the output membership function of the duty cycle which is calculated from the difference in voltage levels. A sinusoidal reference signal is compared with the output signal so as to produce a zero error signal. This helps in tracking the maximum power point under varying solar irradiation and temperature. The waveform of the P-V characteristics and V-I characteristics of the modeled PV system is shown in Fig. 3.44.

Fig. 3.44 Photovoltaic system P-V and V-I characteristics
The maximum power point tracked with different levels of irradiation using fuzzy logic controller is shown in Fig. 3.45.

![Fuzzy MPPT for 370 W PV panel under different irradiation](image)

**Fig. 3.45 Fuzzy MPPT for 370 W PV panel under different irradiation**

### 3.3.4 Intelligent Hybrid Microgrid

The integration of PV/Wind/Battery power system model to form a hybrid microgrid has been presented in Fig. 3.46. The proposed system has been developed by simulation in MATLAB/Simulink environmental as shown in Fig. 3.47.

![Block diagram](image)

**Fig. 3.46 Block diagram**
The proposed intelligent Microgrid model has three major parts, namely Wind power system, Photovoltaic power system and an electric vehicle which is depicted as a Battery Management system. The wind power system has a rectifier circuit which converts the AC power from wind into DC power and then it is connected to the DC bus bar. The photovoltaic power system has fuzzy based MPPT controller to boost the PV power generation during various weather conditions, and then the PV power is fed to the DC bus bar after conditioning. The energy storage system, which in this case is an electric vehicle, has been connected to the DC bus bar through a bi- directional converter. The bi directional converter is operated and controlled by a fuzzy controller, which is capable of controlling the power flow direction based on the RES power and Load demand. Finally, the DC bus bar is connected to a three phase voltage source inverter (VSI) which is then connected to the three phase Microgrid network. The three phase voltage source inverter is controlled by phase lock loop, voltage regulator and current regulator. The above controller supports to integrate the RES power into the Microgrid.

Fig. 3.47 MATLAB/Simulink model of the proposed microgrid
3.3.4.1 Fuzzy Controller Based PLL

The proposed Microgrid system is operated and controlled by fuzzy logic system. The MATLAB/Simulink model of the proposed controller is developed and shown in Fig. 3.48. The proposed controller will generate the pulses for Microgrid connected inverter to improve the system stability and reduce the Total Harmonic Distortion (THD) of the entire system. The developed fuzzy controller (Fig. 4.49) has one input function for each phase voltage as depicted in Fig. 3.50. The fuzzy output membership function has been controlled by the duty cycle of Microgrid connected inverter as shown in Fig. 3.51. The proposed fuzzy controller rules are formed based on input and output membership function as shown in Fig. 3.52. Finally the proposed fuzzy controller has been simulated and observed results such as three phase voltage and current waveforms are presented in detail in the next chapter.

![Fuzzy controller based PLL for Microgrid](image1)

**Fig. 3.48 Fuzzy controller based PLL for Microgrid**

![Fuzzy control model for PLL](image2)

**Fig 3.49 Fuzzy control model for PLL**
3.3.4.2 Battery Management System

As discussed earlier, the battery management system will monitor the state-of-charge of the EV and depending on the same will either charge or discharge. The proposed hybrid PV/Wind integration of Microgrid power system has an intelligent controller based BMS as shown in Fig. 3.53. The proposed BMS controller has been developed by using fuzzy logic controller in MATLAB/Simulink environment as depicted in Fig. 3.54. The BMS controller
operates the battery of the EV very efficiently and improves the system stability level based on load demand. The proposed fuzzy controller has one input such as error value in between RES power and load power demand as shown in Fig. 3.56. The fuzzy controller output has two signals, namely battery charging and battery discharging as shown in Fig. 3.57 and Fig. 3.58 respectively.

There are three main steps while incorporating a fuzzy logic controller. The first one is fuzzification, the second one is membership function, and the final one is defuzzification. In the first step, the crisp sets are converted into fuzzy sets. Then in the second step, each point in the input space is mapped to the membership value between 0 and 1. Finally, the third step produces defined output values corresponding to the membership degrees. Like in case 1, here also a Ni-MH battery is used.

![Fig. 3.53 Hybrid PV / Wind Power system with Battery Management System with UPFC and intelligent controller](image)
The fuzzy rules are formed based on the following conditions.

- Whenever DER power is greater than load power demand, then the battery is operated at charging mode.
- Whenever DER power is less than load power demand, then the battery is operated at discharging mode as shown in Fig. 4.30. The proposed fuzzy controller rules are presented in Fig. 3.59.

In many applications like electric vehicles, microgrids and aerospace industries the combination of more than one renewable source as input is much relevant. In the modern electric grids, hybrid systems play a vital role (Sivaprasad et al. 2016). This hybrid microgrid which is proposed using intelligent control system has been found to be efficient and the results shown are promising.

![Bi-directional converter with fuzzy based battery management system](image1)

**Fig. 3.54 Bi-directional converter with fuzzy based battery management system**

![Fuzzy controller model for BMS](image2)

**Fig. 3.55 Fuzzy controller model for BMS**
Fig. 3.56 Input membership function for BMS

Fig. 3.57 Output membership function for BMS – battery charging mode

Fig. 3.58 Output membership function for BMS – battery discharging mode
3.3.4.3 Modeling of UPFC

The Unified Power Flow Controller (UPFC) is a typical FACTS (Flexible AC Transmission Systems) device that is the most sophisticated and complex power electronic equipment and has emerged for the control and optimization of power flow and also to regulate the voltage in the electrical power transmission system (Paital et al. 2016). The operating principle of the UPFC is discussed as follows. The basic components of the UPFC are two voltage source inverters (VSIs) sharing a common DC storage capacitor, and connected to the power system through coupling transformers. One VSI is connected in shunt to the transmission system via a shunt transformer, while the other one is connected in series through a series transformer.

The series inverter is controlled to inject a symmetrical three phase voltage \(V_{sc}\), of controllable magnitude and phase angle in series with the line, to control active and reactive power flows in the transmission line. So, this inverter will exchange active and reactive power with the line. The reactive power is electronically provided by the series inverter, and the active power is transmitted to the DC terminals. The shunt inverter operates in such a way as to demand this DC terminal power (positive or negative) from the line, keeping the voltage across the storage capacitor \(V_{dc}\) constant. So, the net real power absorbed from the line by the UPFC is equal only to the losses of the inverters and their transformers. The remaining capacity of the shunt inverter can be used to exchange reactive power with the line so as to provide a voltage regulation at the connection point. The two VSIs can work independently of

Fig. 3.59 Fuzzy rules for battery management system
each other by separating the DC side. So in that case, the shunt inverter is operating as a STATCOM that generates or absorbs reactive power to regulate the voltage magnitude at the connection point. Instead, the series inverter is operating as SSSC to regulate the current flow, and hence the power flow in the transmission line. The UPFC has many possible operating modes. In particular, the shunt inverter is operating in such a way as to inject a controllable current in the transmission line.

![Fig. 3.60 UPFC simulation model for Microgrid](image)

The above Fig. 3.60 shows the proposed model that has been developed as a simulation model in MATLAB/Simulink environment. The analysis of the system under various fault conditions is discussed in chapter 4 and the performance is evaluated. The fault conditions introduced in the proposed system are three phase fault, double line to ground fault, line to line fault and line to ground fault. The performance of the system has been analyzed with and without UPFC during three phase fault condition and the voltage and current waveform are presented in the results and discussion part.

In this chapter the methodology adopted in developing the two microgrid models are discussed in detail, wherein one used the reconfigured PI controller and multiple EV while the other adopted an intelligent controller based on fuzzy logic and UPFC. From the two case studies it is evident that the electric vehicle technology when combined as energy storage for a
hybrid microgrid as modeled in this work leads to many possible solutions to the ongoing problem of environmental pollution and energy crisis. It is seen that an EV is capable of smoothing the variations under various climatic conditions and also when a fleet of EVs is incorporated better power sharing is achieved and finally when an intelligent control is applied the efficiency of the overall system is improved and power quality is ensured. This hybrid microgrid model can be deployed in developing countries like India to improvise and adapt to the new trends the power grid has to offer in future.
CHAPTER 4

RESULTS AND DISCUSSION

4.1 Inference from Hybrid Microgrid Model - Case 1

A hybrid microgrid model is one in which more than one type of distributed energy resource is used. As detailed in the previous chapters, a combination of wind and solar PV system is used in coordination with an electric vehicle as energy storage. As India is one of the fastest growing nations in the field of wind energy and solar PV technology, the results obtained from the hybrid microgrid model is most appealing to developing nations like India at this crucial point of time. The main limitation of the extensive usage of DERs is their variability in nature for which an electric vehicle is proposed and the results obtained are promising to deploy this technology in the power sector to enable betterment of the power scenario in India in the near future. The simple master controller which is proposed using reconfigured PI controller is successfully able to control the DERs and DES in the hybrid microgrid. Also the multiple EV configuration is capable of enhancing the power sharing between the different entities. In this section, the results obtained are discussed in detail in the following sections.

4.1.1 Performance of Wind Energy Conversion System

The hybrid microgrid modeled in this work consists of the wind energy conversion system coordinated with other distributed energy resources (DER) like solar PV and distributed energy storage (DES) which, in this case is an electric vehicle as depicted in Fig. 4.1. Here the master controller designed by reconfiguring the PI controller is capable of intelligent management of the hybrid microgrid and is capable of providing a constant power to the grid. It is performing various functions like assessing the input wind and solar resources, dynamic dispatch, state-of-charge estimation and coordinated control.
As discussed earlier, the necessity of a coordinating controller is endorsed from the results obtained wherein, the power fluctuations from the PV inverter are smoothened and a constant quality power is injected into the utility grid. The desired power to the utility grid is given as an input to the coordinating controller. It also tracks the output power from the PV system. Then the difference between these two powers, which is the output of the coordinating controller, can be used as the commanded power for the EV system. A 1MW wind turbine is designed in this work. The mean wind speed is 10 m/s. The power output from the wind turbine is shown in Fig. 4.2. The Maximum Power Point Tracker is used to capture the maximum wind power.

As discussed in chapter 3, a wound rotor induction generator is modeled with a capacity of 0.9 MVA. The rotor diameter is 40 meters and the mean wind speed is 10m/s. The control of the wind energy conversion system was discussed in the previous chapter. The output waveforms are given in this section. Fig. 4.2 shows the power output from the wind turbine. As seen the power level is maintained at 0.865 per unit.
To demonstrate the functioning of the wind turbine model, it was operated at a constant speed of 10m/s which is the average speed as seen from the real field data set. The mechanical speed of the wind turbine is shown in Fig. 4.3. Depending on the wind power extracted from the rotor the mechanical speed of the WTG is fixed as seen in Fig. 4.3. The per unit value of the mechanical speed is simulated and in Fig. 4.4, the mechanical torque produced is given.

In the DFIG modeled in this work, the reference levels are in turn typically set by controllers such as

- An electrical torque controller driving the rotor-side converter $i_q$ current component (flux based controller)
- A capacitor voltage controller driving the grid-side converter $i_d$ current component (voltage based controller)
- Power factor and/or AC voltage controllers driving the $i_d$ and $i_q$ current components on either (or both) rotor side or grid side converters respectively
The wind turbine operates in generating mode when the mechanical power is converted into electrical power. The WRIG, when operated using power electronic interface, helps to extract the available wind power in a better way. The rotor side converter regulates the DFIG rotor speed for maximum wind power capture, maintains the stator output voltage frequency constant and controls the reactive power. The rotor current regulation is used for control and the current regulated power converter determines the desired values of real and reactive powers.

As discussed in the previous chapter, wind turbine model has the generator model and the converter control circuitry. A set of three-phase currents is injected into the grid as shown in Fig. 4.5 and Fig. 4.6 and the real and reactive powers being controlled independently using the decoupled d-q control strategy. The performance of the wind turbine was validated by incorporating the real field data which was averaged to be 10m/s in the measured location.
Fig. 4.5 Stator current

Fig. 4.6 Stator voltage

The objective of the GSC is to keep the dc-link voltage constant regardless of the magnitude and direction of the rotor power. Also GSC can supply reactive power to the grid or it can be designed to regulate directly the stator terminal voltage of the DFIG. The reactive power output is shown in Fig. 4.7. The real and the reactive powers are controlled by controlling the q-axis and d-axis components of the stator. The equations governing the real and reactive powers are depicted in the following equations.

\[
P_s = \frac{3}{2} (v_{ds}i_{ds} + v_{qs}i_{qs})
\] (32)

\[
Q_s = \frac{3}{2} (v_{qs}i_{qs} - v_{ds}i_{qs})
\] (33)
From the simulation results, it can be seen that as the rotor and the grid side converters handle AC quantities of slip and grid frequencies respectively, they are controlled utilizing vector control techniques. As discussed before, vector control is based on the concept of developing a rotating reference frame based on AC flux or voltage, and project stator and rotor currents on such a reference frame. With a suitable choice of reference frames, AC currents appear as DC currents in steady state. For flux based rotating reference $d$-axis rotor current component controls the reactive power of the generator, whereas $q$-axis rotor current component controls the active power or torque.

### 4.1.2 Performance of the Solar PV-EV Combined System

In order to verify the performance of the PV-EV combined microgrid, field data obtained from Centre for Wind Energy Technology (CWET), Chennai, Tamil Nadu, India have been used for this research. The organization provides site data for both solar PV and wind systems. In this work, one-minute data is taken into consideration, as it is meaningful to interpolate the same. The inverters in the electric vehicle should be very fast to mitigate power unbalance, but they are not supposed to work for a long time. Therefore if ten minute data is used, then the interpolation will not be realistic. Hence the solar irradiance and temperature data with a one-minute interval on 1st January 2013 at a site location in Chennai, Tamil Nadu are used. The site description is shown in the below Table 4.1.
Table 4.1 Site Description

<table>
<thead>
<tr>
<th>Station Name/ID</th>
<th>Chennai/1791</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude</td>
<td>12° 57’21.79”’ N</td>
</tr>
<tr>
<td>Longitude</td>
<td>80°12’59.75”’ E</td>
</tr>
<tr>
<td>Elevation/Altitude</td>
<td>1m amsl / 0 m agl</td>
</tr>
<tr>
<td>Site Address</td>
<td>National Institute of Wind Energy, Chennai, Tamilnadu.</td>
</tr>
</tbody>
</table>


All the simulations were carried out with a 100 minute data set starting from 10:00 AM. However, in PSCAD, it was quite time-consuming to actually run a 100 minute data set when the simulation time-step was 50 µs. Such a small time-step had to be used in order to achieve the high-frequency switching of the power electronic converters which were modeled in quite a detail in this work. In order to obtain a realistic solution to this problem, the 100 minutes data set was used in the PSCAD model. All the simulation results were obtained with respect to time (100 minutes) in the x-axis.

Fig. 4.8 shows how the irradiance and temperature have varied during the time interval mentioned before. Due to that variation, the output of the solar PV system changes, which is shown in Fig. 4.9. The output of the PV array varies within the range of 80 kW to 130 kW. This power is captured using the MPPT algorithm as discussed before.
Now, in order to send this power to the utility grid, it is required to hold the DC link voltage of the solar PV inverter to a constant value by the DC voltage controller. The performance of the DC voltage controller in such a varying power scenario is, therefore, important for the correct operation of the solar PV system. In Fig. 4.10, the reference and the actual DC voltages of the DC link are shown. It is observed that even in this varying power scenario, the DC link voltage is successfully maintained at the commanded value.
Another important component of the solar PV inverter is the current controller. The current controller in the $d$-axis has to be fast enough to track the current reference generated by the DC voltage controller. At the same time, the current controller has to be able to limit the current in case of transient events so that the converter valves do not experience high unwanted current beyond its rating. In Fig. 4.11, the tracking of the $d$-axis current controller is shown. Here $I_{d_{ord}}$ is the reference current and $I_d$ is the actual current waveforms. From the reference and actual currents, the successful operation of the current controller is established.

In this case, an electric vehicle is used to absorb the power variations caused due to the variation in irradiation and temperature. In Fig. 4.8, these variations are simulated using the real-time field data obtained from Centre for Wind Energy Technology, Chennai, Tamilnadu, India. The Control circuit of the electric vehicle tracks the $P_{ord}$ and the vehicle power follows the same satisfactorily. The vehicle power varies in the range of $+/-\ 30kW$. The vehicle power tracks the reference power which is shown in Fig. 4.12. In this model, a constant dc source of 5kV is used as a reference.
The control system adapted for the control of PV inverter and electric vehicle are quite similar. However as the DC source used is constant, a separate voltage controller is not needed in this case. Instead, it can directly control the active power commanded (\( P_{EV}^* \)) from the electric vehicle. However, here the active power order comes from the coordinating controller which controls the overall power injection (PV+EV) into the utility grid. Then, the reference current for the current controller is calculated directly from the following equation

\[
    i_{d(ref),EV} = \frac{P_{EV}^*}{v_d}
\]  

(34)

Now, with an objective to obtain a flat power profile injected to the utility grid, a power reference of 100 kW is set in the coordinating controller. It means that if the PV system produces more power than 100 kW, then the EV will absorb the excess power. Similarly, if the PV system produces less power than 100 kW, the EV system will supply the deficit. Obviously, the EV system cannot supply or absorb power for an indefinitely long period. It will be determined by the available state of charge of the EV batteries which are taking part in this V2G and G2V transactions. In this case, it is assumed that the EV system which constitutes the PV-EV combined microgrid, is capable of supporting the PV system within a range of +/- 30 kW. Fig. 4.13 shows that with such a simple implementation of a coordinating controller, the power fed into the grid is maintained perfectly at the commanded value, which is 100 kW in this case. The solar power fluctuations are completely absorbed by the EV system, which helps the combined system to maintain a flat power profile.
It is seen that the battery voltage varies depending on the state-of-charge of the battery which in turn is affected by the changing solar irradiation and temperature. The battery voltage is shown in Fig. 4.14 and Fig. 4.15 shows the state-of-charge of the battery. The initial state-of-charge of the battery is nearly 100%.
As the importance given to renewables and electric vehicle technology is gaining momentum, the study of their integration with the grid becomes important. In this work the microgrid model is used to validate the idea of connecting multiple electric vehicles for grid support. The simulation results show that it is possible to achieve effective energy management using the PI controller.

In this case, to maintain the power fed into the grid when two EV’s are connected in parallel, it is assumed that 50% of power is shared by both electric vehicles. From the simulation result shown in Fig. 4.16, when the time is 5 minutes, the solar power $P_s$ varies and the power is 0.089 MW. At the same time, it is clearly evident that the combination of two EV’s injects 0.035MW each into the grid such that the grid power or the commanded power is maintained at 0.1MW in total irrespective of the variations in solar irradiation and temperature.

The state-of-charge of the electric vehicle 1 (SOC_EV1) and electric vehicle 2 (SOC_EV2) are shown in Fig. 4.16. At the considered time interval of 5 minutes, the state of charge of the EV’s is 79.99% which is close to the fully charged state (Fig. 4.17). It is assumed that both EV’s have the same state of charge at any instant of time. The initial state-of-charge of the battery is taken as 80%.
Thus when a fleet of electric vehicles are connected, during their idle time for V2G and G2V transaction, grid support is enhanced with a proper energy management system and also the microgrid becomes self-sustained.

4.2 Inference from Hybrid Microgrid Model - Case 2

From the previous section results, the importance of coordinating control and the extensive use of multiple electric vehicles is explored technically to prove its relevance in a hybrid microgrid employing reconfigured PI controller. Even though the system operates in a
satisfactory manner further, the possibility of incorporating intelligent control is also looked into. Therefore, to further enhance the performance of the hybrid microgrid, an intelligent controller is also proposed which is capable of reducing the total harmonic distortions in the system and enhances its performance and reliability.

4.2.1 Performance of Wind Power System

In this case also a hybrid microgrid was developed using the combination of wind power system, PV solar power system and electric vehicle. Here the microgrid was modeled with the conventional PI controller and also the proposed fuzzy controller. This study is basically done to improvise the performance of the whole system. A comparison was drawn between the two types of controls and it could be seen that the proposed fuzzy system showed better performance than the PI configuration, which is seen from the THD parameters obtained. The output waveform of the wind energy conversion system is shown in Fig. 4.18. The voltage and the current waveforms for the three phases are depicted clearly.

![Wind voltage and current waveforms](image)

Fig. 4.18 Wind power system output voltage and current waveforms
For efficient use of the wind energy conversion system the rotor speed of the system needs to vary with the wind velocity. The rotor speed is adjusted such that maximum wind power is extracted from the turbine. PQ regulation is used to control the wind energy conversion system. As the speed of the turbine increases, the synchronous generator rotates above the synchronous speed and acts as an induction generator which converts mechanical energy of the turbine rotation into electrical energy which is to be supplied to the off-grid or on-grid connectivity.

4.2.2 Performance of Solar PV System

As discussed earlier in the previous chapter, the maximum power point of the solar PV is tracked to generate maximum efficiency. The PV array’s power output is shown in Fig. 4.20. The different levels of irradiation were depicted in the previous chapter along with the fuzzy tracking of the MPP. The actual irradiation level and the PV voltage are given as the input to the controller, which converts it to fuzzy set. Then the fuzzy set is converted as needed and fed to the PWM generator to control the converter.

Fig. 4.19 PV Power system voltage and current waveforms
The current and the voltage waveforms generated by the PV power system are given in Fig. 4.19. The hybrid system which is a combination of both wind and solar PV is operated in synchronization to obtain the output of the microgrid which is depicted in Fig. 4.21 and Fig. 4.22 respectively.

4.2.3 Microgrid with PI Controller

The wind power is generated as AC quantity which is converted into DC and fed to the DC bus. The solar PV output is DC which is connected to the DC bus through a PI controller. The DC power is again converted into AC and fed to the grid through a voltage source converter. As an energy storage device, the electric vehicle is used as proposed. The output of the microgrid is depicted in Fig. 4.21 and Fig. 4.22.
Once the microgrid current and the voltage waveforms are obtained, the total harmonic distortion is measured and analyzed. The THD for the voltage waveform is shown in Fig. 4.23 to Fig. 4.25 while the current THD values are shown in Fig. 4.26 to Fig. 4.28.

**Fig. 4.22 Current waveform - Microgrid**

**Fig. 4.23 THD value of R – Phase voltage**

**Fig. 4.24 THD value of Y – Phase voltage**
Fig. 4.25 THD value of B – Phase voltage

Fig. 4.26 THD value of R – Phase current

Fig. 4.27 THD value of Y – Phase current

Fig. 4.28 THD value of B – Phase current
4.2.4 Proposed Microgrid with Fuzzy Controller & UPFC

In the proposed model with intelligent controller for control of the microgrid, the PLL is controlled using fuzzy. To improve the power quality an UPFC is connected and controlled using fuzzy and the battery management system is also incorporated using fuzzy logic. The performance of the hybrid microgrid with UPFC is shown in Fig. 4.29.

![Microgrid Voltage - UPFC](image1)

![Microgrid Current - UPFC](image2)

**Fig. 4.29 Fuzzy controller based Microgrid voltage and current waveforms**

In order to prove the effectiveness of the proposed intelligent microgrid, again the total harmonic distortion is calculated for the three phase output current and voltage waveforms. The THD values are represented from Fig. 4.30 to Fig. 4.35. The percentage of THD in R phase is 17%, Y phase is 31% and B phase is 21% in the voltage waveform while in the current waveform the THD value in R phase is 2.05%, Y phase is 1.02% and B phase is 2.34%. The results show that the THD is reduced when a fuzzy controller is employed and power quality is enhanced.
Fig. 4.30 THD value of R – Phase voltage (with fuzzy controller)

Fig. 4.31 THD value of Y – Phase voltage (with fuzzy controller)

Fig. 4.32 THD value of B – Phase voltage (with fuzzy controller)

Fig. 4.33 THD value of R – Phase current (with fuzzy controller)
The comparison between the PI controller based system and the fuzzy based system is clearly shown in Table 4.2. From the values we can see a remarkable difference in the harmonic distortion values which defined the quality of the power supplied to the utility. As per IEEE 519 standard the harmonic distortion allowed is ± 5% and the obtained values are within the specified standard. Since the load connected across each phase varies, the THD values of current also vary.

**Table 4.2 Comparative analysis of Fuzzy and PI controller for Microgrid THD values**

<table>
<thead>
<tr>
<th>Source</th>
<th>THD in %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R</td>
</tr>
<tr>
<td>Voltage</td>
<td>PI 0.23</td>
</tr>
<tr>
<td>Current</td>
<td>3.75 2.05</td>
</tr>
</tbody>
</table>
The battery management system is effectively controlled by the fuzzy controller. Whenever the power generated by DER is greater than the load power demand the battery is charged whereas, if the DER power is lesser than the load power demand, the battery is operated in discharging mode. The battery characteristics are shown in Fig. 4.36.

![Fig. 4.36 Battery characteristics](image)

The inclusion of UPFC helps to increase the stability of the hybrid microgrid. To support this claim different faults are introduced in the system and the output obtained in the presence of the UPFC as well as in its absence is discussed in this section and represented in Fig. 4.37 to 4.42. The faults include three phase fault, double line to ground fault, line to line fault, and line to ground fault.

![Fig. 4.37 Three phase Voltage waveform (0.1 sec to 0.3 sec 3 phase fault) without UPFC](image)
The proposed Microgrid system has been analyzed with UPFC system with the application of a three phase fault condition. The three phase fault has been applied for a time duration of 0.1 to 0.3 second and the observed system voltage and current waveforms are shown in Fig. 4.39.

**Fig. 4.38 Three phase current waveform (0.1 sec to 0.3 sec 3 phase fault) without UPFC**

**Fig. 4.39 Three phase voltage and current waveforms during three phase fault with UPFC**
In Fig. 4.39 the output of the microgrid with UPFC shows substantial support to the microgrid and improves the stability. As a second case, the line to line fault has been applied in the proposed system during 0.1 to 0.3 sec and the system voltage and current waveforms are observed. The controlled system parameters, on the other hand, are shown in Fig. 4.40.

![Microgrid Voltage waveform during L-L fault with UPFC](image)

![Microgrid current waveform during L-L fault with UPFC](image)

**Fig. 4.40 Voltage and current waveform during L-L fault with UPFC**

The Double Line to ground fault has been applied in the proposed system during 0.1 to 0.3 second and the system voltage and current waveforms are observed. The control provided by the UPFC system during the occurrence of the fault is given in Fig. 4.41.

![Voltage waveform during DL-G fault with UPFC](image)
Finally, the line to ground fault has been applied in the proposed system during 0.1 to 0.3 second and the system response is observed and voltage and current waveforms are shown in Fig. 4.42. This sophisticated power electronic equipment has emerged as a powerful control system which helps in optimizing the power flow and also in regulating the voltage.

Fig. 4.41 Three phase voltage and current waveform during DL-G fault with UPFC

Fig. 4.42 Three phase voltage and current waveform during L-G fault with UPFC
4.4 Conclusion

In this work, it has been shown that a coordinated control is capable of maintaining a flat power profile which is fed into the utility grid from a PV system by mitigating the intermittency with electric vehicle in a PV-EV combined microgrid. The reliability of the microgrid is enhanced as back-to-back connected converters are used for bi-directional power flow in the wind energy conversion system. The decoupled d-q control enhances the control of the converters effectively. Power Quality of the hybrid microgrid is improved as reference signals are generated in each case and the actual values track the references faithfully. The coordinated control established is capable of supplying a constant power as input to the grid irrespective of the variations in wind speed and solar irradiation. In this case, it is evident that the EV system which constitutes the PV-EV combined microgrid, is capable of supporting the PV system within a range of +/- 30 kW. The power sharing between the multiple EVs connected shows that the PI controller is capable of assessing the SOC of the vehicles and schedules them accordingly. Both EVs share 50% of the deficit power during V2G transaction.

Also with an idea to further improve the performance of a hybrid microgrid, the second case was taken and the research work clearly presented the modeling of a hybrid PV and wind power for integration into microgrid using an intelligent controller at different parts of the system. The simulations results were evaluated with IEEE 1547 standard and compared with the existing system for proving the effectiveness of the proposed system. The proposed Microgrid power system was modeled with fuzzy logic controller based battery management system in MATLAB/Simulink environment and the simulation results were presented. The UPFC was designed for enhancing the power quality of the proposed microgrid and evaluated under various faults conditions. Based on the simulation results, the performance of the fuzzy logic controller has been justified and has been recommended to microgrid system for improved system stability, reliability, and power quality.
4.5 Scope for Future Work

This thesis has successfully presented the modeling and control of a hybrid microgrid with reconfigured PI controller and multiple electric vehicle configuration. Also an intelligent controller based on fuzzy logic has been proposed for solving the power quality issues. In the current power scenario the smart grid technology is one which is expected to rule the power sector shortly and microgrids are a part of the smart grids. Therefore the perspective of using the wide area controller in the place of UPFC can be studied. Also the protection issues related to the microgrid is not dealt with in terms of the back-to-back connected converters, which can be looked into. When a fleet of electric vehicles is used, congestion could be a problem which draws greater attention and could be sorted out in future. The limitations imposed by the charging stations are however not included in this research work which can be explored.
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