

# Chapter 1

## Introduction

### 1.1 Research Background

Over the last ten years, there has been more and more emphasis on renewable energy sources (RESs) like wind and solar power because of the possible depletion of fossil fuels, rising energy consumption, and environmental pollution [1–4]. Solar and wind energy systems are most popular renewable energy source due to its abundant availability. These renewable energy sources have technical and economic advantages in addition to environmental benefits [5–7]. Hence, integration of renewable energy sources (RES) into electrical energy systems is increasing across the world, with ambitious targets set at the national and international level.

India has set a target of integrating 175 GW of RE by 2022 [8]. At COP 21, as part of its Nationally Determined Contributions (NDCs), India is committed to achieving 40 percent of its installed electricity capacity from non-fossil energy sources by 2030. India is targeting 500 GW of installed generation capacity from non-fossil fuel sources by the year 2030 at the recently concluded COP26 [8]. In order to facilitate this kind of growth, additional study and development are needed to make it feasible for distributed energy sources to be integrated into various power system levels, such as transmission and distribution systems [9–13]. The penetration of Renewable energy sources in India by 2024 is given in Figure 1.1. Further, instantaneous renewable energy penetration in India for the financial year 2023-24 is shown in Figure 1.2.

Table 1.1 shows the target set for 2030 for the renewable energy sources penetration in India [14].

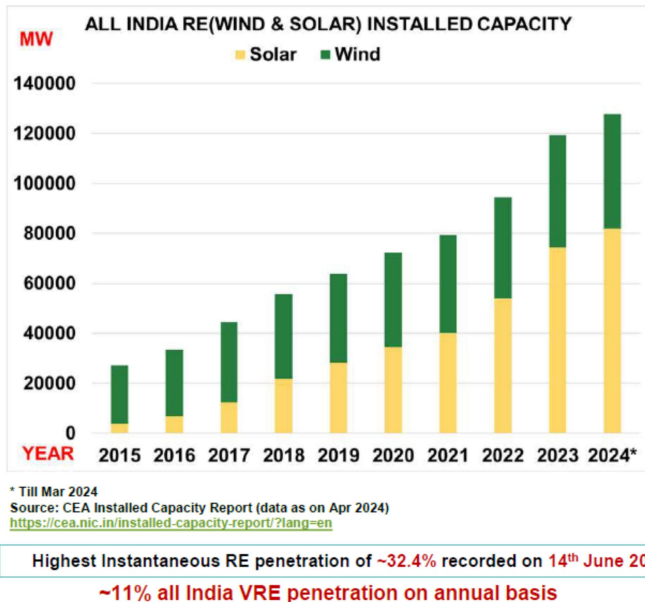


Figure 1.1: India’s Renewable energy sources penetration [14]

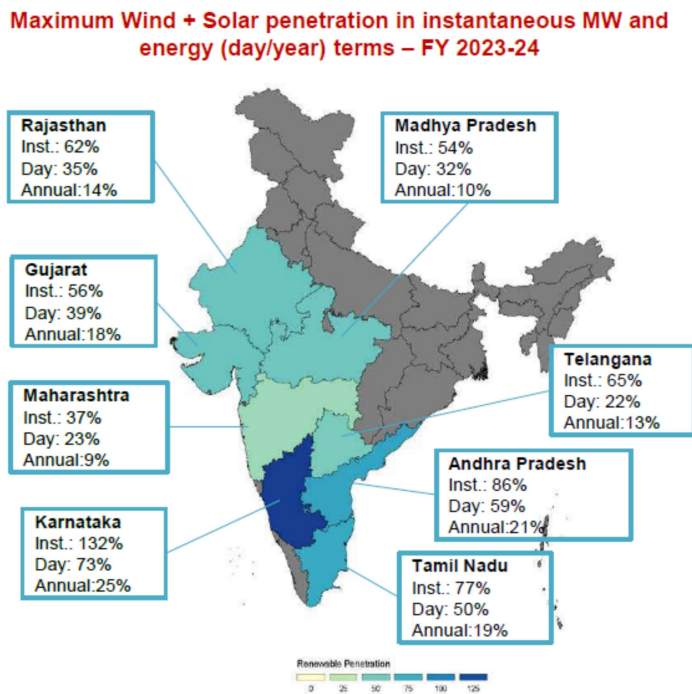


Figure 1.2: Renewable energy sources penetration in Instantaneous MW - FY 2023-24 [14]

## 1.2 Motivation

The growing use of intermittent and variable energy sources creates a number of technical challenges for a safe and stable grid operation. These challenges include the need for

Table 1.1: Renewable Energy Sources in India: Target 2030 [14]

All India Installed Capacity (MW)			
Resource	March 2024	March 2030	% Addition
Hydro	46928	59210	26 %
Small Hydro	5003	18986	279 %
Solar PV	81813	292566	258 %
Wind	45887	99895	118 %
Biomass	10940	14500	33 %
Nuclear	8180	15480	89 %
Coal + Lignite	218178	251683	15 %
Gas	25038	25038	0 %
Total	441967	777358	76 %
BESS	0	41650 (5-hr)	

greater flexibility, frequency stability, voltage stability, and long-term generation-demand balancing issues. Synchronous inertia—the rotating mass of synchronous machines—plays a crucial role in limiting the rate of change of frequency (RoCoF) and preserving frequency stability after a sudden change in generation-load balance. Especially, this inertia plays an important role in the initial moments after the disturbance begins, in an AC grid that is synchronously connected and has a large number of conventional generators and motors synchronized with the grid.

In a traditional large grid, there is a sufficient inertia because of synchronous machines and rotating mass. Experience from around the world indicates that the replacement of traditional synchronous generators by renewable energy sources (RESs) affects the system’s rotating mass, or inertia, especially when the percentage of renewable energy sources is higher. A study on inertia estimation in the entire Indian grid was started, given the substantial growth in renewable energy and the government of India’s ambitious targets for RE integration.

The reduction of equivalent power system inertia due to the large penetration of RESs for different regions worldwide within past few years is shown in the Figure 1.3 [15]. The relation between diminishing inertia and renewable energy penetration in case of

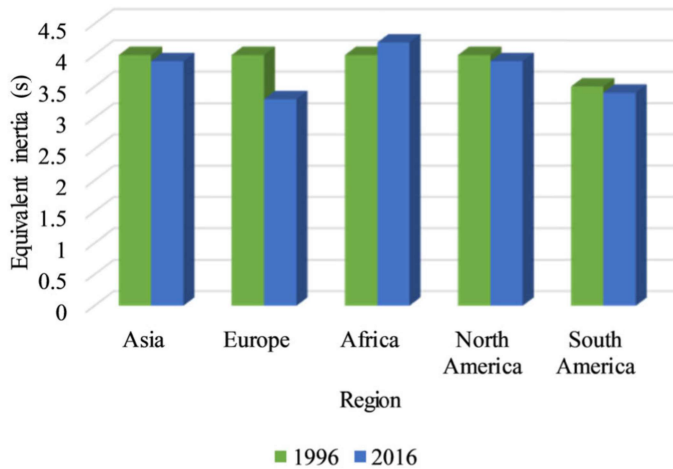


Figure 1.3: Reduction in equivalent inertia in past few years [15]

Indian power system is shown in Figure 1.4 [8]. Figure 1.3 and Figure 1.4 shows that the

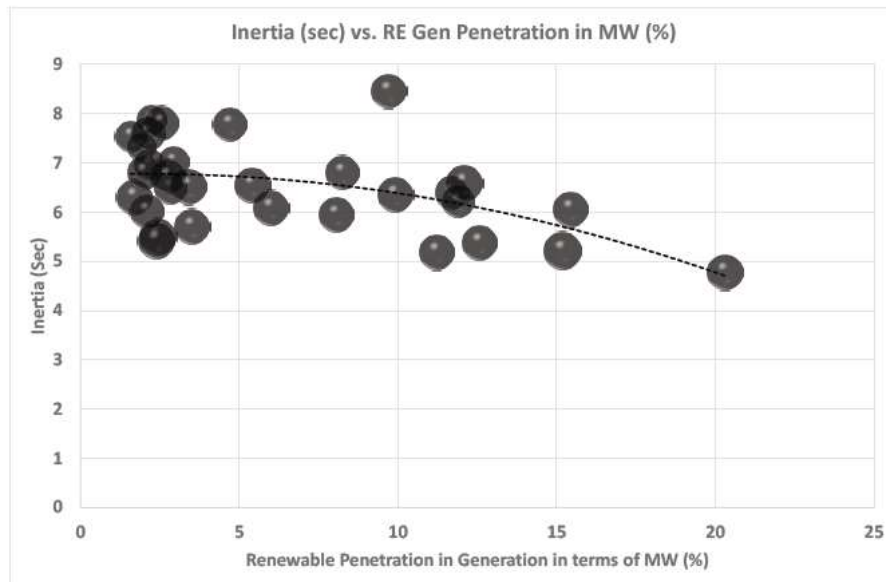


Figure 1.4: Inertia vs Renewable energy sources penetration [8]

large number of RESs are diminishing the equivalent power system inertia every year. So, the measures should be taken to maintain the adequate rotating inertia of overall system to maintain stability. There are so many methods of mimicking inertia virtually, which is explained in the next section.

### 1.3 Virtual Inertia Emulation

Conventional grid-connected inverter provides frequency regulation but doesn't provide inertia. Hence, there is need to emulate inertia in the grid-connected inverter. Virtual synchronous machine control is one of the solution for the inertia emulation. Both, conventional grid-connected inverter and inverter with virtual synchronous machine control is discussed in the following subsections.

#### 1.3.1 Conventional Grid-Connected Inverter with Battery Energy Storage

Active Power control and reactive power control loops provide reference currents for the internal current controller, as shown in Figure 1.5. Finally, current controller gives the reference signal for PWM pulse generation for switches. When it comes to energy storage units for frequency control, batteries stand out due to their high energy density, quick response time, and affordable price. There are many cases that utilize batteries for droop control for frequency regulation.

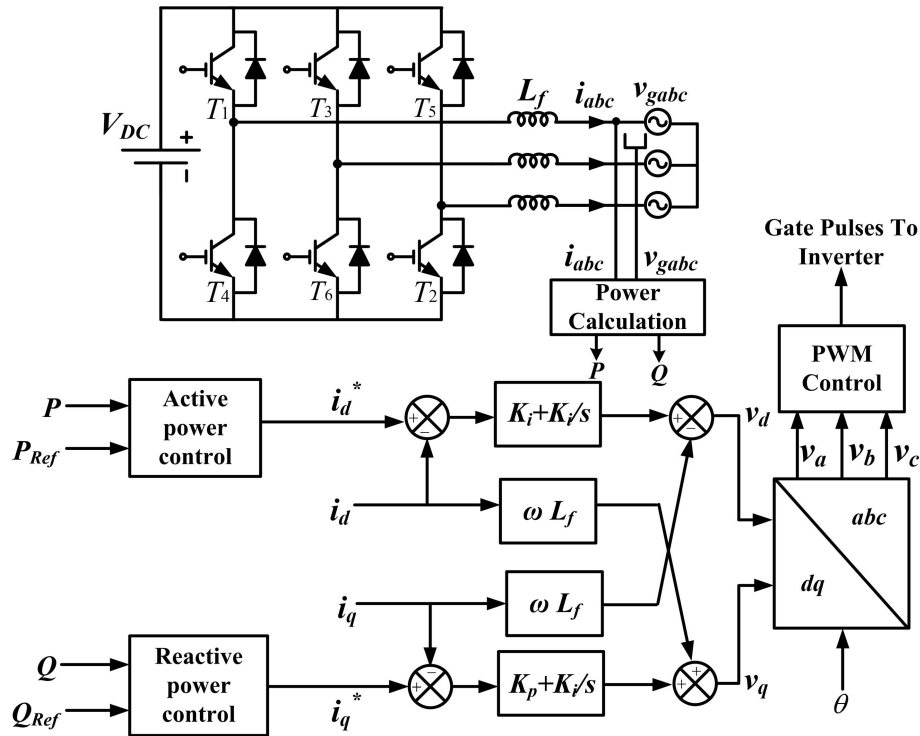


Figure 1.5: Conventional grid-connected inverter

### 1.3.2 Virtual Synchronous Machine for virtual inertia emulation

Other than energy storage systems, virtual synchronous machine (VSM) is the most popular method for virtual inertia emulation in distributed energy source (DES). Since, synchronous generators (SG)s are being replaced by inverter based DESs, inverters with SG behaviours are preferred nowadays to provide inertia emulation as well as frequency regulation. VSM, an inverter mimicking the properties of a synchronous machine, is becoming increasingly popular for virtual inertia implementation as well as grid-forming functions of SG. VSM based system for inertia emulation is shown in Figure 1.6. Various

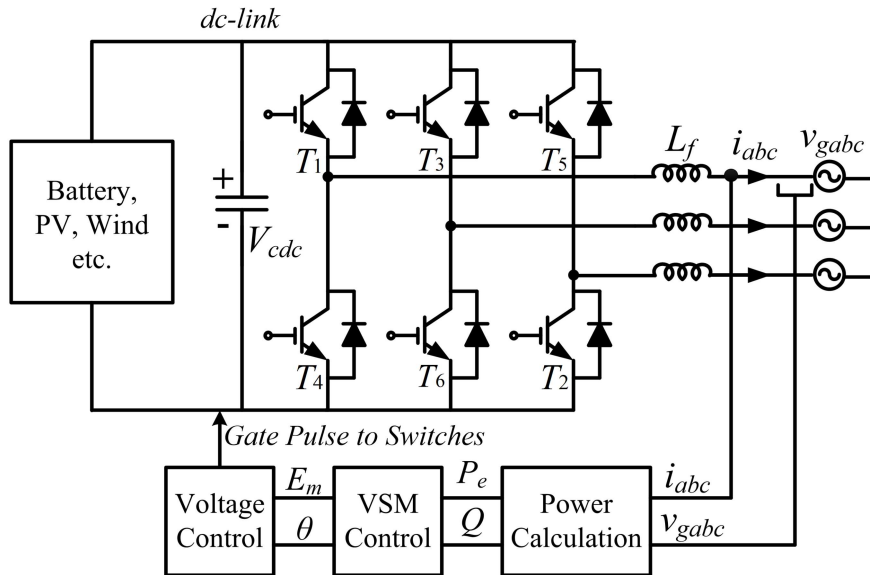


Figure 1.6: VSM based grid-connected inverter

VSM models are available in literature [16–31]. VSM contains the complete mathematical model of SG covering both electrical and mechanical part. Virtual synchronous generator (VSG) is one of the VSM model used to mimic SG characteristics. VSG may be implemented with battery or any renewable sources like PV or wind energy system. VSM is shown in Figure 1.6. Our research work is focussed on applying this VSG for different applications in microgrid based distributed energy sources with Battery Energy Storage system (BESS), Photo Voltaic (PV). The same VSG with battery energy storage system is integrated with an extra series converter to mitigate voltage power quality problems.

## 1.4 VSG with battery energy storage system

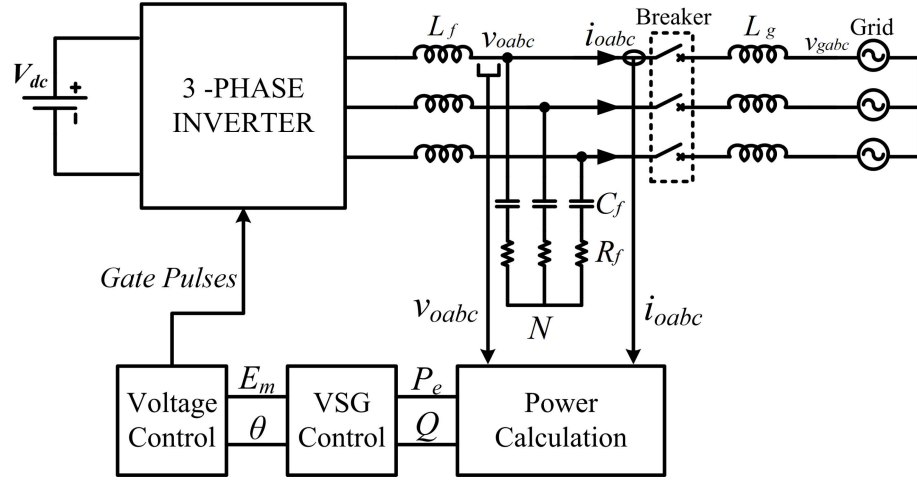


Figure 1.7: VSG control of BESS

VSG implementation in the BESS operated grid-connected inverter is shown in Figure 1.7. This is the simplest VSG system for inertia emulation. Here, the dc-link input is stiff, so VSG doesn't need any dc voltage control loop. VSG is primarily a voltage-controlled inverter. The AC output voltage across the load is maintained through an inner voltage loop. The active and reactive power loops provide the reference voltage angle and magnitude, respectively to the voltage control loop. Virtual inertia and damping are emulated in the active power loop. Comparison of VSG with the traditional current controlled grid-connected inverter is shown in Table 1.2.

Table 1.2: Comparison of VSG with conventional grid-connected inverter

S.No	Conventional grid-connected inverter	VSG
1.	Current controlled	Voltage-controlled
2.	PLL required for grid-synchronization	Self-synchronization is used
3.	Doesn't emulate inertia	Inertia is present in the active power control
4.	Operates in grid-connected mode	Both grid-connected and islanded mode
5.	Rate of change of frequency is high	Low rate of change of frequency
6.	Grid-following inverter	Grid-forming inverter

In place of BESS, VSG is also implemented with PV. Grid-connected PV system based on VSG is explained in Section 1.5.

## 1.5 VSG based Grid-tied PV System

VSG based grid-connected PV system is shown in Figure 1.8. PV inverter system consists of a PV panel, DC-DC converter and an inverter. Output of the inverter is connected to the grid. Basic building blocks of PV generation are PV cells. A photovoltaic array,

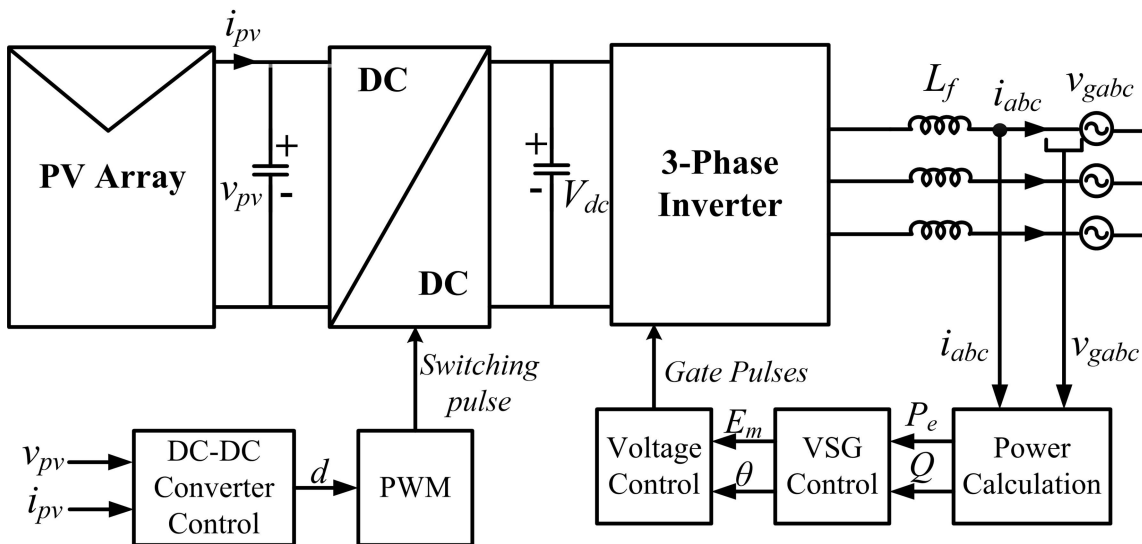


Figure 1.8: Grid-connected PV inverter with VSG

which can have any number of PV modules and panels, is the entire power-generating unit. I-V characteristics of the PV cell is shown in Figure 1.9. The output of the PV cell

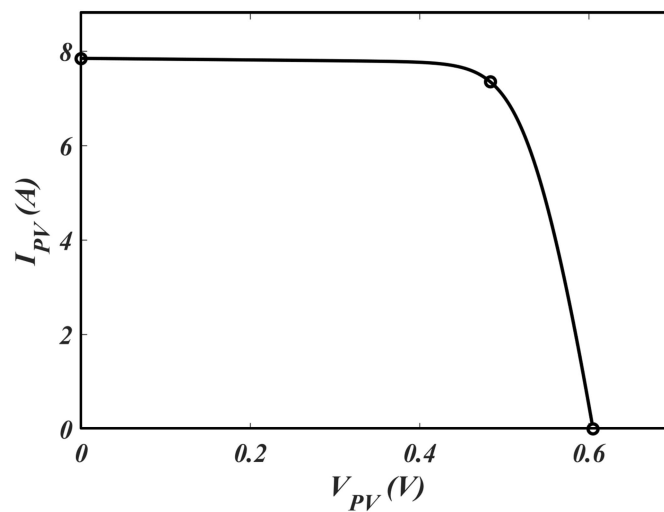


Figure 1.9: I-V characteristics of PV cell

is expressed by:

$$I_{PV} = I_0 \left[ \exp \frac{qV}{nKT} - 1 \right] - I_L \quad (1.1)$$

Output current  $I_{PV}$  and voltage of the PV cell  $V_{PV}$  is very low. Hence, to increase the power of the PV generation, PV array with a number of modules are used. But to avoid the large size of PV array, a boost DC-DC converter is used to further boost the DC output of the PV array. The DC-DC converter maintains a stiff DC link voltage  $v_{dc}$ . Dc-link is connected to the inverter, which delivers AC output to either the load or the distribution grid.

Economically speaking, distributed generation is more expensive than centralized utility-scale generation because of economies of scale, and centralized generation is also easier to manage. Unique advantages of integrating distributed solar PV power include decreased line losses, improved grid resilience, avoided generation costs, and lower operating costs. The variable, unpredictable, and geographically dispersed nature of solar PV systems presents certain technical and financial challenges to utilities and system operators despite these advantages.

- PV array doesn't consists any rotating part like conventional SGs. DC-DC converter and inverter contains only power semiconductor devices (IGBT and MOSFET) and passive components like capacitor and inductors. Hence, PV system has no kinetic energy or inertia to respond to any sudden disturbances.
- Maintaining the frequency of a power system close to its nominal value (either 50 Hz or 60 Hz depending on the grid) is crucial. Frequency deviations occur when there is a discrepancy between generation and load. As photovoltaic (PV) generation becomes more prevalent, the system's inertia decreases further, posing a serious threat to the frequency stability of the system.
- Also, PV system operates on MPPT in most of the cases. Hence, there is no reserve power available in the PV panel. In case of frequency disturbances, PV can not contribute to the frequency regulation services.

The solution to all the problems discussed above is addressed in this research as follows:

- To maintain the power reserve, PV system is operated at less than MPPT to participate in frequency regulation.

- Conventional, PV system doesn't have inertia. Hence, virtual inertia is implemented in grid-connected PV system using VSG. With this feature, VSG based PV systems can also be grid-forming solutions, unlike conventional PV system.

Another application of VSG is in power quality improvement. VSG circuit can be modified to form a UPQC so that it will compensate power quality problems in addition to VSG functions. VSG based UPQC is discussed in the next Section 1.6.

## 1.6 VSG based Unified Power Quality Conditioner (UPQC)

The primary objective of the power system utility is to provide sinusoidal voltage of constant magnitude and frequency. Due to the increasing penetration of the power electronics converter-based renewable energy sources in the distribution grid, the power quality of the supply system has become an important issue. Modern power systems are facing many power quality-related issues, such as voltage unbalance, harmonic current, voltage sag and swell, flicker, etc. Hence, to mitigate the power quality issues, different kind of compensators are used. There are many existing compensators, like dynamic voltage restorer (DVR), static compensator (STATCOM), unified power quality conditioner (UPQC) etc. UPQC, as shown in Figure 1.10, is the most popular one as it comprises the qualities of DVR as well as STATCOM. Hence, UPQC can compensate both voltage and current power quality issues.

Despite the ability to improve power quality, UPQC has some limitations. UPQC comprises only two inverters, i.e., shunt and series inverters, which don't have any rotating mass or inertia.

Hence, to enhance virtual inertia in power system in addition to the power quality improvement, a VSG control algorithm can be implemented. VSG inverter can supply load current harmonics but it can't mitigate voltage power quality problems. Hence, one more series converter at the dc link is added with the VSG inverter, to mitigate the voltage power quality problems such as voltage sag, swell, grid voltage harmonics etc. This arrangement looks like a UPQC and called as a VSG-UPQC. So, the VSG-UPQC will be able to improve the power quality as well as enhance the virtual inertia

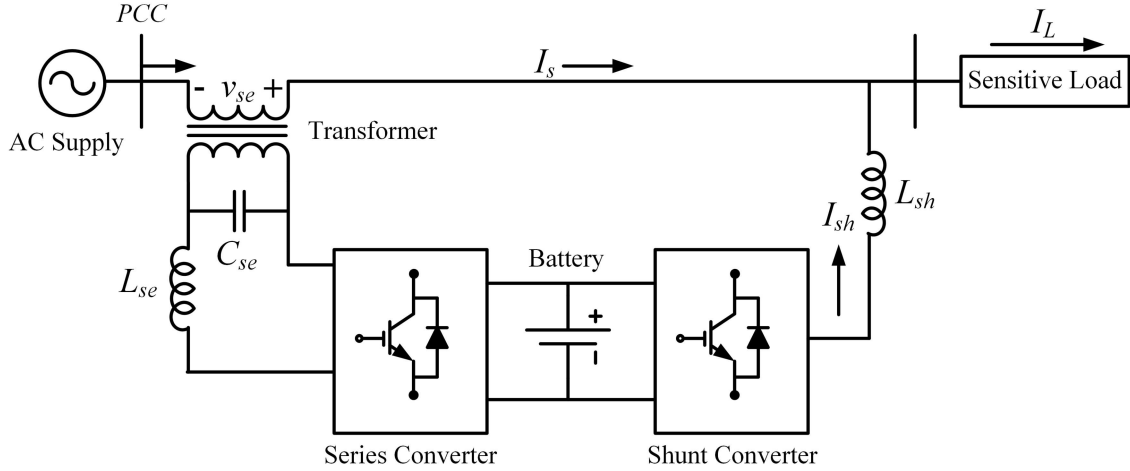


Figure 1.10: Block diagram of UPQC

in a RES dominated grid. VSG-UPQC comprises of two converters, namely series and shunt converters. DC link is shared by both converters of VSG-UPQC. Series converter is connected in series with the distribution grid through an injection transformer. The shunt converter is connected in parallel to the load. Series converter is responsible for mitigation related to voltage power quality problems such as voltage sag, voltage swell, voltage harmonics, etc. Shunt converter mitigates the current harmonics generated by the non-linear load.

The series converter is voltage controlled to inject the voltage through an injection transformer to maintain the load voltage constant. Shunt converter is also voltage-controlled and incorporates VSG control algorithm. Shunt converter supplies the load and compensates the harmonics generated by the load current. Hence, VSG-UPQC compensates both voltage- and current-related power quality problems and also provides the inertia.

## 1.7 Literature Review

This section discusses about the research going on in the area of virtual synchronous generator. Subsection 1.7.1 discusses about the literatures related to the inertia emulation using VSG.

### 1.7.1 Virtual Synchronous Generator

The low inertia of power systems has an adverse effect on conventional power system stability [32,33]. Firstly, lower inertia causes poor frequency response during the event of disturbances because, the kinetic energy wouldn't be sufficient to keep the frequency at a certain level [34,35]. Secondly, a significant drop in total inertia leads to a quick acceleration or deceleration of the system frequency, which causes to fail the safety mechanisms of the generating units [36,37]. To relieve these problems brought by inverter-based RESs, a virtual synchronous generator (VSG) is introduced in [38]. VSG is presented in [39–41] to address the instability issues brought up by the insufficiency of inertia in power electronics-driven renewable systems. Similar to the droop control in microgrids [23], VSG replicates the features of an already existing synchronous generator to make sure that the electric grid operates efficiently and safely. Numerous models of the VSG exist in the literature [42]. One of the variants is the synchronverter [43], which adopts the phase-locked loop (PLL) for synchronization.

Inverters can operate in current source (grid-following) or voltage source mode (grid-forming or VSGs). In a centralized power grid, inverters are interfaced as current source inverters to inject the current into the point of common coupling (PCC) [44–46]. However, grid-forming inverters or VSGs are preferable nowadays because of the microgrid development, which needs to operate in islanded mode, as well. Grid-forming inverters have more flexibility and better performance under weak grids than grid-following. Hence, a grid-forming VSG with the improved PLL operation is presented in [47] for stable operation under transient conditions. Further, a self-synchronized VSG is presented in [48], which completely removes the PLL unit. A different approach is presented in [49] to mimic synchronous machines using voltage components called voltage-based virtual synchronous machines (VSM). A virtual flux orientation-based VSG is presented in [50] to decouple the active and reactive power. A VSM-based electric vehicle charger is presented in [41], which can supply households in the absence of a grid with the help of an electric vehicle battery. To get a better look into the design procedure of VSG parameters, such as inertia and damping, a small signal modeling of VSG is presented in [51]. All the above-mentioned VSG control methods work in voltage-controlled mode. However, a grid-forming vector current control scheme is presented in [52] to emulate the VSG characteristics in the existing current-controlled inverter systems. Nonetheless, the

mentioned VSG techniques have not addressed stability problems during transient conditions.

Voltage-source-based VSGs [53–56] have more flexibility and better performance under weak grids than current source-based VSGs. Grid-forming VSGs are useful in voltage and frequency control and work independently in a microgrid. Since a synchronous machine is a constant voltage, constant frequency source, voltage-controlled VSGs are much closer to emulating the characteristics of synchronous machines than current-controlled VSGs. Also, with voltage-controlled VSGs,  $Q-V$  and  $P-\omega$  droop characteristics can regulate active and reactive power according to the frequency and voltage variations, making them a suitable alternative to conventional generators like synchronous machines. But, the voltage-controlled VSG requires a synchronization scheme that is used only at the starting. Hence, different synchronization methods existing in the literature are discussed in the subsection 1.7.2.

### 1.7.2 Synchronization Methods for VSG

Smooth synchronization is required for the smooth operation of inverters in grid-connected mode or an autonomous microgrid. Phase-locked-loop (PLL), frequency-locked-loop (FLL), and their variants have been used to synchronize renewable sources-based inverters in autonomous microgrids or grid-connected modes. In [57], a second-order sequence filter-based FLL is implemented to synchronize the output voltages of solar and wind energy sources in an autonomous microgrid, whereas an improved PLL with a variable gain controller is used in [58]. A combination of third-order generalized integrator-based PLL and FLL is proposed in [59] for solar and battery energy storage system-based islanded microgrids. Complex coefficient filter-based-PLL and all-pass-filter-based PLL are introduced in [60,61] for synchronization of wind, solar, and battery energy storage-based distributed microgrids. All these PLL approaches in [57–61] are implemented in an autonomous microgrid. PLL implementation for grid integration of the current regulated VSG inverter is employed in [62,63]. When voltage imbalance and distortion have a negative impact on frequency estimation, PLL performance may suffer, especially under exceptional circumstances. While being incorporated into or removed from the grid, VSG synchronization is essential to the grid. It is essential for the VSG to supply the grid with the necessary power during running condition [64,65]. To ensure the proper integration of the inverter with

the grid, it has become popular [66–70] to use synchronization tools such as PLL and its equivalents [71]. This adds a synchronization loop, an extra computational burden, to the closed-loop control. Being non-linear, tedious, and difficult to change the control variables for fine tracking of angle and frequency are drawbacks of the PLL. Slow-synchronization control techniques may compromise system stability.

The synchronization control algorithm should facilitate the effortless shifting of VSG from islanding to grid-connected mode. A VSG is an inverter controlled to act like a synchronous generator. In light of this, we may synchronize the VSG with the grid using the same concepts for synchronous generators. As a result, voltage-controlled VSG is a good choice for an effortless transition between islanding and grid connection modes. Numerous PLL-less synchronization methods have been developed recently [72–77]. In [72], a self-synchronization synchronverter without an additional synchronizing mechanism is presented. This makes the entire synchronization process considerably faster and more accurate by eliminating the time-consuming portion of the controller, including PLLs. The number of proportional-integral (PI) controllers utilized in PLL-based approaches is decreased by using this technique. However, while integrating VSG into the grid, a PI regulator is still necessary in the power loop, and multiple adjustments in the control part are required. Additionally, it necessitates a solid state breaker, adding needless complexity to the VSG hardware architecture. A predictive pre-synchronization control approach is put forth in [73]. Here, synchronization is achieved by two PI regulators as opposed to a virtual inductance and resistance, which slows the VSG controller. The PLL unit in [74] is replaced by a 3-phase synchronverter incorporating endogenous synchronization traits. No supplementary controllers, such as PI controllers, are present in this built-in synchronization mechanism. New settings may disrupt the reactive power flow between the grid and the VSG during switching between the two modes. Hence, a mode identification mechanism is also required, as in [72]. An auto-synchronizing VSG controller is described in [75]. This controller uses a virtual resistance to calculate the required signals during self-synchronization and before connecting to the grid. In [76], an additional structure is employed to ensure a seamless transition between grid-connected and standalone modes at an additional cost. In [77], a phase difference acquisition method for synchronization is presented that calculates virtual power and utilizes it to get the phase difference.

All the above-mentioned schemes use PLL or many PI regulators in the control al-

gorithm for synchronization purposes. Further, some of the existing self-synchronizing methods require more numerical calculations. Also, various control modifications are required for different operating modes. Hence, the objective of the proposed synchronization method is to obtain a seamless transfer of VSG from standalone to grid-connected mode without using any extra dedicated synchronizing units or PI controllers.

The parameters of VSG discussed in Subsection 1.7.1 are constant. Active power and frequency of the VSG oscillates more in the events of large disturbance. Since, the inertia and damping are constant, they can't be changed for the different kinds of transients. Hence, there is a need to adaptively change the inertia and damping for different kind of disturbances. So, different adaptive control methods of VSG are discussed in the next subsection 1.7.3.

### 1.7.3 Adaptive control of VSG

When the generation from renewable energy sources fluctuates significantly, the output power and frequency of the VSG may oscillate. VSG techniques discussed in Section 1.7.1 have not addressed stability problems during transient conditions. A number of control methods were put forth to lower the oscillatory output of real power and VSG frequency. An enhanced power decoupling method for VSG is presented in [78] to improve its stability. An integrator is introduced into the active power control loop [79] to enhance the transient stability of VSG under grid faults. In addition, to get better dynamic behavior, an optimal control method of VSG is presented in [80], considering the limitation of frequency acceleration (slope) and deviation in VSG frequency. In essence, the output characteristics can be changed directly by modifying the variables of VSG, i.e., inertia and damping, which affect the oscillations of power and frequency [81]. A novel approach to adaptive inertia control (adaptive  $J$  control) is presented in [82] by choosing different inertia values in different states. However, this strategy does not take the effect of the damping factor into consideration. An adaptive inertia-based fuzzy synchronverter is presented in [83]. But this scheme also doesn't consider the virtual damping effect in an active power loop. The adaptive damping control of VSG for damping out the frequency oscillation is presented in [84].

Inertia and damping choices affect the reliability of VSG as well as the cost-effectiveness of energy storage configurations. The virtual inertia of VSG helps in supporting the micro-

grid frequency as well as VSG. Even though, the optimum values of inertia and damping are used, those parameters are fixed throughout the operation of the VSG. Hence, automatically adjusting inertia and damping-based VSG is presented in [85] to suppress the frequency transients. When calculating the damping and inertial power as described in [85], the computational load on the digital signal processor is increased due to the usage of online optimization (DSP).

In [86], a new auto-tuned (AT)-VSG-based frequency control approach is presented to lessen the DSP's computational load. In [87], adaptive virtual inertia, as well as virtual damping control of VSG (alternating  $J$  and  $D_P$  control), is presented, in which alternating values of inertia and damping are used in different intervals. In addition, the size of the DC storage element and the cost of the system are greatly influenced by the choice of the damping parameter and inertia. Hence, the optimized design of the parameters of VSG will have an impact on the stability and storage capacity of the renewable energy system [88]. In [89], [90], artificial neural network-based control of a virtual synchronous generator is presented. Parameters of VSG are predicted by training the neural network in [89], [90], which is a complex process. In [91], an adaptive dynamic programming method for VSG is presented to suppress the power and frequency oscillations. A robust damping control strategy for VSG is presented in [92] to suppress the oscillations in active power during disturbances, but it doesn't reflect the inertia effect.

One of the issues with the aforementioned adaptive control methods, such as adaptive inertia control, variable inertia as well as variable damping method, is that extreme values of both the VSG parameters have been chosen in different intervals, but there is no explanation for the effect on the other control loops because of the extreme values of inertia and damping. Also, there is no analysis found in the literature that considers the energy storage requirement for designing the parameters of VSG active power loop in the case of robust/adaptive control of virtual inertia and damping.

The VSG discussed above are implemented in battery storage system. VSG can also be implemented in the RESs. Hence, the literature related to the grid-connected PV system is discussed in the next subsection 1.7.4.

### 1.7.4 Photovoltaic Virtual Synchronous Generator

Solar energy is the most important renewable energy source since it is the most abundant, quietest, and most promising renewable energy source currently available. Photovoltaic (PV) sources often employ power electronic devices such as inverters in the grid [93]. As long as the penetration of these PV sources into the power grid is within acceptable limits, the stability of the power system remains unaffected. As PV sources offer almost negligible inertia, the increasing penetration of these sources may cross the limits in the future and dominate the conventional SGs of the power system; they reduce the overall inertia of the power system. Hence, PV systems fail to react to grid transient situations like traditional synchronous generators [94].

VSG is the best alternative to emulate inertia and damping characteristics in the PV inverter. In addition, the active power-frequency and reactive power-voltage droop control of VSG regulates the active and reactive power according to frequency and voltage variations. So, VSG addresses the stability problems by offering adequate virtual inertia in inverter-based PV energy sources. In addition, it lowers the maximum frequency excursion and rate of change of frequency (RoCoF). Hence, PV inverters with VSG control (PV-VSG) are a better alternative to traditional grid-following PV inverters.

Two-stage grid-tied PV system has been discussed in various literatures [95–99]. A two-stage single-phase PV-VSG with energy storage is presented in [100]. In addition, a supercapacitor-battery-based three-phase, two-stage PV-VSG is presented in [24] to modify the existing grid-following PV inverter to grid-forming PV-VSG. However, the configuration of [101] is very complex, involving two inverters and dc-dc converters, resulting in extra costs. In [102], a battery is used with two-stage PV-VSG to support the power imbalance created by the grid disturbance while maintaining the maximum power point tracking (MPPT) operation of the PV source. But this comes at the cost of a big battery size. A coordinated VSG control for a two-stage PV-VSG system with reduced battery size is presented in [103] to achieve MPPT and grid support. In addition, to boost the transient behavior in the event of grid disturbances, a robust controller is designed for the DC-DC converter of the battery in [104] for a two-stage PV-VSG.

In all the above methods, the DC link voltage is stiff owing to the battery energy storage system (BESS), but the existing VSG control technique fails in the PV system where energy storage is absent. In [105], a two-stage PV system incorporating an im-

proved VSG control without the BESS is presented. However, the DC-DC conversion part is still there, incorporating additional costs. Consequently, a single-stage PV-VSG is proposed in [106], eliminating the DC-DC conversion part. Here, the MPPT and the grid side power are controlled solely by the VSG. PLL is used for grid synchronization of PV-VSG. Hence, the performance deteriorates in the presence of non-linear loads. In addition, the transition of PV-VSG from grid-connected to islanded mode is not smooth with non-linear loads. Moreover, PV systems usually run in MPPT mode to extract the maximum power production. So, they can not absorb or release more power in the event of frequency transients due to the lack of power reserve. Hence, PV-VSG working at MPPT does not participate in frequency regulation. The concept of the power reserve for a single-stage PV-VSG is yet to be studied. Also, the conventional PV system requires a separate controller for STATCOM operation. Both these issues have been addressed in the proposed work.

VSG discussed in Section 1.7.3 comprises a single converter which can mitigate current power quality problems only. But, to mitigate the voltage power quality problems, one series converter in combination with shunt converter is required. The combination of shunt and series converter is normally termed as UPQC. The literature review regarding UPQC with active power flow is discussed in below section 1.7.5.

### **1.7.5 VSG-UPQC**

Maintaining power quality (PQ) is the fundamental requirement of distribution grid for uninterrupted supply. As the number of inverter based renewable energy sources rises, the electrical grid encounters different kinds of power quality problems [107,108]. Also, the nonlinear loads on the power system has recently increased significantly [109] as a result of increasing number of adjustable power electronic drives, inverter-based equipments, and other products. Therefore mitigation of the PQ problems [110,111] has always been a task for the utilities. This is also necessary due to the emerging trends of microgrids [112]. PQ standards demands sinusoidal and balanced load currents, and sinusoidal and balanced grid voltage. Voltage related power quality problems are sag, swell, harmonics and unbalance [113]. These problems are due to faults in the grid and very severe for the UII. PQ issues related to the currents are current unbalance, harmonics. Non-linear loads and the RESs integration in the grid are the main causes of the current harmonics [114].

There are number of mitigation devices are existing in the literature to solve the PQ problems. Basically, 3 types of configuration is used: Series converter or DVR, shunt converter or STATCOM and UPQC. Series converter DVR is used for the mitigations of voltage PQ issues [115, 116]. Likewise, shunt converter or STATCOM is employed to compensate the current PQ problems [117, 118]. However, UPQC [119, 120] is the best possible configuration that uses DVR in conjunction with the STATCOM to address issues with both voltage and current power quality [121–124].

UPQC can be adopted in different structures. In [125], a current source based UPQC has been discussed. A single-phase transformer-less UPQC is presented in [126] which comprises of two half-bridge inverters as DVR and STATCOM. This UPQC gives the same performance as the transformer based UPQC. A single-phase modular multilevel matrix converter based UPQC is presented in [127] to improve the PQ in the medium/high-voltage distribution grid. [128] presents a hybrid UPQC with an isolated bi-directional DC-DC converter at common dc-link which allows isolation as well as the bidirectional power flow between DVR and STATCOM. In [129], a ten-switch UPQC is introduced instead of conventional twelve switch UPQC. This configuration is capable of maintaining the same power quality improvement without increasing the switches VA rating. [130] presents a different configuration of UPQC with series active filter as a current source and shunt active filter as a voltage source. This configuration uses the control scheme in ABC reference frame without using any coordinate transformations.

In [131], concept of controlling complex power through series active filter named as UPQC-S is introduced. Optimal size of UPQC based on VA loading is discussed in [132] to reduce the instantaneous VA burden on UPQC. In addition, [133] presents a new control of UPQC with a non-stiff source to reduce the dc-link voltage of UPQC without compromising its compensation capability. A new mechanism is presented in [134] to reduce the dc-link voltage ripple due the instantaneous power difference between both the converters of UPQC. [135] presents a versatile UPQC which can be connected to either a 3-phase-3-wire system or 3-phase-4-wire distribution system.

All these systems discussed earlier have only a shunt and series converter connected at the dc-link without any storage systems or renewable sources. Recently, some new technologies are being added to the UPQC for multiobjective operations. The common dc-link can be utilized to interface renewable resources that offer various functioning modes

[136, 137]. Moreover, combining battery energy storage with a renewable energy source through a common dc-link is a better solution, as in [138, 139]. This configuration works seamlessly in grid-connected as well as islanded mode, but, these configurations are not capable of mitigating PQ problems. To offer power quality improvements, [140] presents the power flow and stability analysis of a multifunctional PV-DG system integrated with a UPQC that perfectly works in islanded mode also. [141–143] discusses the power quality improvement technique for the combination of energy storage and renewable systems at the dc-link of UPQC.

All the above-discussed UPQC configurations can solve only power quality-related problems like harmonic issues or load-created problems like unbalanced currents, etc., but they don't provide inertia. In addition, the conventional UPQC can't provide any inertia and frequency support. Due to this, there might be some instability issues with the increasing number of converter-based renewable sources. Traditional synchronous generators support the frequency and voltage and improve grid stability by adding inertial mass. Hence, to replicate the characteristics of synchronous generators, VSG control algorithm is used for virtual inertia implementation. So, the inertia reduction problems associated with the increase in renewable energy penetration may be minimized by mimicking the synchronous generator characteristics in the inverter [17]. Various control algorithms are suggested in the literature for portraying the functional features of a synchronous machine using voltage source converters [38–43]. The versatility of modifying advantageous aspects and excluding unwanted characteristics of the synchronous machine is one of VSG's additional benefits. For brief periods, VSG can enhance grid frequency stabilisation.

VSG comprises the shunt converter only. Hence a series inverter is added at the common dc-link to form a structure like UPQC. This modified VSG in combination with series inverter is called as VSG-UPQC. VSG-based operation of STATCOM to mimic the SG is already in the literature [144]. But, till now, there has been no study on the VSG integrated operation of UPQC. Hence, this section is focused on the modified VSG to work like a UPQC.

## 1.8 Organization of the Thesis

This thesis presents virtual synchronous generator control of grid-tied inverters for inertia emulation. There are major dependability issues with the grid as a result of the increased penetration of renewable energy sources. The idea is to mimic synchronous generator characteristics like voltage, frequency, and active and reactive power control in an inverter for effective operation in a renewable energy source-based power system. The rest of the thesis is organized as follows:

- Chapter 2 presents the mathematical modelling and block diagram of the virtual synchronous generator. The control algorithm of VSG is developed using the swing equation of a SG. VSG consists of an inverter and LCL filter. Filter design is explained in detail for the grid-connected operation. Then, the parameter design of the active and reactive power control loops of VSG is discussed in this chapter. The development of a hardware prototype of the VSG with all the components is discussed.
- Chapter 3 presents a seamless transition of VSG using a virtual synchronizing torque and voltage-based synchronization controller from standalone to grid-connected mode. The small signal stability of the proposed synchronizing controller-based VSG is also demonstrated. The proposed method requires no additional controller to identify the unwanted islanding situations because, the operating mode can be identified with the help of synchronizing torque. The proposed method does not need to shift to different control algorithms while changing between grid connection and stand-alone modes. The effectiveness of the suggested controller is established by comparing the results of the VSG incorporating the proposed controller with the existing synchronization methods.
- Chapter 4 presents a flexible virtual inertia and damping control strategy for a virtual synchronous generator (VSG) for the effective utilization of energy storage. VSG power and frequency oscillate when a sudden disturbance in the power demand occurs in the distributed generation system. This chapter focuses on minimizing the frequency oscillations as well as the power oscillations of VSG during transient conditions or disturbances. The impact of varying inertia and damping on the active

power control loop of VSG is investigated. The proposed control method is verified in the developed experimental prototype. In addition, proposed control algorithm is compared with the currently available adaptive control approaches like adaptive inertia control (adaptive J control) and alternating inertia and damping (alternating J and DP control) based VSG.

- Chapter 5 presents a seamless mode control (SMC) algorithm for a single-stage photovoltaic virtual synchronous generator (PV-VSG) system. In addition, there is no additional energy storage requirement to participate in frequency regulation under grid frequency disturbances. However, it can operate and seamlessly transfer between Daytime VSG operation and a nighttime VSG operation. It provides reactive power support during nighttime working as a STATCOM. The effectiveness of the proposed controller is verified with the developed experimental prototype of a PV-VSG under changing solar irradiance, grid frequency deviation, load change, and non-linear load. A seamless transition of the PV-VSG from grid-connected to standalone mode and STATCOM operation during nighttime is also demonstrated.
- Chapter 6 presents a multifunctional unified power quality conditioner (MUPQC) for distributed generation (DG) applications to emulate the behaviour of a synchronous generator to provide voltage and frequency support besides the power quality enhancement. The shunt converter's control algorithm imitates the characteristics of synchronous generators while compensating for local current harmonics, whereas series converter compensates for the voltage power quality problems. So, this proposed MUPQC assists in frequency regulation and also has the ability to operate seamlessly between grid-connected and standalone modes. Moreover, this proposed MUPQC eliminates the need for PLL. The proposed control strategy of the MUPQC is validated by performing a MATLAB simulation.
- Chapter 7 presents the conclusion and future scope of the work in the area of VSG control for RESs application.