# CHAPTER 1
# INTRODUCTION

Renewable energy has seen a spike in popularity in latest decades of environmental concerns about pollution and the finite supply of fossil fuels. Among the world's leading renewable energy sources, the photovoltaic system (PV) turns solar power into electricity. In the 1960s, the space programed adopted PV as a cost-effective power supply. Stand-alone PV power plants were widely used in rural and remote locations in the 1980s and 1990s as an attractive and cost-effective option for supplying electricity [1]. The solar energy sector has grown rapidly during the past two decades due to substantial advances in power electronics and solar panels. PV electricity generation costs are predicted to fall as a result of this growth. Since solar panel prices have fallen dramatically, the number of PV installations has increased significantly. The installed capacity of renewable energy for electricity generation in India reached 911.53 GW at the end of 2021, compared to 138.9 GW in 2014[2].India will have a total solar power generation capacity of 383 GW by 2020-21. Upwards of 42 GW of solar capacity has been installed in India in the previous seven years, an increase of more than 700%.

Rooftop and ground-mounted PV systems are available in a wide range of capacities, from a few kilowatts to hundreds of megawatts, depending on their location. On either hand, ground-mounted photovoltaic systems are installed on the ground while roof-type systems are installed on the roofs of institutional buildings, residential, or commercial. Both grid-connected and stand-alone solar power systems can be installed with on-grid/off-grid PV system. In the case of a grid-connected PV system, excess power generated by the PV system can be fed back into the grid [2]. PV systems can be categorized based on their power capacity from a small-scale to a utility. Between 1 MW and 10 MW, utility-scale PV is connected through one or more interconnection transformers to medium-voltage distribution feeders, such as the 27.6 kV feeders. PV systems with a power range of 10kW to 1000kW are referred to as medium-scale PV systems [2]. They can be installed on both small and large buildings. Depending on the size of the PV system, medium or low voltage distribution feeders are used. Up to ten kilowatts is considered a small-scale PV system.

## 1.1 Electricity Generation through Distributed Generation (DG) System

The electric power system relies heavily on the distribution system to ensure that customers receive a steady supply of electricity[4]. As a result, poor power quality in the distribution system has a serious influence on other components of the power system, such as loads. This implies that the loss of any one component in the supply line causes the power supply to be cut off to the end customers in most distribution systems. Distributed Generation (DG) has become increasingly popular in recent years for a variety of reasons, including increased demand, technological and economic advancements, and environmental concerns [6]. IEEE defines DG as "the generation of electricity by facilities that are sufficiently smaller than central generating plants to allow interconnection at practically any point in a power system" [2-3][6]. In recent years, wind and solar energy-based DGs have emerged as the most popular.

## 1.2 Grid-Integration Challenges for Photovoltaic Systems

By using DGs, transmission network expansion will be less expensive. As a result of these advantages, new distribution system challenges have arisen. Harmonics, flickering voltage, and Temporary overvoltage (TOV) are some of the problems associated with utility[4][18]. The power of PV systems can rapidly fluctuate due to diverse sunlight availability and climatic circumstances (for example, the movement of clouds). It will degrade the dynamic and steady state behavior of system. As a result of the PV system's increased use of voltage regulators including load tap changers and capacitor banks, voltage profile alterations such as temporary overvoltage (TOV) and steady state overvoltage have been observed. Large PV systems connected to the grid, on the other hand, generated power flow in the opposite way, resulting in excess voltages at PCC, which could limit future DG installations [7][10-11]. Utilities mandate that PV systems adhere to IEEE Standard 1547, IEC 61727, and Standard 929-2000 in order to avoid any of these issues [14]. Traditionally, electricity distributors employed capacitor switching and under load tap changers to regulate voltage, but these devices failed in the presence of solar power systems and significant load changes. Overvoltage occurs at PCC when a solar power system is integrated to the grid. This overvoltage is called steady-state overvoltage[14][18]. If these are higher than the electricity distribution companies' interconnection regulations, the solar power system is denied connection.

## 1.3 Shunt-connected Static Reactive Power Compensator (STATCOM)

Voltage regulation has become an essential issue in the integration of DG resources such as PV solar power systems since they may have a negative impact on voltage levels[4]. Voltage regulation in distribution systems has traditionally relied on the use of shunt capacitor banks (SCs), on-load tap changes (OLTCs), and step type regulators (SVRs). These devices, on the other hand, operate on the basis of unidirectional power flow and typical load changes. Traditional voltage regulators are unable to work properly because solar and wind power systems can generate reverse power flows. Controllers known as FACTS (Flexible AC Transmission Systems) can be used to overcome the limitations of electromechanically controlled transmission systems. With the development of the shunt connected static compensator (STATCOM)[35], controlled reactors and switched capacitors were replaced by the voltage source inverter (VSI). For example, STATCOMs have several advantages over conventional SVCs since they use self-commutated power semiconductor devices such as GTO, IGBT and so on. This is unlike variable impedance type SVC which uses thyristor devices. Traditionally, distribution systems use shunt capacitor banks, on-load tap changers, and step voltage regulators (SVRs)[37]. But these devices work with unidirectional power flow and usual load changes. Due to potential of reverse power flows from solar and wind power systems, typical voltage regulators fail. To manage the voltage, Flexible AC Transmission Systems (FACTS) devices such as Static Var Compensator (SVC) [36-38] or Static synchronous Compensator (STATCOM) [102] exchange reactive power at the feeder where solar power systems are attached. To compensate for reactive power loss, the STATCOM system utilizes a DC-bus capacitor, solid state switches, filter components and an interfacing transformer. In addition to power factor correction, the STATCOM can manage voltage flicker and transient over voltage (TOV). The voltage differential between STATCOM terminals and PCC promotes reactive power flow in both directions. When STATCOM's terminal voltage exceeds PCC's, it generates reactive power and acts as a shunt capacitor.

When its terminal voltage is lower than PCC, STATCOM absorbs reactive power like an inductor. In practice, the STATCOM's semiconductor switches are not lossless, so the DC capacitor's energy is lost due to internal converter loss. So the STATCOM must draw active electricity from the grid to keep the capacitor charged. Active power generation is possible if the STATCOM is equipped with an energy storage device or a DC source such as a photovoltaic panels.

## 1.4 Multi-purpose Single-stage Photovoltaic system

The unbalance of the instantaneous DC input and AC output powers in single/three-phase inverters causes double-line frequency voltage ripple on the DC-bus. This power mismatch requires a capacitor to store energy. The power pulse is stored in the capacitor as static energy. Using the two-stage inverter, the DC-bus voltage and capacitor size can be customized to meet the specific needs of the design. Electrolytic capacitors can be replaced with film caps to extend the DC-bus capacitance lifespan, as the capacitance of the DC-bus is lowered. However, the reduction in capacitance results in a high double-line frequency voltage ripple on the DC-bus, which results in a series of odd harmonics in the output current. It's the same voltage as the PV voltage in a single-stage inverter at MPP (MPP). Because of their huge capacitance, electrolytic capacitors are commonly utilized, yet they are also the main cause of inverter failure [3]. Using a film capacitor reduces the capacitance of the decoupling capacitor, reducing cost and increasing longevity. Active solutions using additional circuitry to separate the AC pulsing power have also been devised [4, 5]. These active approaches aim to reduce capacitance by raising the DC-bus voltage$V_{DC}$. However, high voltage stress on power components and switching losses must be carefully managed. There is another way to handle this issue. Two-stage inverters allow for substantially higher voltage ripple on the DC-bus than single-stage inverters while maintaining MPPT efficiency. This double-line voltage ripple causes harmonic distortion in output current. These harmonics have a substantial impact on the power system, loads, and protective relaying [7, 8]. Multi-purpose PV systems are converters that can do more than only convert DC to AC power [36, 37]. Globally, multi-purpose PV systems are being developed and deployed in power systems [38-40]. This section discusses multi-purpose PV systems controls and applications, as well as the essential standards for DG integration.

### 1.4.1 Functions of Multi-Purpose Single-stage PV systems

An important step forward in the integration of distributed energy resources has been made possible by the advancement in the PV system. PV converters are being reprogrammed with additional capabilities that can support electric grid and help improve the penetration of renewable energy in electric power systems through this approach. FACTS-like features for providing ancillary services have also been included in wind inverters [50, 51] as a parallel development. While PV systems convert DC power to AC power using a Voltage Source Converter (VSC), STATCOMs provide reactive power exchange utilizing a Voltage Source Converter (VSC). A main objective of the PV system act as STATCOM for the providing reactive power regulation during nighttime and also during the daytime, together with the production of real power. Reactive power assistance can be provided by existing PV systems without a significant increase in cost. To increase utility capacity, a multipurpose PV -STATCOM control for PV inverters has been presented here.

### 1.4.2 Grid Synchronization

Using its voltage-regulated oscillator, the phase-lock loop extracts phase-angle from a grid voltage signal. An angular frequency and phase angle are determined for the grid-connected converter control block, preventing islanded mode, first used to synchronize grid-assist photovoltaic systems (PV), which use comparators to detect polarity deviations in the sensed grid voltage. Multiple zero-crossing detections complicate phase-angle extraction when abnormal grid voltage or weak grids occur. Because stationary frame PLLs only need one voltage signal to synchronize, they are more efficient than alternative techniques. The error signal for the low-pass filter (loop filter, i.e., LF) is provided by a multiplier phase detector (PD) (LF). It generates a 100Hz ripple error signal that proliferates through the LF [8][68-69]. A 100Hz ripple term can be lowered by inserting an additional low-pass filter, but at the expense of bandwidth, phase margin, and full synchronization speed[70] [76]. The DQ PLLs can convert grid parameters to DC quantity and estimate frequency and phase angle. DQ PLL computes frequency and phase angle using two signals, direct and orthogonal (quadrature). Using phase delay filters, differentiation of the input signal, Inverse Park's transform, Hilbert transform, and second-order generalized integrator (SOGI)[71][83], an orthogonal signal is generated from a direct signal, i.e., measured grid voltage. This eliminates the 100Hz ripple and increases the inherent synchronization speed and bandwidth over a conventional PLL. The commonly used phase-locked loop (PLL) technique requires complex design and tuning to attain a good stability margin. Inverters with single or three-phase grids can use SOGI-FLL to detect phase angle[72]. For the control system appropriately selected parameters, additional feedback selection will increase synchronization speed during grid irregularities, enhances robustness during grid irregularities and thus predicting appropriate phase angles[74]. SOGI-FLL has the best performance with distorted harmonic components but poor performance with unbalance grid due to negative sequence. Dual SOGI-FLL performs best with no DC offset in the detected grid voltage. DSOGI-FLL can track grid voltage dips, increases, harmonics, imbalance, and frequency fluctuations. It does so even if no PI controller is present. Modified DSOGI-FLL (MDSOGI-FLL) is efficiently designed to encounter DC offset along with all DSOGI-FLL features[74-75].

### 1.4.3 Modeling & Simulation of Multipurpose PV system and Assessment

The Simulink/ MATLAB software was used to verify the validity of the study system and controller. It has been proposed in [61] to use a grid tied PV system for the compensation during a unbalanced and/or non-linear load. Using the MATLAB/Simulink, modeling of Photovoltaic panel has been modeled and characteristics observed by considering different scenario in context of irradiation and atmospheric temperature. The various grid synchronization techniques are simulated during ideal and non-ideal grid conditions. The Phase Lock loop(PLL), synchronous reference frame based phase lock loop, second order generalized integrator(SOGI) based PLL, second order generalized integrator (SOGI) with Frequency lock loop, dual SOGI-FLL, open loop PLL, modified DSOGI-FLL are simulated and carried out comparative analysis of them. An active shunt filter or reactive power compensation capability has been added to the typical PV system, as seen in[23][27][48]. The various Maximum power point tracking algorithm like Pertube & observed, Incremental conductance, current sensor less MPPT for single-stage grid connected inverter are simulated and discuss prone and cons of these techniques.

#### 1.4.3.1 Implementation using WAIJUNG block-set of Simulink/MATLAB

Model based programming using a WAIJUNG block-set of MATLAB/Simulink in real time offers more accurate views of controller performance than software studies. In a real-time research, actual sensed ADC signals, discrete control model and DAC signals carried out for observation are used in the control process. ARM Cortex M4 is 32 bit microcontroller with the capability of digital signal processing. A WAIJUNG block-set of MATLAB/Simulink is capable to generate C code or hex file for ARM Cortex M4 STM32F407VG microcontroller through KEIL IDE. The KEIL IDE provides hardware debugging for this real time application. A MPPT control, current control, and voltage control are implemented on ARM Cortex M4 STM32F407VG microcontroller using model based programming for grid connected PV system.

#### 1.4.3.2 Experimental Validation

The controller must be validated one last time in the laboratory using a hardware implementation. Now that the small-scale prototype of single-stage grid connected PV system has been established, controller of multi-purpose PV inverter with specific goals has been set up in a laboratory setup. To compensate for harmonics and/or reactive power in [18], the authors employed a grid-connected PV system that was tied to an actual lab setup. Reactive power correction is provided in [23] for the lab validation of a 5 kW solar system. The control system of 5kW multipurpose PV system is realized using a model based programming in the WAIJUNG block set of Simulink/MATLAB to achieve following control objective: PCC voltage regulation and power factor correction by providing the reactive power support to the grid. The control variables of PV arrays, PV inverter and grid are used in control system designing for the model based programming using a 32-bit ARM cortex microcontroller (STM32F407VG). The current sensor less MPPT is implemented and observed the performance. The results of this study were compared with simulation result.

#### 1.4.3.3 Standards for Grid Integration of Distributed Systems

Distribution systems frequently use DGs and DRs, or distributed generation stations (DGs), and distributed resource stations (DRs)[4]. The influence of distributed resources (DR) on the electric power grid makes their integration a critical resource challenge (EPS). Integration consequences can be wide-ranging due to changes in DR interconnection location and power system characteristics. A few of the DRs impacts on the power system include poor control during reverse power flow, overvoltage, under-voltage, and voltage unbalance. Using IEEE standard 1547-2003, system designers can minimize lots of further potential harms for their systems and power grid. DRs are prohibited by IEEE standard 1547-2003 from actively controlling PCC voltage or causing other Local power system service voltages to deviate from Range A [14]. By this standard, DR voltage regulation may interact with other devices installed by the regional grid operator. IEEE has developed a new integration standard, IEEE Standard d 1547a-2014, due to various studies on voltage management by Distributed Resources. To actively engage in voltage regulation through active and reactive changes, regional grid operators and DR operators will need to be coordinated with and approved by "Standard 1547a-2014 says. The Area power system service voltage at other regional grids must not fall below the ANSI C84.1-2011 1995, Range A criterion as a result of the DR ", it's. As a result, even in the presence of extra voltage regulators, distributed resources like wind turbines, solar panels, energy storage systems, and fuel cells can regulate voltage[1-2][8][14].

## 1.5 Control of Multipurpose PV System (PV-STATCOM)

For a traditional PV system, a STATCOM is a voltage source converter (VSC) that converts DC electricity to AC power. A STATCOM, on the other hand, exchanges reactive power while a PV system provides active power. These two principles together can enable both active and reactive power. A novel method for using a PV inverter as a STATCOM has been developed [36-38]. The PV system is clearly working below its rated power production for approximately 80% of the day, leaving the inverter capacity underutilized. Also, when the sun isn't shining, the PV inverter is inactive. The above unique STATCOM PV solar system design uses the remaining inverter to exchange reactive power with the grid to manage voltage. This revolutionary technology can provide several advantages at little cost. The leftover capacity of the PV inverter may be used to manage voltage and power factor. The multipurpose PV inverter in "Partial STATCOM mode" exchanges reactive power with remaining capacity of the inverter. In this mode, PV converter generates active power first, and then exchanges reactive power with leftover inverter capacity [18].

However, the multipurpose PV system converts into a complete STATCOM automatically during transients or faults. In this situation, the multipurpose PV system disconnects the solar panels and swaps reactive power as a STATCOM for the grid. This method of operation is called "Full STATCOM mode". That is, the multipurpose system PV system decides dependent on system requirements, transient/disturbance kind, time of day, and remaining inverter capacity. Due to the unfavorable impact of DG systems on the voltage profile, utilities have restricted DG connectivity. These inverters can help increase the connection of DGs in distribution networks since they can fully regulate voltage with reactive power assistance. It remains to be seen if the multipurpose PV system control can assist increase PV system installation as DG units. Motivation and Scope of Thesis.The primary goals of PV systems are to reduce the cost of the power converter stage, raise the efficiency of both converters and PV arrays, and significantly improve converter dependability.

Since the characteristics of photovoltaic (PV) modules are affected by solar radiation and temperature, it is necessary to develop control logic for single-stage grid-connected photovoltaic (PV) systems that is simple, efficient, and reliable in order to collect as much power as possible at every operating point. The single-stage PV system should behave as multipurpose system by performing the active power injection along with reactive power exchange to the utility grid for the strengthening utility grid. Furthermore, to modify MPPT algorithm without using a current sensor for the single-stage grid interfaced PV-STATCOM.

### 1.5.1 Experimental setup

An experimental setup consists of a three phase power card consisting IGBT , IGBT driver cards with S.C. (Short Circuit) protection , 32-bit DSP based microcontroller STM32F407VG , For DC side separate voltage hall sensor, for ac side 3 set of C.T. (Current Transformer) and P.T. ( Power Transformer ) with DC offset adjustment , unipolar ADC in a microcontroller, 8 set of series connected PV panel strings, three-phase inductive load, three-phase resistive bulb load of 200W, manual DPDT switch, and 3-phase VARIC as a utility grid. The inverter currents and PCC voltage are sensed and scaled into proportionally within 3V by 3-set of current transformer (CT) and power transformer (PT) and scaling circuits, respectively. It is to be taken care that microcontroller has uni-polar ADC pins with the limitation of maximum voltage 3.3V at ADC pins. Hence DC offset circuits are required to converter bi-polar signal into unipolar signal. The role of sensors circuit is sensed as well as scaled into 3V (for the safety) and DC offset circuits add 1.5V DC into scaled ac signals to make unipolar signal, which is given to the ADC pins of microcontroller. The hall sensors are used to measure current and voltage of PV strings and scaled into 3V to be used in MPPT algorithm to generate active current reference for the control approach of presented PV system. The discrete model of control system of single-stage grid connected system is designed using WAIJUNG block set for STM32F407VG microcontroller in Simulink/MATLAB environment. Software coding and calculation of cycles for different measurement and control of different respective parameter, which must be compatible with the hardware, design of photovoltaic system. The sizing calculation work has been carried out. It includes below works:

1) Grid synchronization strategies
2) ADC count loop calculation
3) Control card design and selection
4) Current control loop and voltage control loop strategy implementation
5) Hardware protection strategies

Hence, to achieve these objectives, the research work reported in thesis are:

1. The goal of the work is to develop the complete hardware of voltage source inverter for photovoltaic system. Design and analysis the control logic based on inner current and outer voltage loop. It also incorporates MPPT based inverter control. [Single stage conversion].

a)To combine two independent control strategies (i.e. MPPT control for PV side and inverter control for grid side in two-stage grid interfaced system) into one control strategy for single stage operation of voltage source inverter for photovoltaic system.

b) To design and implement control strategy for the protection of photovoltaic system.

2. To modify the control strategy of single-stage grid connected system for the transforming into multi-purpose PV inverter, which is able to managed smartly active power injection along with fulfilling the need of reactive power at PCC of grid without oversizing inverter(which is also known as Partial PV- STATCOM).

3. It can regulate a reactive power current through quadrature – axis (i.e. q-axis) current control within 1-2 cycles during load variation.

4. The modified Dual-SOGI and tan-arc method is employed as grid synchronization techniques to detect phase angle of PCC voltage for the control system during non-ideal grid conditions including dc offset rejection, and also eliminates harmonics component

as well as negative sequence component for phase-angle computation in a tan-arc method.

5. A modified MPPT algorithm is employed to extract the maximum power during the PV intermittency without using a DC current sensor.

## 1.6 Outline of Thesis

A chapter-wise summary of this thesis is given below:

Chapter 2 demonstrates brief overview of grid connected photovoltaic system (PV), topologies, and control structure of PV system. Discussion on two-stage grid connected PV system and single-stage grid connected PV system. It also gives survey on maximum power point tracking algorithms. It describes the overview of operating principle of STATCOM including mathematical analysis. It also gives survey on control strategy during abnormalities in grid.

Chapter 3 detailed discussion of the Grid Synchronization techniques in Three-Phase Power Converters under ideal and non-ideal grid situations. The comparative assessment of grid synchronization techniques discuss with simulation as well as experimental results.

Chapter 4 presents the modelling of grid connected PV system including current and voltage control. It also includes controller design of inner current loop and outer voltage loop. Mathematical analysis of reactive power support provided by single-stage grid connected PV system to the utility and presented modified MPPT without DC current sensor at PV side.

Chapter 5 provides detailed description of experimental set-up of hardware. It includes detailed description of model-based programming for single-stage grid connected inverter using WAIJUNG block-set in a Simulink/MATLAB and STM32F407VG ARM controller. It also includes about signal scaling for sensor and hardware protection code. It also discusses experimental results of the proposed single-stage grid connected PV system.

Chapter 6 sums up the thesis's findings and highlights its important points. Ongoing studies utilizing this multipurpose single-stage grid connected PV system are also being considered.

Thesis ends with a complete Bibliography.