CHAPTER 1

INTRODUCTION

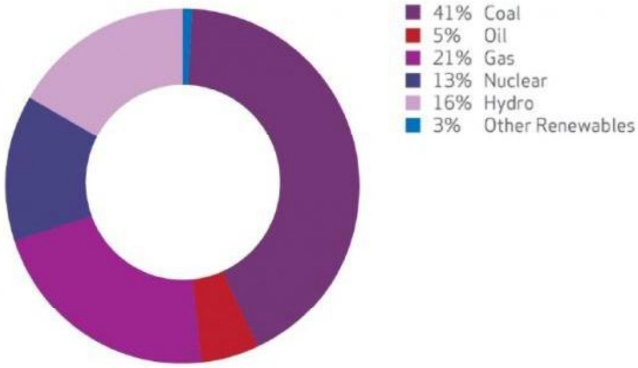
1.1 INTRODUCTION

This chapter presents the background and the motivation for the research work, with an overview of Research and Development in the area of solar energy utilization in the past, present and future; the economics of solar PV energy generation; and, lastly the realization of the renewable generation through subsystem approach such as micro-grid while touching upon the technical issues in the control of converters in micro grids. Finally, the aims and objectives of the research work are briefed and the organization of the thesis is presented.

1.2 BACKGROUND AND MOTIVATION

1.2.1 Overview of World Energy scenario

Power generation from renewable energy sources is gaining more and more attention and visibility because of the exponential growth of energy demand, along with the fact that the energy sector is the key domain in limiting the climate changes. Fossil fuel based power generation contributes for CO_2 emission, but the growth of this generation has continued over decades as seen from the International Energy Agency (IEA) Market Report (2011-2013)as given in Figure 1.1, and Table 1.1.



Source: IEA 2011

Figure 1.1 Total World Electricity Generation mix by Fuel

Table 1.1 Percentage of coal based electricity generation in various countries

Country	Electricity generated from coal (%)
South Africa	93
Australia	78
India	68
Israel	58
Greece	54
Poland	87
Kazakhastan	75
Czech Rep	51
USA	45
PR China	79

Source: IEA, 2012.

Every year approximately 7 million tons of carbon dioxide is exhausted from coal-fired power generating stations around the globe. Perhaps the coal-fired power plants are the major contributors of greenhouse gas emissions and a major cause for the environmental implications as seen from a report of IEA shown in Figure1.2

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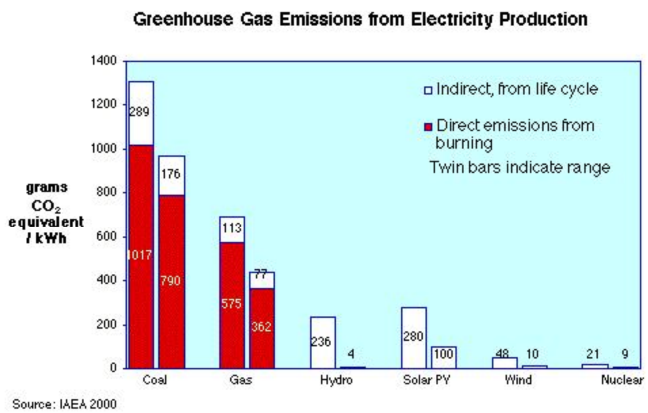


Figure1.2 Greenhouse gas emissions from electricity production

The total coal consumption and greenhouse gas emissions are going on rising in an unstoppable manner that has been the driver for drawing increased attention for renewable energy since the year 2000. In the recent years, wind and solar photovoltaic technologies have seen a major scale-up. Renewable electricity generation grew at a yearly average of 2.8%, whereas the growth seen in the total electricity generation is 3%. As per IEA's Renewable energy market report (2013), to achieve reduction in energy related CO_2 emissions to half from today's levels by 2020, the renewable generation must be doubled to that of the present figures. Renewableenergy is now the fastest-growing power sector with the objectives of making the global energy system much cleaner and diversified which will make up almost a quarter of the global power mix by 2018.

Non-OECD countries with China as a leader should be the major stakeholder of the global increase in renewable energy generation from now until 2018. Such a rapid deployment in OECD countries is expected to compensate for slower growth in other parts of the globe such as Europe and the US.

1.2.2 Energy scenario in India

The capacity addition of coal-based generation has been consistently increasing in China and India over the last few decades as presented in Figure1.3, of IEA's statistics. This is of utmost concern for International bodies like IPCC (2013), UNDP, and UNEP etc., who are working on the assessment of climate changes. Remedial measures at various levels have been taken, to cut or slow down the growth of emissions in India in various sectors like energy, transport, industry etc. Because of the continued action plans and monitoring now, the scenario is showing positive trends.

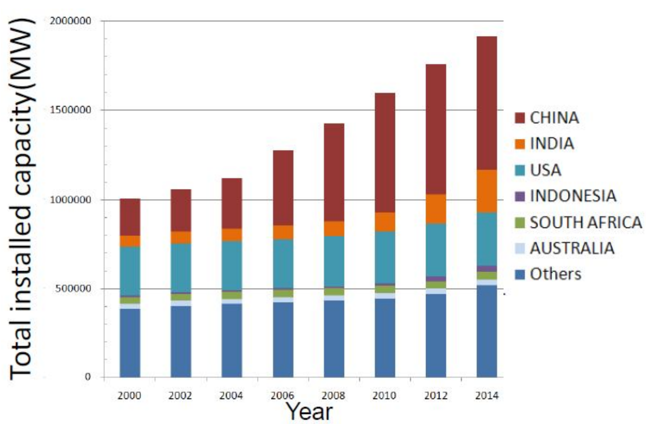
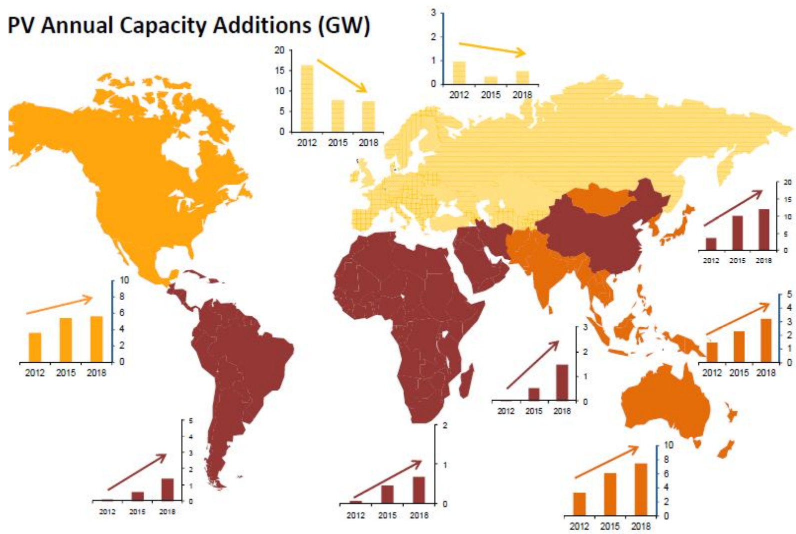


Figure1.3 Trend of installed capacity in coal based generation

Because of the policy uncertainties, the capacity addition of both on-shore as well as off-shore wind forms is becoming volatile. As per IEAs projected statistics (2013) as seen inFigure1.4, a strong growth in Solar PV capacity addition is seen in countries like India, China, Middle East and Latin

America. India is blessed with a great solar potential with an average of more than 300 days of sunshine over a year. Besides this, the other reasons are strong government backing with Five Year Plans, eased rules for grid connection, generation based incentives, generous low cost finance and robust manufacturing etc.



Source: IEA-2013

Figure1.4 Solar Photovoltaic (PV) capacity additions in GW

Yet there are some emerging challenges in the deployment of solar PV systems like challenging economic conditions, policy uncertainties, and most importantly the technology-related grid integration issues.

1.2.3 India's Inititative on Solar Power generation – Jawaharlal Nehru National Solar Mission(JNNSM)

In continuation of the global initiatives for renewable energy utilization along with the National Action Plan on Climate Change, Government of India has launched the Jawaharlal Nehru National Solar Mission on the 11th January, 2010. The Mission has set the ambitious target of deploying 20,000 MW of grid connected solar power by 2022 and is aimed at reducing the cost of solar power generation in the country through (i) long term policy; (ii) large scale deployment goals (iii) aggressive R&D and (iv) domestic production of critical raw materials, components and products, and as a result achieving grid tariff parity by 2022.As per Ministry of New and Renewable Energy (2009), the mission will create an enabling policy framework to achieve this objective and make India a global leader in solar energy. Government of India has set up a task force to give greater focus to the use and development of solar photovoltaic technology. The task force will study and develop an understanding about the areas of use of solar photovoltaic in the country, potential for deployment of the technology, available technology, products and solutions worldwide and future developments as per JNNSM Report (2009).

As per the Indian Electricity Act 2003, Renewable Purchase Obligation (RPO) mandated all electricity distribution licensees to purchase or produce a minimum specified quantity of their requirements from Renewable Energy Sources. The State Electricity Regulatory Commissions fix the minimum RPO for different states which is available in the state-wise RPO Targets (2012). However, Renewable Energy (RE) sources are not uniformly spread across different parts of the country. Here the concept of Renewable Energy Certificates (REC) assumes significance. Through REC, the mismatch between the availability of RE sources and the requirement to meet the minimum RPO can be bridged. i.e. REC mechanism will overcome the geographical limitations and provide flexibility to achieve RPO fulfillment.

Now, the distribution companies, Open Access consumer and Captive Power Plants (CPPs)etc., have the option of purchasing the REC to meet their Renewable Purchase Obligations (RPO). This is expected to give a drive to RE capacity addition in the countryas per the report of REC framework (2010).

1.2.4 Solar Energy Economics

In the past, the cost of solar panels was the restricting factor for the widespread use of solar PV systems, but now the module efficiencies are continuously improving as seen from Figure 1.5 (NREL 2013) thus making the module price trends to decline. As a constructive consequence, the PV system costs are coming down, which is a scintillating scenario for the growth of large-scale PV systems.

Over the last two decades, the cost of manufacturing and installing a photovoltaic solar power system has decreased by 20% with every doubling of installed capacity as reported in the McKinsey Quarterly (2008). The cost of generating electricity from conventional sources has been rising because of the exponential hike in the price of fossil fuels like coal, natural gas and oil. As a result, the solar power is becoming more economically attractive with improvements in the technologies and their performances, for years to come. A recent statistics of ATKearney Utilities (2013) predicts that solar power will achieve grid parity with conventional power between 2016 and 2018 as shown in Figure1.6.

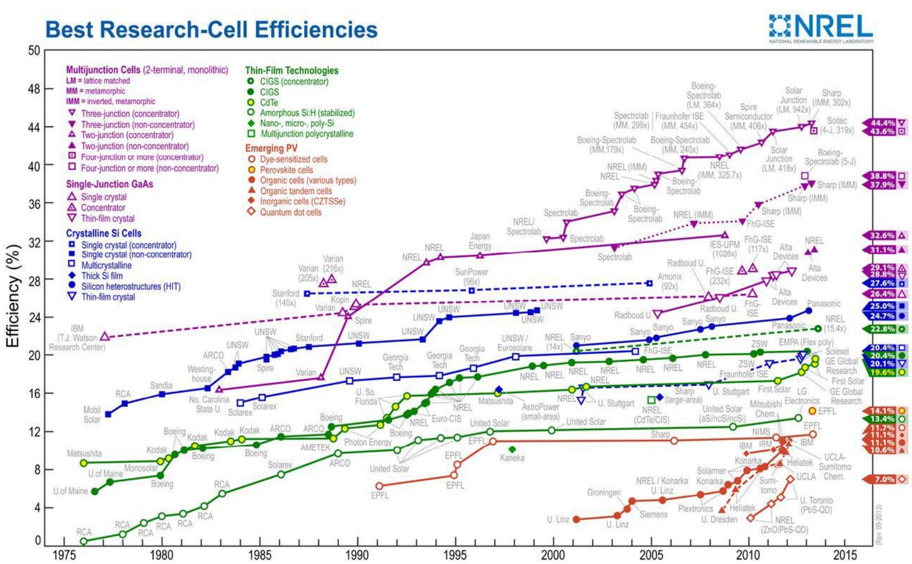
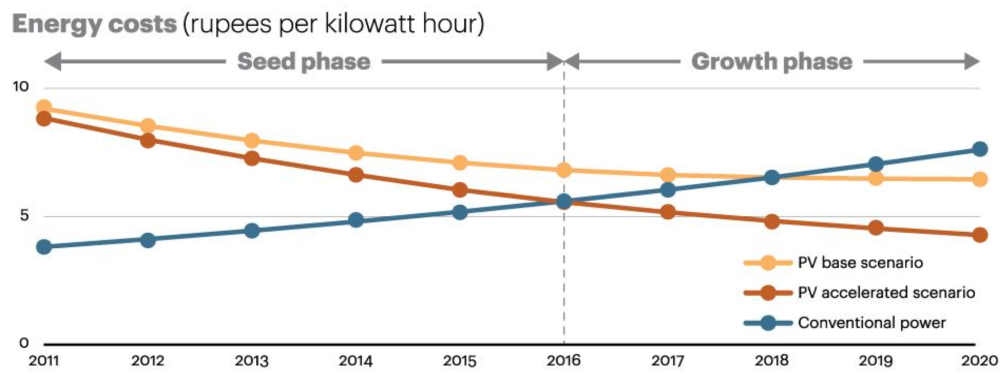


Figure1.5 Best Research cell efficiency records by NREL

Now, efforts are needed to increase the number of qualified workforce from research to system installation and maintenance, to ensure technology development, quality installations and sustained improvement. An article on Energy Technology perspectives (2008) by IEA suggests that R&D expenditure in solar energy should increase by two to four times in order to reduce the CO_2 emissions by 50% at global level by 2050.



Source: ATKenerly (2013)

Figure1.6 Energy costs for electricity from various sources

Also, superior co-ordination among the researchers is needed across the globe in the near future for sharing of innovative research ideas, international testing facilities for systems, research on new semi conducting and insulating material etc. Thus, the scope for the grid tied solar PV systems is very bright for the years to come.

1.2.5 Interconnection of Renewable energy sources into the Grid – Technical Issues

The electrical energy systems are going to undergo large-scale uplifts due to the interconnection of various Renewable energy sources (RES) into them. The outcome of such a transition will thus provide high standard utility services through distributed energy resources, sophisticated sensors and measuring units, better communications and net metering facilities enabling bidirectional power management etc. The integration of RES into the utility will modify the nature and direction of power flow in them that was originally following a radial path. These capabilities are to be attained through power electronics that serves as the interface between the generator and the utility/grid.

Besides the control capabilities of the power electronics, energy management becomes a challenging task when, a major share of the generation is from RES in the utility. Under such circumstances, the effect of removal or reconnection of RES will create a major impact on the utility. The other major technical issues with increased RES usage are the electricity supply and demand balance, i.e. they should be balanced in shorter periods typically as low as a few hours or even shorter than that. Additional challenges are put forth on the power system planning and operation with high renewable energy generation allowed or penetrated into the grid, including management under low-demand periods by curtailment of excess electricity generation. Thus, a more flexible system better than the present oneis needed to accommodate increasing levels of renewable generation. Increase in the system flexibility requires a large range of supply side and demandside options, requiring a huge technological advance, new operating procedures, advanced business solutions, and new government rules. With higher energy demand, growth and high levels of renewable penetration will increase the grid integration challenges.

From the point of view of the power system-planning, increased renewable energy penetration into a power system increases the vulnerability of it due to loss of generation thus decreasing the stiffness of the power systems. This may restrict the growth of renewable energy generation due to requirement of capacity increase of spinning reserves, adding of necessary storage into the grid, addition of fast responding power plants to tackle high wind/solar seasons, adding of large energy storages, strict demand management etc. These factors restrict the renewable energy penetration levels in growing economies, where the electricity even today is treated as a fuel, with weak grids of low short circuit impedances.

1.2.6 Micro-grids

A micro-grid is the recent attempt for the solution of the renewable penetration problem in growing economies as reported by various authors viz. Robert. H Lasseter & Paolo Piagi (2004), Bagnan Beidou et al. (2010), Kueck et al. (2005), Reed et al. (2010), DOE Smart Grid report (2009), Robin Podmore & Marck Ramon Robinson (2012), Meysam Shamshiri et al.(2012) and Mehrizi-Sani & Reza Iravani (2010)(2012). A micro-grid approach treats the generation and the associated loads as a subsystem. i.e. it consists of a collection of loads and sources operating as a single controlled region that powers a local area. This gives the flexibility to control the generation locally, thus eliminating the need for central load dispatch and making the system more reliable. The supply demand balance can be maintained within the controlled region even for very short periods. Varieties of sources of generation are available within micro-grids such as diesel engines, gas/micro-turbines, photovoltaic, fuel cells and wind turbines etc. The micro-grid does have a utility interconnection point, and it can operate with or without the utility connection, depending on the mode of operation, the availability of generation, presence of the utility etc. Converter systems through which most of the generators are tied to the system enable the control capabilities for the micro-grids.

1.2.7 Overview of control schemes for Voltage source converters in Micro-grids

Renewable energy sources are commonly connected to the grid or micro-grid through single or multi-stage power electronic converters as reported by Kadri et al. (2011), Haque et al. (2010), Blaabjerg et al.(2006) Teodorescu et al. (2006), Waleed Al-Saedi et al. (2013) and many others. These converter systems are designed with one or more of the following control requirements viz. (i) Independent control of active and reactive powers (ii) synchronization to grid, (iii) meeting the harmonics standards, (iv) control under healthy and fault grid conditions and (v) islanding detection and isolation, (vi) Galvanic isolation between the source and the utility especially under grid fault condition. The standards for grid interconnection of distributed resources are not the same across the world. The utility companies of different countries follow different sets of rules depending on their grid type. The rules are usually based on the national or international standards, but often these standards are similar, proposed by some of the major international standardization organizations viz. (i) International Electro-technical Commission –IEC (ii) Institute of Electrical and Electronics Engineers – IEEE (iii)American National Standards Institute (ANSI). These bodies update the standards periodically and the most recent one is IEC/IEEE/PAS 63547 "The Publicly available specifications" (2011). Based on these international standards, Central Electricity Authority, Ministry of Power, Govt. of India has released CEA regulations (2012). The converter systems should comply with the standards addressing voltage, frequency, harmonics and distortions, power factor, DC current injection, flicker etc., measured at the point of common coupling (PCC). Some of the major grid standards are presented in tables 1.2, 1.3, 1.4and in 1.5.

Table 1.2 Public distribution grid voltage harmonics limits – EN 50160

Odd Harmonics				Even Harmonics	
Non multiple of 3		Multiple of 3			
Order h	Relative volt. %	Order h	Relative volt. %	Order h	Relative volt. %
5	6	3	5	2	2
7	5	9	1.5	4	1
11	3.5	15	0.5	6 to 24	0.5
13	3	21	0.5		
17	2				
19, 23, 25	1.5				

Table 1.3 Disconnection time for voltage variations

IEEE 1547		IEC 61727		VDE 0126-1-1	
Voltage range %	Disconnection Time (s).	Voltage range %	Disconnection Time (s)	Voltage range %	Disconnection Time (s)
$V < 50$	0.16	$V < 50$	0.10	$110 \leq V < 85$	0.2
$50 \leq V < 88$	2.00	$50 \leq V < 85$	2.00		
$110 < V < 120$	1.00	$110 < V < 135$	2.00		
$V \geq 120$	0.16	$V \geq 135$	0.05		

Table 1.4 Maximum current harmonics

IEEE 1547 and IEC 61727					
Harmonics Order	$h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h$
%	4.0	2.0	1.5	0.6	0.3
Total Harmonic Distortion (THD) < 5.0%					

Table 1.5 Disconnection time for frequency variation

IEEE 1547		IEC 61727		VDE 0126-1-1	
Frequency range %	Dis-connection Time (s).	Frequency range %	Dis-connection Time (s)	Frequency range %	Dis-connection Time (s)
$59.3<f$ 60.5	0.16	$49 <f< 51$	0.20	$47.5<V$ <52	0.2

There has been an intense research attempt on the design, development and analysis of different control scheme for grid connected voltage source converters (VSC) during the last couple of decades. Traditionally VSCs were used for the electric motor drive systems with different control techniques ranging from the natural reference frame to the synchronous reference frames, with conventional controllers to artificial intelligence based controllers etc. Fortunately, many of the control techniques developed for the motor drive systems are suitable for the operation of VSCs in the utility/grid connected applications also. When they are operated in the grid connected applications, they are subjected to different types of transients, disturbances and parameter variations due to the prevailing conditions of the grid from time to time. At the same time, they have to fulfil the standards mentioned above. Most of the control structures and techniques available in the literature share some commonalities as follows:

- **Grid synchronization**

  When an asynchronous link is to be maintained and power transfer to the active grid is to be controlled through converters, the information about the phase, the form and magnitude of the grid voltage need to be obtained continuously. These measurements are very vital whatever be the type of control adapted. They act as the inputs to the rest of the control scheme to achieve synchronization. Thus, every grid connected converter scheme will have a synchronization technique. A wide variety of synchronization methods are available in the literature authored by

Haque et al. (2010), Kaura et al. (1997), Chung Se-Kyo (2000(a)), (2000(b)), Rodriguez et al. (2007), Venkatramanan & Vinod John (2010), Ghoshal et al.(2011), Noguchi et al.(1998), Agirman et al. (2003) and Kwon et al. (1999). They suggest the synchronization methods both for normal operating conditions and for abnormal operating conditions. The Phase Locked Loop (PLL) using Synchronous Reference Frame (SRF) is a commonly used technique especially when the control loops are designed to operate with DC quantities and with the Space vector PWM (SVPWM) for voltage control of VSIs.

- **Active Power control loop**

In conventional control scheme for grid-connected converters, the active power control loop will be usually an outer loop. This will provide the necessary reference quantities to the inner control loop by adapting various methodologies viz. the instantaneous power balance between the input and the output of the converter, maximum power point tracking algorithms, direct power control etc. This loop uses either a conventional Proportional Integral (PI) controller or an advanced Proportional Resonant (PR) controller and forces the actual power to follow the reference power or force the dc link voltage to follow its reference valueas utilized by Verdelho et al. (1998), Mishra et al. (2009), Alejandro Munduate et al. (2009), Omar , (2012), Choi & Sul (1998), Bin Liu et al.(2013), Zmood & Holmes (2003) Kadri et al. (2011), Haque et al. (2010), Blaabjerg et al.(2006), Teodorescu et al. (2006) and Waleed Al-Saedi et al. (2013).

- **Reactive power control loops and UPF operation**

This is also an outer loop in conventional control scheme for grid-connected converters, i.e. this loop also provides the necessary reference quantities to the inner control loop. This loop receives the reference quantity according to one or more of the following requirements (i) the reactive power support to be provided by the converter, (ii) The power factor at which the current to be delivered, (iii) voltage control at the ac grid. However, for UPF operation this reference is set to be zero for most of the time.

- **Inner current loop for accounting filter drops**

Two inner current loops receive the reference values from the output of the active and reactive power control loops. The output of these loops directly drives the PWM switching scheme that follows these loops. Normally the inner loops are to be faster than the outer power loops. These inner current loops account for the series voltage drop that occurs at the output filter of the converter when it is delivering a particular reference power. As the converter output voltage is the vector sum of the ac grid voltage and the series drop, the switching scheme should make the converter output voltage to be higher than the ac grid voltage by the series drop to enable the power flow to happen into the ac side. These details are reported by various authors viz. Zmood & Holmes (2003) Kadri et al. (2011), Haque et al. (2010), Blaabjerg et al.(2006) Teodorescu et al. (2006) and Waleed Al-Saedi et al. (2013), Malinowski et al. (2001)(2009).

- **Decoupling of active-reactive powers with inner current loop**

The inner current loop will often have to perform a feed forward decoupling action, for decoupling the dependency of active and reactive powers on each other. Moreover, this independency is very vital in practical schemes, especially under transient conditions. For e.g. in a solar PV converter system if a 0.5 pu change is required in reactive power reference as demanded by the grid conditions, and it is required to keep the active power reference constant say at 0.5 pu. Under transient condition, the active power delivered will reach a value greater than its reference. However, the feedback controller regulates this condition back to it reference value, but the line might have already tripped due to over load during this correction period. This dependency is due to the cross coupling terms existing between the active and reactive power current components due to the non-unity power factor current in the filter inductor. This is reflected as a cross coupling term linking the d-axis and q-axis currents in synchronous reference frame controller as conveyed by Milosevic (2003), Ostlund Stefan (2008) and Fernando Briz et al. (2000).Thus, the controller's performance is highly dependent on the structure and model of the system. Nevertheless, the control should be immune to structural change and model changes, and should remain dynamics free.

- **Pulsed width modulation (PWM) for meeting the harmonic standards**

The PWM block receives the inputs from the inner current loops, and can generate either constant frequency gating pulses in case of sine PWM or space vector PWM or variable frequency gating pulses in case of current regulated PWMs like hysteresis or bang-bang control etc. The reference to this block will be a voltage reference or a current reference depending on the PWM scheme. Now-a-days space vector PWM is preferred over sine PWM because of the following features viz. capability to control the three phase voltages independently, simple digital implementation, better dynamic response, better utilization of the dc link voltage and lower harmonic distortion, which is a mandatory requirement in grid connected systems as per the reports of IEEE (2011) and CEA-India (2012).

1.2.8 Role of Emulators in the testing of micro-grids

A well-known fact is that, in micro grids several renewable energy sources and conventional energy sources operate together. The switching in and switching out of any distributed generator will cause variation in the structure and model of the micro-grid at any point of time during the operation. So, it becomes necessary to ensure that the control structure and its action should be independent of the system and the operating conditions. From the discussions above, it is clear that intense testing of micro-grids in both the component level and configuration level is very important in the aspect of investigation and demonstration of the adequacy of the design with reference to the reviews of Robin Podmore & Marck Ramon Robinson (2010), Meysam Shamshiri et al.(2012) and Mohamed & Mohamed (2012). The testing is to be carried out both under steady state conditions and during transient conditions. To simulate various network configurations under specific input-output conditions, real-time simulators i.e. emulators are vital. Emulators give the flexibility of obtaining different energy flows, creating fault conditions, creating transient conditions help understanding the electricity distribution networks meticulously. For example, micro-grids working under islanded mode, the dynamics are very fast as there are no significant time constants present within the network. The unpredictability of supply and demand is very common under islanded condition, which puts the stability and efficiency of the network under threat and test. Most of the generators are nature driven, and so for consistent performance of the interfacing power converters and the control loops, the experiments need to be repeated for every load/grid condition at every possible input condition. With an actual renewable energy source, it is not practical to repeatedly set the steady state and transient ambient conditions at all ambient values as required. Thus, emulators representing any renewable energy source are primarily intended as a power source to the converters in experiments to verify the reliability and repeatability of operation of the converter in steady state as well as in transient conditions of all possible input/grid conditions. Such a hardware simulator has to produce outputs effectively as will be given by a renewable energy source at any operating condition. Besides the renewable source emulator, the system emulators are also very much crucial in the development of fail-safe micro-grids. System emulators will have the network parameters for the actual spread length corresponding to micro-grids represented by lumped circuit parameters, thus allows the testing of various generators operating on it in a synchronized manner under various conditions. By the use of these emulators the smart grid system designers will get the response from low cost, safe, and easily configurable simulators and emulators instead of waiting for expensive and hardwired deployments for their testing. This will make the micro-grids to be operator-centered and operator-friendly.

1.3 AIMS OF THE RESEARCH WORK

1.3.1 Identification of the Research issues

Some of the biggest challenges on the Micro-grid controls are:

- The existing iterative MPPT techniques cannot be used directly with inverter control. Modification of the existing MPPT techniques is required. Also, the convergence and the oscillations around the operating point need to be improved.
- How to achieve an asynchronous link to maintain synchronism between the converter and the utility?
- The control loops are normally dc, but the controlled parameters are the ac currents injected into the grid. This puts a challenge of how to derive dc control loops from ac quantities.

- Independency in the control of active and reactive powers for meeting the dynamic needs of the loads .i.e control of active power should not affect the reactive power delivered and vice versa by means of decoupling of the active-reactive power control loops.
- The commonly used feed forward, multivariable, feedback type of decoupling methods make use of nominal grid impedance values in their control loop, which lead to loss of independency when adapted for micro-grids, where the grid impedance is not fairly constant under various operating conditions.
- For achieving a perfect independency in the active-reactive power control in micro-grids, a dynamic decoupling is required between the active and reactive power loops.
- Handling the transient conditions during intentional connection and disconnection of micro grid and/or unintentional disconnection due to loss of mains.
- Making the control strategy valid for both grid-connected and islanded condition.
- The power quality is to be maintained for harmonics and other related issues as per the norms of International bodies like IEEE, IEC etc.
- How to ensure the repeatability of the input and the grid/ load conditions for testing and field trial of the developed grid connected converter systems?

1.3.2 Objectives of the Current Research Work

- Design and develop a three phase inverter to transfer power from solar panels to the grid within a micro-grid under both grid connected as well as islanded condition.
- Design, develop and hardware implement a digital control for the grid connected three phase inverter in the synchronous reference frame

(SRF) with dc control loops, so as to control the active and reacitve powers independently irrespective of the structure and/or model changes within the micro-grid.

- Development of a new non-iterative MPPT technique which can be directly applied to the inverter control and can obtain an active power reference for the inverter control loop. This power reference is to be used in the outer active power loop for delivering a prescribed quantity of power by the inverter.
- Design, develop and hardware implement a solar PV emulator which will act as a source of power for testing of the PV powered inverter under all combinations of input/output and grid conditions, so as to investigate the controller action and also to demonstrate the adequacy of the design.
- Design and hardware implement an online grid impedance measurement stage which calculates the grid impedance as a result of the structural changes of the micro-grid due to switching in and switching out of various distributed generators.
- Introduce a feedforward dynamic decoupling with the measured grid impedance value between the direct and quadrature axis control loops for achieving independent control of active and reactive power so that the decoupling is independent of the system and operating conditions.
- The developed system is to be tested on the existing micro-grid emulator for the confirmation of the proposed control methodology.

1.4 ORGANIZATION OF THE THESIS

Chapter 1 of the thesis briefs about the overview of the need for renewable energy utilization, the energy economics, the tolarable percentage of renewable energy penetration and the technical issues in the grid connection of the renewable energy sources. This serves as the basis for understanding and identifying the specific research issues and defining the area of rearch starting from the broad area to the narrow area in which the research and the thesis is focused on.

Chapter 2 gives the understanding from literature survey conducted for this research work. It is intended to give the state-of-the-art control schemes and strategies proposed by various authors available in the literature.

In chapter 3 the basic concepts of current control of grid connected three phase inverter in the synchronous reference frame (SRF) is explained, with an emphasise on the need for SRF control in grid connected converters. For validating and verifying the design of SRF-PI controlled grid connected VSI, simulations are carried out and the results are presented.

Chapter 4 briefs about a novel non-iterative MPPT technique using OC-SC values of solar PV array, including the design details and test results.

Chapter 5 briefs about the modeling, design and development of a solar PV emulator which will act as a source of power for testing of the developed PV powered inverter for obtaining repeated test conditions in this research work.

Chapter 6 explains the theory of implementation of a discrete Fourier Transform based dynamic online grid impedance measurement stage which calculates the grid impedance using sensed voltages and currents, from the inverter output. The need, the theory and the implementation of decoupling the active-reactive power control loops in grid connected inverter schemes is also explained in Chapter 6. The proposed methodology of introducing a feedforward decoupling with the online measured grid impedance value between the direct and quadrature axis control loops for a typical micro-grid is presented with the results.

Chapter 7 summarizes the conclusions drawn and the scope for future work from the execution understanding and the experimental results of the research work.