CHAPTER 4
GRID INTEGRATION OF RENEWABLE ENERGY SOURCES

4.0 Introduction

The integration of the distributed and renewable energy sources into an electric power grid can be done in many ways along with power quality solution. The electric output of distributed energy systems can be integrated to the electrical power grid via three basic interconnection interfaces such as synchronous machines, asynchronous (induction) machines and power electronic interface. Most of distributed and renewable energy sources are conventionally integrated with power electronic converters to improve the quality of power. The power-electronic technology plays an important role in renewable energy source based power generation and in integration of renewable energy sources into the electrical grid. During the last few decades, power electronics has undergone a fast evolution, which is mainly due to two factors. The first one is the development of fast semiconductor switches that are capable of switching quickly and handling high powers. The second factor is the introduction of real-time computer controllers that can implement advanced and complex control algorithms. These factors together have led to the development of cost effective and grid-friendly converters.

In this chapter, grid interface schemes for distributed power generation systems are presented for wind energy systems and solar photo-voltaic systems in addition to micro-grid interface for renewable energy systems and custom power device interface for renewable energy systems.

4.1 Need for Integration of Renewable Energy sources

Traditionally, the electric power system is not designed to accommodate renewable energy generation and storage at the distribution level. The electric utility companies are using numerous types of electric power system architectures based on different designs and choices of equipments. The overall evolution of the grid has not been monolithic or based on a uniform approach to establish the most technically up-to-date, integrated system. As a result, there are major issues and obstacles to an orderly transition to using renewable energy sources with the grid.

The optimization of the overall electrical system performance is one of most important aspect for the long-term economic viability of distributed renewable energy systems. In order to achieve some of these benefits, power electronic interfaces are necessary to integrate with the existing electrical power system. The power electronic interfaces offer unique capabilities over traditional interconnection technologies. As the price of power electronics and associated control systems decrease, these types of interconnection interfaces, along with their benefits, will become more prevalent in use with all types of distributed renewable energy system.

With the increasing use of renewable energy systems and its technological advancement, it is becoming more important to understand the integration of these systems with the electric power systems. The new markets and benefits for distributed renewable energy applications include the ability to provide ancillary services, improve energy efficiency, enhance power system reliability, and allow customer choice. The advanced power electronic interfaces will allow distributed renewable energy systems to provide increased functionality through improved power quality and voltage/VAR support, increase electrical system compatibility by reducing the fault contributions, and flexibility in operations with various other distributed renewable energy sources, while reducing overall interconnection costs.

4.2 Grid Interface of Renewable Energy Sources

A general configuration of grid interface of renewable energy source is shown in Fig. 4.1. The input power in various forms is transformed into electricity by means of a power conversion unit whose configuration is closely related to the input power nature such as solar, wind, hydrogen, etc. The power generated from these various sources can be delivered to the local loads or to the utility network, depending on the need of the hour.

The main purpose of input side power electronic interface function is to extract the maximum power from the input source which contains the necessary circuitry to convert power from one form to another.

The grid interface converters includes both a rectifier and an inverter or just an inverter. The inverter is compatible in voltage and frequency with the electric power system to which it will be connected and contain the necessary output filters. The power electronic interface can also contain protective functions for both the distributed renewable energy system and the local electric power system that allow paralleling and disconnection from the electric power system. These functions would typically meet the IEEE Std. 1547 interconnection requirements[6], but can be set more sensitive depending on the situation and utility interconnection requirements. This interface will also contain some level of metering and control functionality. This will ensure that the distributed energy system can operate as designed. The controllers used for input side and grid side power electronic interface controllers are explained in detail in sections 5.1 to 5.3.

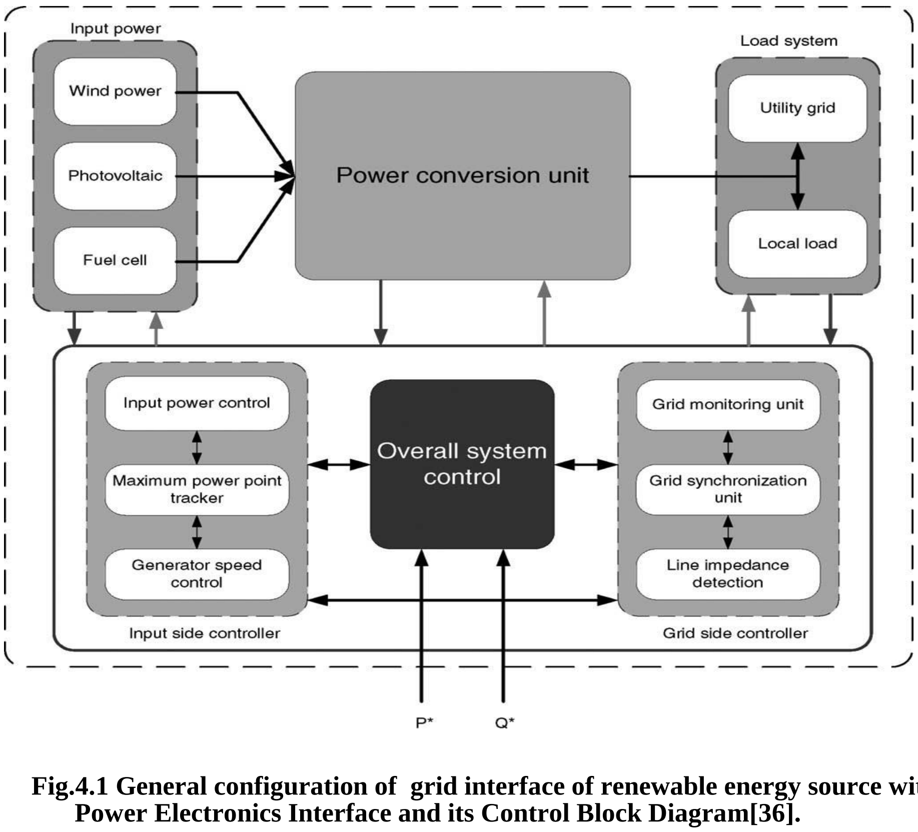

Fig.4.1 General configuration of grid interface of renewable energy source with Power Electronics Interface and its Control Block Diagram[36].

4.3 Grid Interface of Wind Energy System

Wind energy has matured to a level of development where it is ready to become a generally accepted utility generation technology. Wind-turbine technology has undergone a dramatic transformation during the last 15 years, developing from a fringe science in the 1970's to the wind turbine of the 2000's using the latest in power electronics, aerodynamics, and mechanical drive train designs. In the last ten years, the world wind-turbine market has been growing at over 30% a year, and wind power is playing an increasingly important role in electricity generation, especially in countries such as Germany and Spain. The legislation in both countries favors the continuing growth of installed capacity. Wind power is quite different from the conventional electricity generation with synchronous generators. Further, there are differences between the different wind-turbine designs available in the market. These differences are reflected in the interaction of wind turbines with the electrical power system. An understanding of this is, therefore, essential for anyone involved in the integration of wind power into the power system.

The wind energy system interface with grid can be broadly classified into two categories. They are without power electronic interface and with power electronic interface.

4.3.1 Grid Interface of Wind Energy Systems without Power Electronics Converter

Most of these topologies are based on squirrel-cage induction generator (SCIG), which is directly connected to the grid. A soft starter is usually used to reduce the inrush currents during start up [6]. Moreover, a capacitor bank is necessary to compensate for the reactive power necessary to the machine, as shown in Fig.4.2.

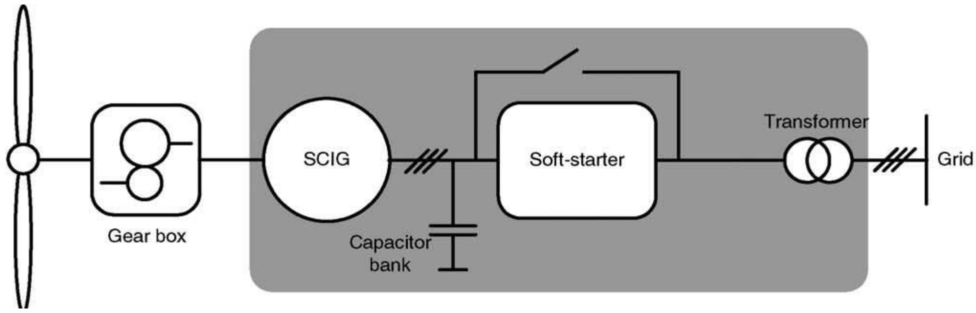

Fig.4.2 Wind Energy System Interface without Power Electronic converter[36]

4.3.2 Grid Interface of Wind Energy Systems with Power Electronic converters

Wind energy systems with partially rated power converters and much more improved control performance can be obtained. The partially rated power converters provide two types of solutions.

The first solution of grid interface of wind energy system with partially rated power converter is shown in Fig. 4.3, where the generator is an induction generator with a wound rotor. An extra resistance controlled by power electronics is added in the rotor, which gives a speed range of 2 to 4%. The power converter for the rotor resistance control is for low voltage but high currents. At the same time an extra control freedom is obtained at higher wind speeds in order to keep the output power fixed. This solution also needs a soft starter and a reactive power compensator.

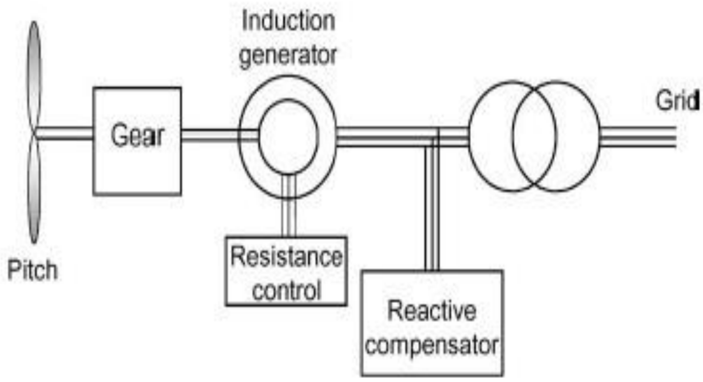

Fig. 4.3 Wind Energy Grid Interface Topologies with partially rated power electronic converters [37].

Second solution is using a medium scale power converter with a wound rotor induction generator as shown in Fig. 4.4. A power converter connected to the rotor through slip rings controls the rotor currents. If the generator is running super-synchronously, the electrical power is delivered through both the rotor and the stator. If the generator is running sub-synchronously the electrical power is only delivered into the rotor from the grid. A speed variation of 60% around synchronous speed may be obtained by the use of a power converter of 30% of nominal power. Furthermore, the required rating of the power converter can be higher, depending on the designed fault handing capability as well as the ability of controlling reactive power, which gives a better grid performance. The solution is naturally a little bit more expensive compared to the classical solutions, however it is possible to save on the safety margin of gear, having reactive power compensation/production and more energy captured from the wind.

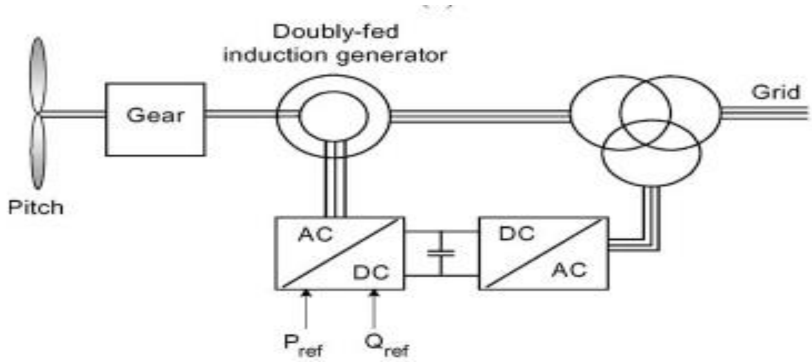

Fig.4.4 Wind Energy Grid Interface Topologies with Medium Scale Power Electronic Converter for Wound Rotor Induction Generator [37].

4.3.2.1 Grid Interface of Wind Energy Systems with Full Scale Power Converters

Wind energy systems with a full-scale power converter between the generator and grid, gives extra losses in the power conversion but it will gain added technical performance. Fig. 4.5 shows four possible solutions with full-scale power converters. The solutions shown in Fig.4.5. (a) and (c) are characterized by having a gear. A synchronous generator solution as shown in Fig. 4.5(b) needs a small power converter for field excitation. Multi pole generator systems with synchronous generator without a gear are shown in Fig. 4.5(b) and (d). Permanent magnets are used for the system shown in Fig. 4.5(d), which are still becoming cheaper. Various power electronic interfaces may be used with permanent magnet wind power generators [7-9]. Simulation tools are developed to investigate the design and operation of the wind turbines[10]. All four solutions have the same controllable characteristics since the generator is decoupled from the grid by a voltage-sourced dc-link. The power converter to the grid enables a fast control of active and reactive power. However, the negative side is a more complex system with a more sensitive power electronic part. Comparing the different wind turbine systems with respect to performance shows a contradiction between the cost and the performance. By introducing power electronics, many of the wind turbine systems behave like a power plant. With respect to control performance, they are faster, but the produced real power depends on the available wind. On the other hand, they may always be able to deliver reactive power, which can be used for power system control.

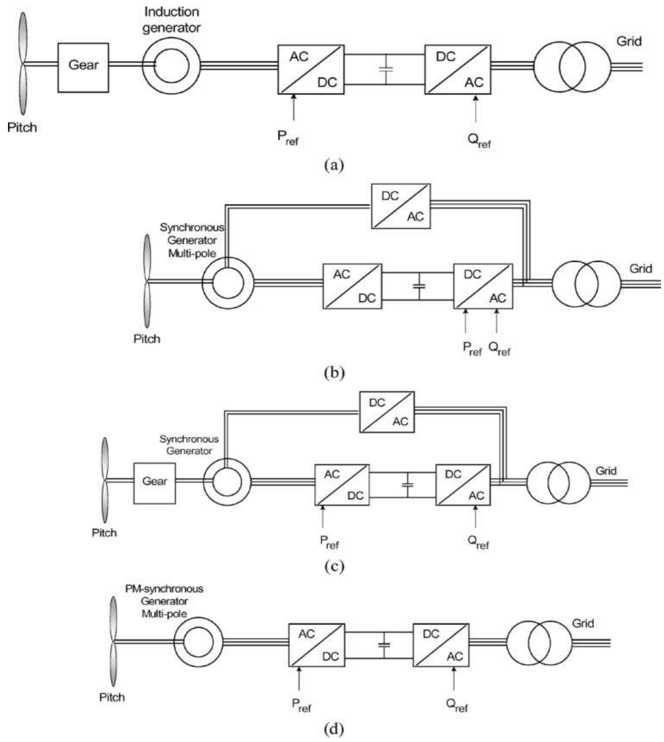

Fig. 4.5 Wind energy systems with full-scale power converters with active and reactive power control: (a) induction generator with gear, (b) Multi-pole synchronous generator (c) synchronous generator with gear and (d) Multi-pole permanent magnet synchronous generator [37].

4.4 Grid Interface of Solar Photovoltaic System

The photovoltaic system generally produces low-voltage output from the PV panels. To increase the voltage or power rating, more number of such units can be connected together in series or parallel. Generally, power conditioning systems such as DC-DC converters and inverters are often required to supply normal customer load demand or send power to the grid, as shown in Fig.4.6.Voltage boosting and regulation is possible either in DC or AC stage of the system. Normally LCL filter is used between PV system and grid for current smoothening.

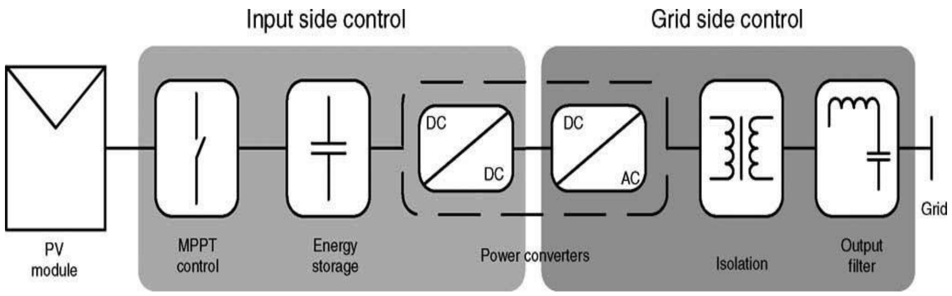

Fig.4.6. General Structure of Grid Interface of Solar Photovoltaic System [36].

One requirement of standards is that the inverters must also be able to detect an islanding situation and take appropriate measures in order to protect persons and equipment. In this situation, the grid has been removed from the inverter, which then only supplies local loads. This can be troublesome for many high-power transformer-less system, since a single phase inverter with a neutral-to-line grid connection is a system grounded on the grid side.

The centralized inverter system is illustrated in Fig. 4.7(a), where tens of PV modules are connected in series and/or parallel, and connected to the inverter. This may require an individual design for each installation, thus a nonflexible design is achieved. The inverters for this power range are mostly connected to a three-phase utility, thus no decoupling is necessary. The power losses are normally higher in this configuration, than for the two other systems presented, mainly due to mismatch between the modules and the necessity of string diodes. However, the voltage generated by the series connected modules may be high enough to avoid voltage amplification, e.g., transformers or boost converters. Moreover, the benefits of mass-production cannot be reached, and for that reason the inverters may be rather expensive.

The string inverter system shown in Fig.4.7 (b), is a reduced version of the centralized inverter with a single string of modules connected to the inverter [9]. The input voltage may be high enough to avoid the voltage amplification. This requires roughly 15 modules in series for European systems. PV-modules are still rather expensive as discussed above. Therefore, voltage amplification must be a part of the string inverter in order to allow for fewer modules to be connected to the inverter. Besides this, the total open-circuit voltage for 15 modules may reach as high as 700 V, which calls for 900-V MOSFETs/IGBTs in order to allow a 75% voltage de-rating of the devices. The voltage amplification can be realized with a boost dc/dc converter, or with a transformer embedded in a high-frequency dc/dc converter. There are no losses associated with the string diodes and a separate MPPT can be applied for each string. This is believed to increase the overall efficiency, when compared to the centralized inverter.

The multi-string inverter is a further development of the string-inverter, where several strings are interfaced with their own dc/dc converter to a common dc/ac inverter. Thus, the operator may start his/her own PV power plant with a few modules. Further enlargements are easily done because a new dc/dc converter, with PV modules, can be plugged into the existing platform, with all electrical connections in a single connector on the back plane. A flexible design with high efficiency is hereby achieved.

The ac-module shown in Fig. 4.7(c) is a reduction of the string inverter, where each PV module has its integrated power electronic interface to the utility. The power loss of the system is lowered due to the reduced mismatch among the modules, but the constant losses in the inverter may be the same as for the string inverter. Also the ac-module concept supports optimal operation of each module, which leads to an overall optimal performance. Moreover, it has the possibility to be used as a plug-in device by individuals without specialized knowledge. Finally, the single cell converter system is the case where one large PV cell is connected to a dc/ac converter. This is beneficial for the thin-film types of PV cells, including the photo electro-chemical cells which can be made arbitrary large by an inexpensive “roll on-roll off” process. The main difficulty in realizing such a converter is that the input power may reach 100 W per square meter cell, at 1 V across the terminals.

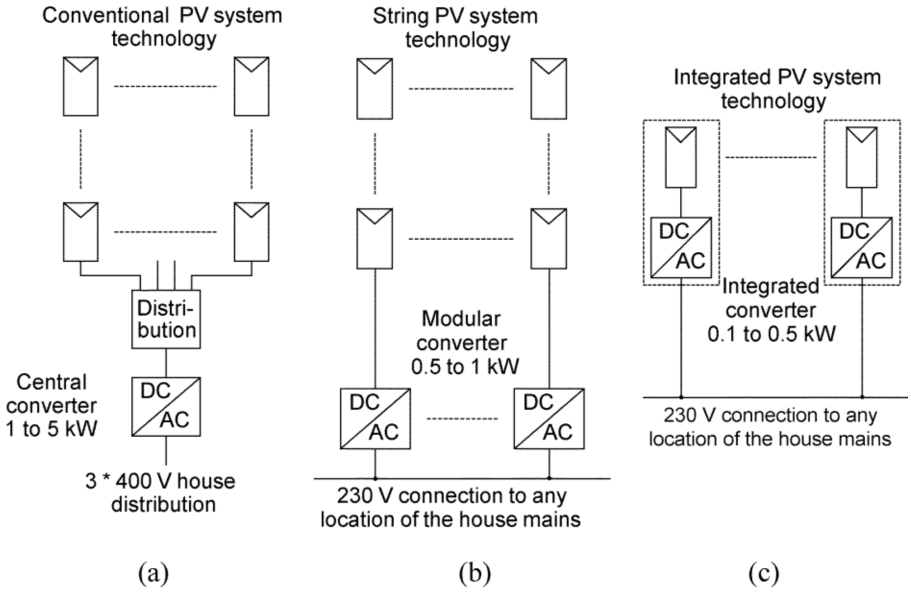

Fig.4.7 Configuration of PV systems interface with grid: (a) Centralized scheme, (b) String technology, and (c) Modular concept.

4.5 Micro grid Interface for Renewable Energy Systems

Micro grids are an interesting option for consolidating several renewable energy sources and energy storage elements on a single bus before connecting them to the grid. A micro grid is in a broader sense defined as a system of sources with power electronic interfaces, traditional generators, controlled loads, and uncontrolled loads connected in parallel through a common bus with impedances[24]. Figs. 4.8 - 4.10 shows the several examples of micro grids, varying by their bus types.

Fig.4.8 shows a micro grid with a line frequency bus. This is very similar to a standard grid connection with line frequency loads, but the main difference is the presence of local generation that can supply the local loads in the event that the grid is unavailable. An isolation switch at the point of common coupling between the micro grid and the main grid can be shown to enable stand-alone operation.

DC and high frequency (HF) AC bus micro grids utilize [Fig.4.10] this separation between the micro grid and the main grid to gain the advantages of running a system at something other than 50 Hz. The first notable difference with these systems is the grid interface converter. This converter is an extra component, adding to the cost of the system, but it provides isolation between the micro grid and the main grid even when the micro grid is not in stand-alone operation. This keeps fluctuations on one system from impacting the other as severely as would be the case if there were a direct connection. Converters on a dc bus system tend to be simpler than those on a line-frequency or HF AC bus system, and the control for a DC bus system [Fig.4.9] is simplified since frequency control is not a consideration; the high frequency bus provides some benefits to loads like compressors and fluorescent lighting, reduces the size of passive components and transformers, and makes harmonic filtration easier since the harmonics are at much higher frequencies. One additional component to note on the HF AC bus micro grid is the unified power quality conditioner (UPQC). This device is a combination of a series and shunt active filter, and acts to regulate the reactive power on the internal bus to ensure good power quality to the local loads.

The micro grid has a significant advantage over separately connected systems in that common components such as the step-up transformer can be combined to reduce the total number of components. Furthermore, the integration of the renewable energy sources and the energy storage on a common bus increases the overall efficiency by reducing the transmission losses between them. The main disadvantage of the micro grid is that the internal bus must be regulated in order to accommodate the local loads. For cases where the primary concern is to connect a renewable energy source and an energy storage element to each other and to the grid for delivery to non-local loads, this local load support is not necessary.

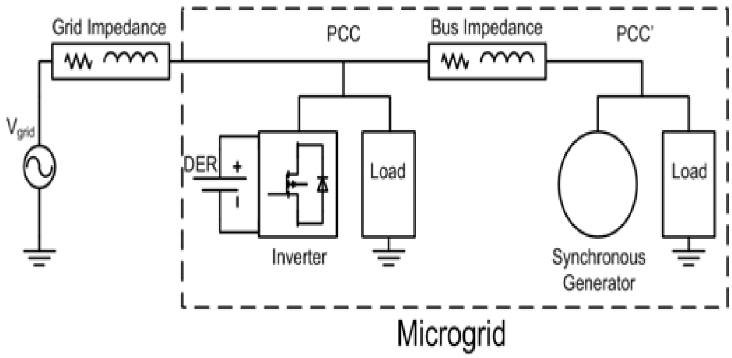

Fig.4.8 Line Frequency micro grid Topology [24].

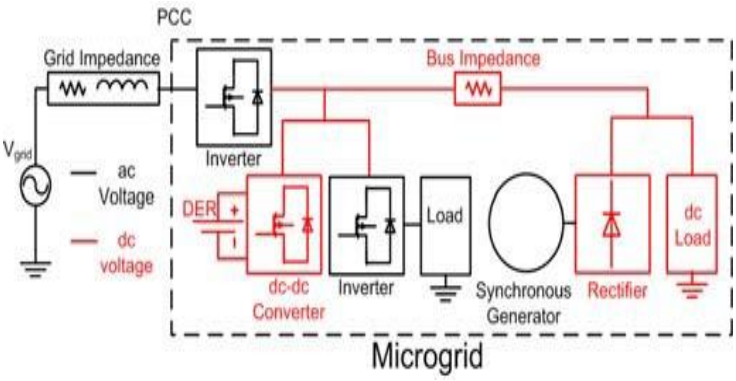

Fig.4.9 DC micro grid Topology [24].

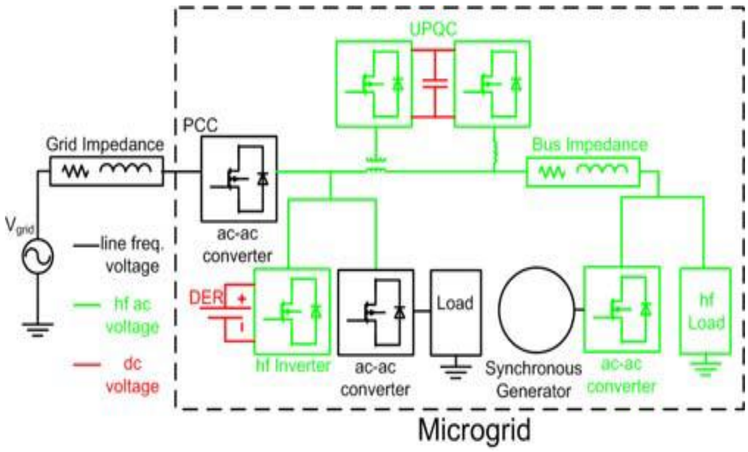

Fig.4.10 High Frequency AC micro grid Topology [24].

4.6 Custom Power Device Interface for Renewable Energy Systems

Recently custom power devices are playing vital role in power quality improvement and grid integration of renewable energy sources. The custom power concept was first introduced by N.G. Hingorani in 1995.These devices are family of power electronic converter devices which are applicable to the distribution systems to provide power quality solutions. Though deployment of renewable energy generation systems still requires high investments, cost-effectiveness of required equipment can be improved if additional control functions are incorporated to the interface converters, with the aim of improving power quality at the connecting point. In this sense, interface converters for renewable sources can be treated as custom power devices. Thus every new installation of renewable source generation can be seen as an opportunity to add custom power features, to improve quality of supply in locations where electric grids are weak or where sensitive loads need to be protected against power quality problems from the supply mains.

The custom power devices STATCOM (Shunt Active Filter),DVR (Series Active Filter) and UPQC (Combination of Shunt Active Filter and Series Active Filter) are the latest developments in interfacing devices between distribution supply (grid) and consumer appliances to overcome voltage/current disturbances and improve power quality by compensating the reactive and harmonic power generated or absorbed by the load [32].

4.6.1 Shunt Active Filter (DSTATCOM) Interface for PV System

The inclusion of shunt active filter with PV system would be very helpful for improvement of power quality. The shunt active filter uses a p-q theory discussed in section 5.3.1 for utility interface inverter control. The circuit diagram of the shunt active filter interface with PV system is shown in Fig.4.11. For the purpose of stable control, constant voltage control is applied and any kind of MPPT control can be applied to PV system. The output terminal of the PV array is connected to the smoothing capacitor (DC link side) interfacing the PV system with shunt active filter. The target of the shunt active filter interfaced PV system is that along with conventional shunt active filter role, it should exporting power to the grid without any additional hardware requirements.

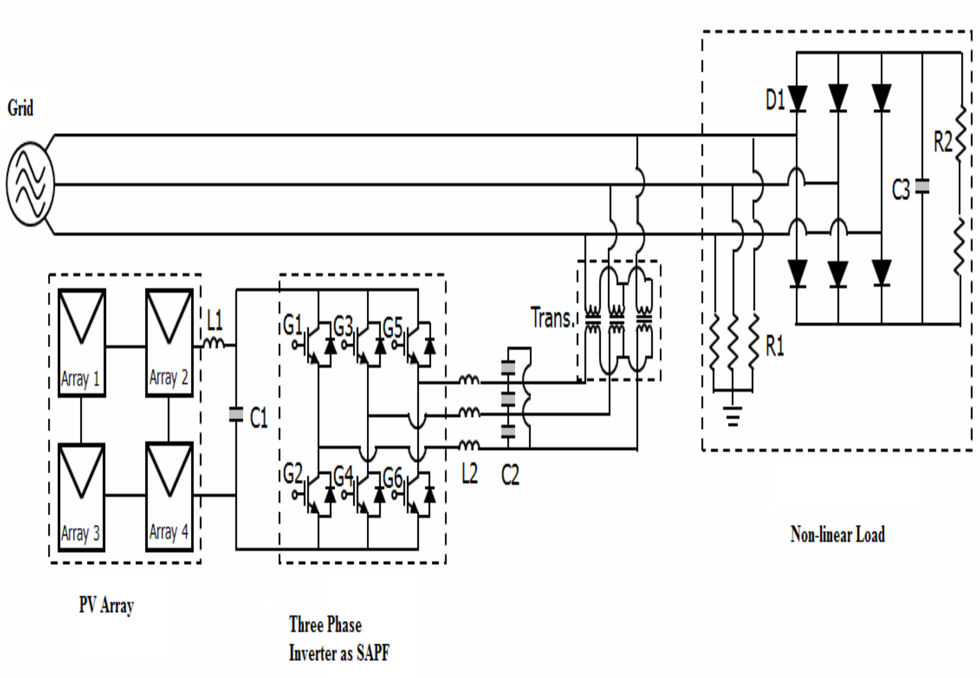

Fig. 4.11.Shunt Active Filter interface for PV system.

4.6.2 Shunt Active Filter Interface for Wind Energy System

The Wind Energy Conversion System uses a PMSG driven by a fixed pitch wind turbine. The configuration of this WECS is illustrated in Fig.4.12. In this configuration, the shunt active filter (VSI) is controlled in such a way that it can be used to inject real power into the grid for energy extraction from the wind turbine during linear or non-linear load conditions. During nonlinear load conditions, shunt active filter (VSI) can be used also as active power filter for harmonic and reactive compensation. To control the performance and the effectiveness of the WECS, the shunt active filter is operated based on the concept of instantaneous p-q theory as explained in section 5.3.1. The control input is a current error signal which is the difference between the actual current injected by shunt active filter and the desired or reference current waveform[42].

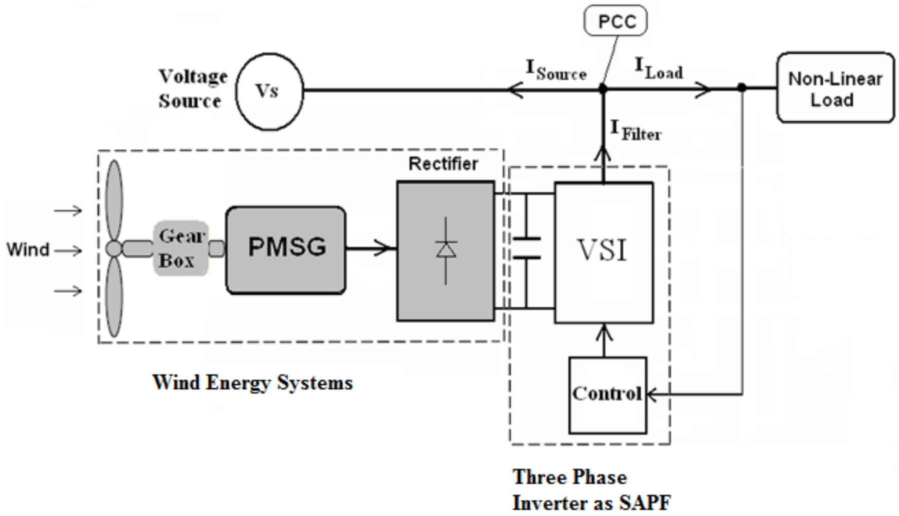

Fig.4.12. Shunt Active Filter Interface Wind Energy Conversion System[42].

4.6.3 Shunt Active Filter Interface for PV-Wind Energy System

The shunt active filter interface for different renewable energy sources is illustrated in Fig.4.13. In this configuration small wind energy system with conditioner and PV system with its MPPT controller are connected to the common DC-DC converter which can be used to adjust the value of the output voltage of the renewable energy sources to the voltage value of the dc-side capacitor of the shunt active filter. The available energy is then managed by the controller of the active filter. The shunt active filter interface is capable of simultaneously compensating power quality problems such as low power factor, current imbalance and current harmonics, and also of injecting the energy generated by renewable energy source to grid with a very low THD[34]. Even when there is no energy available from the power source (when there is no sun or wind) the shunt active filter can still operate, increasing the power quality of the electric grid. Applying a control strategy based on the Instantaneous Reactive Power Theory discussed in section 5.3.1, it is very simple to inject reactive “energy” when necessary, or to inject the energy with unit power factor.

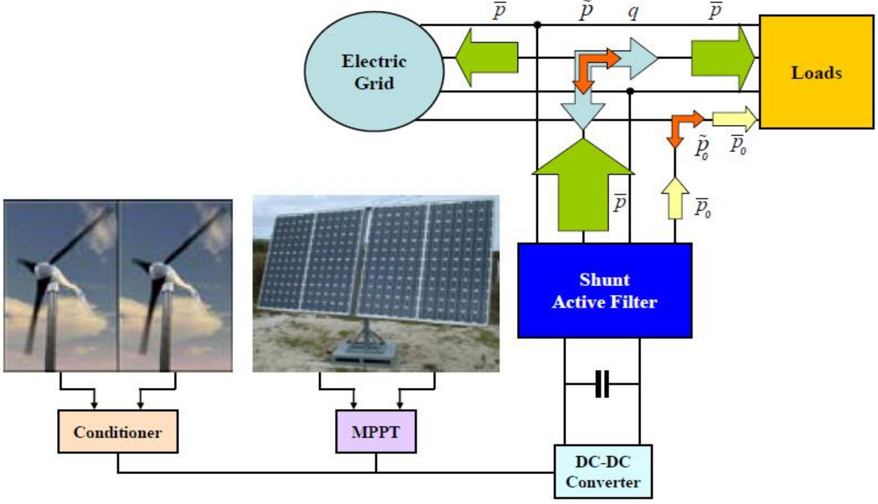

Fig.4.13. Shunt Active Filter Interface for Renewable Energy Sources[34].

4.6.4 Series Active Filter (DVR) Interface for Renewable Energy System

The DVR is a series connected custom power device to protect sensitive loads from the supply side disturbances. It cal also act as a series active filter, isolating the source from harmonics generated by loads. It consists of a voltage source PWM converter equipped with a DC capacitor and connected in series with the utility supply voltage through a low pass filter (LPF) and coupling transformer as shown in Fig.4.14. This device injects a set of controllable AC voltages in series and in synchronism with the distribution feeder voltages such that the load side voltage is restored to the desired amplitude and waveform even when the source voltage is unbalanced or distorted.

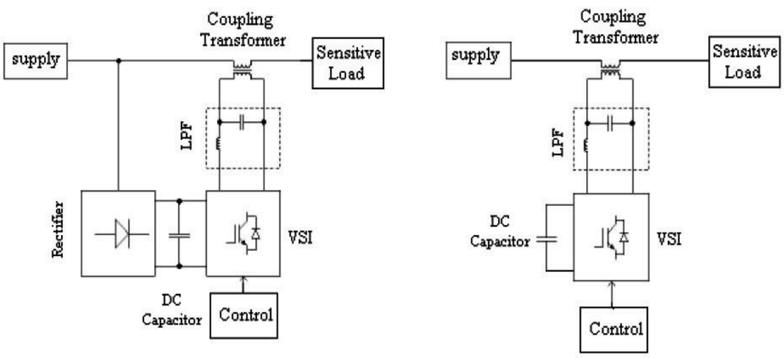

Fig. 4.14 Dynamic Voltage Restorer (a) Rectifier supported DVR b) Capacitor supported DVR [32].

DVR can also be used with BESS to control the reactive and active power flow with harmonic voltage mitigation for a grid connected, distributed generation system as shown in Fig.4.15.[26].

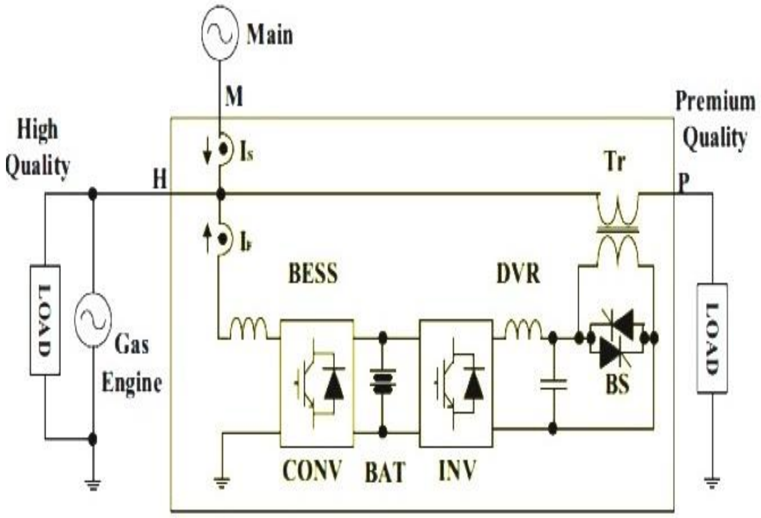

Fig.4.15 Power Quality Control using DVR and BESS [26].

4.6.5 UPQC Interface for Renewable Energy System

UPQC is a combination of series active filter (DVR) and shunt active (DSTATCOM) filters, connected back-to-back on the DC side and share a common DC capacitor as shown in Fig.4.16. The series component of the UPQC is responsible for mitigation of the supply side disturbances; voltage sags/swells, flicker, voltage unbalance and harmonics. It injects voltages so as to maintain the load voltages at a desired level; balanced and distortion free. The shunt component is responsible for mitigating the current quality problems caused by the consumer such as poor power factor, load harmonic current, load unbalance etc. Source currents become balanced sinusoids and in phase with the source voltages.

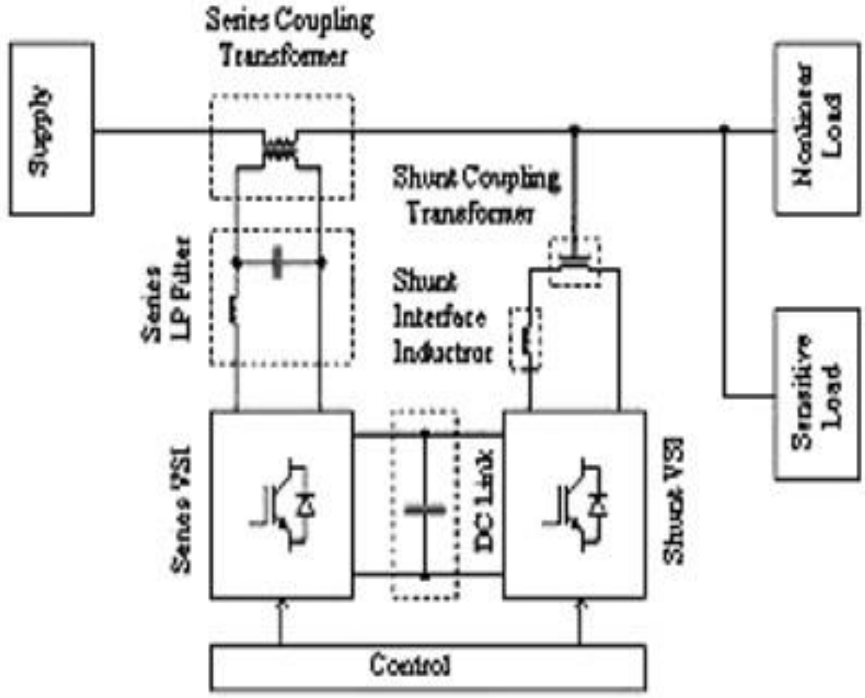

Fig. 4.16 UPQC Interface for Renewable Energy System [32]

Recent research reports[32] show that significant research and development has been carried out on the application of UPQC to grid connected PV and wind energy systems. As the UPQC can compensate for almost all existing PQ problems in the transmission and distribution grid, placing a UPQC in the distributed generation network can be multipurpose.

A structure has been proposed in [32]shown in Fig.4.17 and Fig.4.18 where PV and wind energy systems are connected to the DC link in the UPQC as an energy source. It works both in interconnected and islanded mode. UPQC has the ability to inject power using PV to sensitive loads during source voltage interruption. The advantage of this system is voltage interruption compensation and active power injection to the grid in addition to the normal UPQC abilities. But the system's functionality may be compromised if the solar resource is not sufficient during the voltage interruption condition.

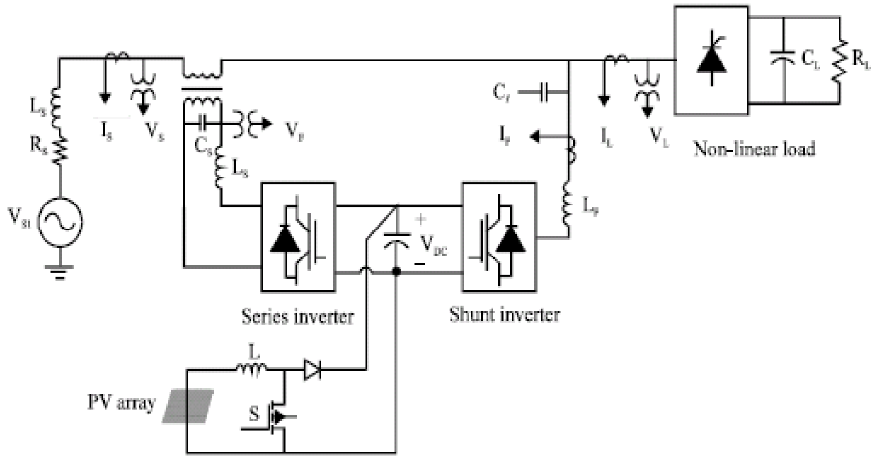

Fig.4.17 UPQC with grid connected PV system[32].

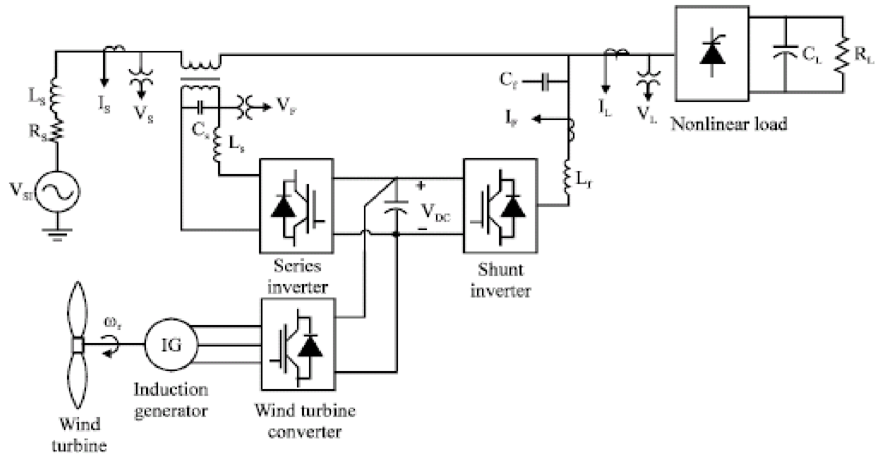

Fig.4.18 UPQC with grid connected wind energy system[32].

4.7 Conclusions

This chapter deals with different renewable energy sources interface units to the grid. The advantage of renewable energy system's power electronics interface can be optimized to reduce cost and maximize efficiency. These systems tend to be simple and have less components since they only have to deal with a single type of source such as PV array, battery bank or wind energy system though they can become more complex if they have to deal with multiple sources in parallel or in series even if those sources have the same characteristics. The renewable energy sources also can be integrated with grid using micro grid configuration and using custom power device interface.