Three-Phase Single-Stage Photovoltaic System With Synchronverter Control: Power System Simulation Studies

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ABSTRACT The performance of a grid forming inverter integrating solar PV/Wind farms with the grid is currently a topic of wide interest. Synchronverter control is one of the well-known grid forming converter techniques. Evaluation of synchronverter control in the benchmark system will help in understanding its operation when connected to a larger system. Therefore, this article investigates the performance of three phase single-stage photovoltaic (PV) system with a synchronverter control in the North American medium voltage (MV) benchmark system. The main objective is to conduct an exploratory study of the PV based synchronverter system when subjected to various disturbances. The modeling of PV array, controllers like synchronverter, dc-link voltage control, ac voltage control and their design is discussed in detail. The simulation studies for different cases are carried out by creating various disturbances like changes in solar radiation, temperature, load, faults, etc., in the benchmark system. Furthermore, under fault conditions, response with/without voltage droop mechanism in synchronverter is studied. All the offline simulations are carried out in PSCAD/EMTDC environment. Further, the real time test studies are validated on Controller-Hardware-In-Loop (CHIL) platform in Real-Time-Digital-Simulator (RTDS). From this simulation study, it is concluded that Synchronverter Control can be a viable option when used as a grid forming technique.

INDEX TERMS Distribution generators, grid-connected inverter, PV-synchronverter system, synchronverter, virtual synchronous generators (VSG).

NOMENCLATURE

LIST OF ABBREVIATIONS

PV Photovoltaic.
MV Medium voltage.
CHIL Controller-Hardware-In-Loop.
RTDS Real-Time-Digital-Simulator.
STC Standard Test Conditions.
DG Distribution generator.
DPC Direct power control.
EDPC Enhanced direct power control.
DFIG Doubly Fed Induction Generator.
WT Wind Turbine.
VOC Virtual oscillator control.
SPC Synchronous power control.
VSG Virtual Synchronous Generator.
VSC Voltage source converter.

SG Synchronous generator.
ES Energy storage.
VSI Voltage source inverter.
PCC Point of common coupling.
IGBT Insulated Gate Bipolar Transistors.
SPWM Sinusoidal Pulse Width Modulation.
MPPT Maximum power point tracking.
RoCoF Rate of change of frequency.
DSP Digital signal processor.

LIST OF SYMBOLS

\[ V \] Output voltage of PV cell [V].
\[ I \] Output current of PV cell [A].
\[ V_{pv} \] Output voltage across PV array [V].
\[ I_{pv} \] Output current of PV array [A].
\[ R_{shp} \] Equivalent shunt resistance of PV cell [Ω].
\[ R_{spv} \] Equivalent series resistance of PV cell [Ω].
\[ I_{phs} \] Photocurrent of each PV cell [A].
\[ I_{ox} \] Reverse saturation current [A].

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Distribution generators (DGs) are gaining popularity due to its technical and environmental benefits and become an alternative solution to solve the energy crisis[1]. Power electronic converters are used in DGs to interface with the grid to improve the performance of DGs and ensure power quality. The increase in penetration of DGs has challenged the grid network in terms of intermittent power generation, fault current level, etc. Large disturbance in the system is caused by voltage spikes and inrush current, which may damage power electronic devices [2]–[4]. These large disturbances pose significant challenges for the stable operation of DGs. This concern has motivated the application of power electronic converters to support the grid and allows more renewable energy to integrate with the grid.

Traditionally, the power converters are operating in a grid following mode and act as a current source with conventional current control techniques [5]. In [6], the PV-based grid-connected inverter simulation study is carried out with conventional current control technique. The study is carried on MV benchmark system, which includes a principle of operation, parameter selection, control design and fault analysis of system. Apart from the grid following converters, grid forming converters are now coming into picture. Different grid forming controller strategies are discussed in [7]–[12]. Droop control grid forming technique originates from the governor action and enables sharing the power as per VSCs rating when operating in parallel. The stability issues are arise in droop control when high droop gain is used [8]. Another grid forming approach is direct power control (DPC), in which output voltage gives the phase angle reference and that is why it is categorized in a grid forming converter [9]–[10]. The enhanced direct power control (EDPC) is proposed in [11], for Doubly Fed Induction Generator (DFIG) driven by variable speed Wind Turbine (WT) application. In this approach, the switching pattern for VSCs is produced from hysteresis control. The virtual oscillator control (VOC) is coupled oscillator-based grid forming control. The key advantage of VOC is that it synchronizes the parallel connected inverter without inter-inverter communication [8]. The swing equation-based control with virtual inertia capabilities based synchronous power control (SPC) is another grid forming control approach [12]. It has a cascaded control structure with inner current control, outer voltage control and reference for outer control is generated by the swing equation. Hence, it creates complexity in tuning of controller [12]. ‘Virtual Synchronous Generator’ (VSG) is one of the techniques used in grid forming converters that emulates inertia [13]–[16]. The idea is to make a voltage source converter (VSC) work like a synchronous generator (SG). Synchronverter is one of the various models of VSG [17] and operates the power converters in grid forming mode by implementing self-synchronize technique [18]. The mathematical equation and control part which regulates the frequency and voltage of SG are embedded in the controller so that it mimics SG and extracts several advantages of it. The core advantage of the synchronverter is that it provides inertia for frequency regulation. For the realization of inertia support, VSG control applied to VSC requires energy storage (ES) such as dc-link capacitor, supercapacitor and batteries [19]. There are several studies present in the literature that discusses various aspects of synchronverters like stability analysis and dynamic performance, active and reactive power loop decoupling, small-signal modeling, modified synchronverter, etc. [20]–[23]. One of the major challenges in system is coping with various types of faults, which damages the power electronics devices. Fault analysis study of the synchronverter is done in [24]. It does asymmetric fault analysis using the instantaneous symmetric component method. It can be noted that in the literature, fault analysis of synchronverter based system always considers source as an ideal dc source. To the best of the authors knowledge, fault analysis with PV source is yet to be carried out.

\[ I_{sc}(STC) \] Panel short circuit current at STC [A].
\[ V_{oc}(STC) \] Open circuit voltage of a PV panel at STC [V].
\[ n_p \] Number of cells in series per panel.
\[ N_p \] Number of cells in parallel per panel.
\[ N_p \] Number of panels in series.
\[ T_e \] Standard temperature at STC [°K].
\[ T \] Operating temperature of the PV panel [°K].
\[ K_i \] Temperature coefficient of PV short circuit current [%/°C].
\[ K_i \] Temperature coefficient of PV open circuit voltage [%/°C].
\[ G_{nom} \] Nominal solar radiation at STC [W/m²].
\[ G \] Solar radiation at STC [W/m²].
\[ q \] Charge of electron $1.602 \times 10^{-19}$ [C].
\[ k \] Boltzmann’s constant $1.38064 \times 10^{-23}$ [J/K].
\[ G \] Ideality factor.
\[ V_{dc} \] Dc-link voltage [V].
\[ I_{dc} \] Dc input current to the VSC [A].
\[ C_{dc} \] Dc-link capacitance [μF].
\[ n \] Modulation index.
\[ m_d \] d-axis modulation index.
\[ m_q \] q-axis modulation index.
\[ i_{sd} \] d-axis output current of VSC [A].
\[ i_{sq} \] q-axis output current of VSC [A].
\[ L_f \] Inductance of filter [mH].
\[ R_f \] Internal resistance of $L_f$ [Ω].
\[ C_f \] Filter capacitor [μF].
\[ R_d \] Damping resistance in series with $C_f$ [Ω].
\[ L_t \] Leakage inductance of the interface transformer [mH].
\[ P_{pv} \] Output power of PV array [W].
\[ P_s \] Output power of the inverter [W].
\[ P_{dc} \] Power stored in a dc-link capacitor [W].
\[ V_{pcc} \] Voltage amplitude of PCC voltage [V].

**I. INTRODUCTION**

Distribution generators (DGs) are gaining popularity due to its technical and environmental benefits and become an alternative solution to solve the energy crisis[1]. Power electronic converters are used in DGs to interface with the grid to improve the performance of DGs and ensure power quality. The increase in penetration of DGs has challenged the grid network in terms of intermittent power generation, fault current level, etc. Large disturbance in the system is caused by voltage spikes and inrush current, which may damage power electronic devices [2]–[4]. These large disturbances pose significant challenges for the stable operation of DGs. This concern has motivated the application of power electronic converters to support the grid and allows more renewable energy to integrate with the grid.

Traditionally, the power converters are operating in a grid following mode and act as a current source with conventional current control techniques [5]. In [6], the PV-based grid-connected inverter simulation study is carried out with conventional current control technique. The study is carried on MV benchmark system, which includes a principle of operation, parameter selection, control design and fault analysis of system. Apart from the grid following converters, grid forming converters are now coming into picture. Different grid forming controller strategies are discussed in [7]–[12]. Droop control grid forming technique originates from the governor action and enables sharing the power as per VSCs rating when operating in parallel. The stability issues are arise in droop control when high droop gain is used [8]. Another grid forming approach is direct power control (DPC), in which output voltage gives the phase angle reference and that is why it is categorized in a grid forming converter [9]–[10]. The enhanced direct power control (EDPC) is proposed in [11], for Doubly Fed Induction Generator (DFIG) driven by variable speed Wind Turbine (WT) application. In this approach, the switching pattern for VSCs is produced from hysteresis control. The virtual oscillator control (VOC) is coupled oscillator-based grid forming control. The key advantage of VOC is that it synchronizes the parallel connected inverter without inter-inverter communication [8]. The swing equation-based control with virtual inertia capabilities based synchronous power control (SPC) is another grid forming control approach [12]. It has a cascaded control structure with inner current control, outer voltage control and reference for outer control is generated by the swing equation. Hence, it creates complexity in tuning of controller [12]. ‘Virtual Synchronous Generator’ (VSG) is one of the techniques used in grid forming converters that emulates inertia [13]–[16]. The idea is to make a voltage source converter (VSC) work like a synchronous generator (SG). Synchronverter is one of the various models of VSG [17] and operates the power converters in grid forming mode by implementing self-synchronize technique [18]. The mathematical equation and control part which regulates the frequency and voltage of SG are embedded in the controller so that it mimics SG and extracts several advantages of it. The core advantage of the synchronverter is that it provides inertia for frequency regulation. For the realization of inertia support, VSG control applied to VSC requires energy storage (ES) such as dc-link capacitor, supercapacitor and batteries [19]. There are several studies present in the literature that discusses various aspects of synchronverters like stability analysis and dynamic performance, active and reactive power loop decoupling, small-signal modeling, modified synchronverter, etc. [20]–[23]. One of the major challenges in system is coping with various types of faults, which damages the power electronics devices. Fault analysis study of the synchronverter is done in [24]. It does asymmetric fault analysis using the instantaneous symmetric component method. It can be noted that in the literature, fault analysis of synchronverter based system always considers source as an ideal dc source. To the best of the authors knowledge, fault analysis with PV source is yet to be carried out.
Commonly, PV systems are connected to the power system at sub transmission voltage level. PV systems are anticipated to be connected to distribution networks where loads and local generators are also present. For better understanding of control, dynamic characteristics, and performance of large scale PV systems to be employed as DGs, a detailed study on benchmark system is required. A similar study is performed on 1.4 MW PV system in [6] with the conventional current control in grid following mode. On the same line, and in view of the ongoing development in grid forming converters, a similar study is required to be performed on the synchronverter, which is one of the grid forming technique. From the literature, it is apparent that such a performance investigation of synchronverter on a benchmark system considering a PV source is yet to be carried out.

This article investigates the performance of the PV synchronverter on benchmark system, which is North American Medium Voltage distribution system [25]. The contributions can be summarized as follows:

- Modeling of the power circuit, the control scheme and controller design of the grid connected PV system is presented to help in developing a synchronverter control based grid forming simulation model for study.
- Response of the system with the change in parameters like change in solar radiation, change in load, control parameter \( J \) is explored.
- Response of PV system with MPP and nonMPP mode of operation is studied when a disturbance is created in the distribution system.
- Effect of disturbance created in distribution system on voltage profile and voltage regulation is studied.
- Also, performance of the PV system for different fault conditions is investigated and the contribution of voltage droop mechanism is highlighted.
- The system under study is simulated using PSCAD/EMTDC software. It is validated through CHIL real time simulation using RTDS.

The organization of the paper is as follows. Section II describes the details of the power circuit. Section III discusses the controller in PV system. Section IV describes the controllers design. Section V discusses simulation of the system under various conditions. Section VI shows Real Time Simulation results with CHIL and RTDS. Possible future extensions of the present work are discussed in section VII. Section VIII presents the conclusion.

II. PV-SYNCHRONVERTER WITH NORTH AMERICAN MV BENCHMARK SYSTEM

Fig. 1 shows the complete system taken for study. PV source rating is taken as 1.4 MW which is achieved by a combination of series and parallel PV panels called PV array. The PV panels generate the low voltage; hence PV array is formed to build higher voltage for single-stage configuration, which is around 800 V at maximum power point (MPP) and around 1000 V at open circuit. The dc-link capacitor \( C_{dc} \) is connected parallel to the PV array to maintain the dc-link voltage \( V_{dc} \). The single-stage IGBT based voltage source inverter (VSI) is used as an interface between the PV source and distribution system. The output of VSI is interfaced with the grid at point of common coupling (PCC), using a low pass filter and interface transformer. The high-frequency harmonics injected by PV system into the grid are filtered.
using LCL filter. \( L_f \) is a filter inductor in series with resistance \( R_f \). \( R_f \) represents the internal resistance of inductor \( L_f \) and resistance of IGBT switches. \( C_f \) is a filter capacitor in series with damping resistance \( R_f \). Current through inductor \( L_f \), voltage across capacitor \( C_f \) and voltage across dc-link capacitor \( C_{dc} \) and PV current \( I_{pv} \) are used as feedback signals for the controller. The VSI is connected to the benchmark system through \( \Delta /Y \) interface transformer. The leakage inductance of the interface transformer is represented as \( L_f \). The PV system is connected to the North American MV network, which is addressed by CIGRE Task Force [25]. This benchmark system is for network integration of DGs and this test system facilitates the analysis and validation of developed methods and techniques [26]. The primary HV voltage is 115 kV and then it is step down to 12.47 kV. The network lines are modeled as PI model and network loads are modeled as voltage dependent loads. On each bus, loads are connected, and some buses also have single phase subnetwork. The benchmark system has unbalance distribution of load. The PV system is connected to benchmark system at BUS 3, as shown in Fig. 1. Some of the simulation case studies are carried out by creating a disturbance in the distribution system. The tests are carried out by creating fault on bus 4 as shown in Fig. 1, or disconnecting load on bus 1, as the maximum load is connected on bus 1.

### A. PV POWER GENERATION

The low power PV cells are connected in large units to form a PV module. PV modules are connected in series and parallel to form a PV panel. The combination of series and parallel connection of PV panel constitutes a PV array. The entire PV generation is also called as a PV farm. The different equivalent circuits of PV cells have been proposed in literature [27]–[29], for example, single-diode, two-diodes and three-diodes equivalent circuits of PV cell. The single diode based PV cell circuit is widely used for power system studied because of its simplicity and accuracy [30]. The equivalent circuit of single diode PV cell is shown in Fig.2. It consists of a diode connected in parallel with current source, parallel resistance \( R_{shpv} \) representing the leakage resistance of \( pn \) junction and series resistance \( R_{spv} \) represents the internal resistance of PV cell.

In this article, a PV cell model is based on an equivalent single diode circuit, which is proposed in [30]. The required capacity of PV power system is generated by connecting PV panels in series and parallel to create complete PV panel array. The mathematical model used to describe solar PV source is as follows [30], [31].

\[
I_{pv} = a_1 G - \frac{a_2}{1 + a_3} \left( e^{a_1 V_{pv} + a_4 I_{pv}} - 1 \right) - a_3 V_{pv} \tag{1}
\]

where, \( I_{pv} \) is a PV array current and voltage across PV panel is \( V_{pv} \), which is equal to dc-link voltage \( V_{dc} \). The coefficient of PV array \( a_1, a_2, a_3, a_4 \) and \( a_5 \) are derived from equation in [31].

\[
a_1 = \frac{N_p I_{phx}}{K_1}, \quad a_2 = \frac{N_p I_{ox}}{K_1}, \quad a_3 = \frac{q}{nkTnN_s}, \quad a_4 = \frac{qR_{spv}}{nkTnN_s}, \quad a_5 = \frac{n_pN_p}{N_sN_rR_{shpv}K_1}, \quad K_1 = \frac{R_{pv}}{R_{shpv}}
\]

where, \( I_{phx} \) and \( I_{ox} \) are given in (2) and (3), as shown at the bottom of the next page, respectively. \( I_{sc(STC)} \) is the panel short circuit current at Standard Test Conditions (STC), \( V_{oc(STC)} \) is the open circuit voltage of a PV panel at STC. \( n_s \) and \( n_p \) are the number of cells in series per panel, and the number of cells in parallel per panel, respectively. \( N_s \) and \( N_p \) are the number of panels in series and the number of panel series strings in parallel, respectively. \( T_s \) is the standard temperature at STC and \( T \) is the operating temperature of the PV panel, \( R_{shpv} \) and \( R_{spv} \) are the equivalent shunt resistance and series resistance of each cell, \( K_f \) is temperature coefficient of PV short circuit current, \( K_V \) is temperature coefficient of PV open circuit voltage, \( G_{nom} \) is the solar radiation at STC, \( q \) is charge of electron and \( k \) is the Boltzmann’s constant.

The PV curve of simulated PV model is shown in Fig. 3. The PV curve is simulated when maximum solar irradiance is available i.e., \( G = 1 \text{ kW/m}^2 \) and for \( G = 0.8 \text{ kW/m}^2 \). It is observed that the peak power is generated at 0.8 kV.

### B. UTILITY INTERFACE

The PV power is injected into the grid by using dc-ac converter. The two-level inverter has two valves in each leg...
and hence it consists of 6 Insulated Gate Bipolar Transistors (IGBT). The switching strategy used is Sinusoidal Pulse Width Modulation (SPWM). The relation between dc voltage and VSC output AC phase voltage magnitude of the fundamental component is given in (4).

\[
V_s = \frac{V_{dc}}{2} m
\]  

(4)

where, \(V_s\) is AC output voltage of VSC in space phasor domain, \(m\) is a modulation index in space phasor domain and \(V_{dc}\) is the PCC voltage and current. To overcome this issue, the filter voltage and current are directly fed to the grid, it will distort voltage and current but also disturb the equipment’s. If same from 2 kHz to 15 kHz. These harmonics not only disturb the switching frequency [32]. VSI frequency is generally chosen as a function of the model [33].

The inertia of a synchronous generator is observed and clearly identified from equation (7) and (8). The \(\omega\) and \(J\) plays a similar role as \(V_{dc}\) and \(C_{dc}\) respectively. The detailed derivation for calculating equivalent inertia coefficient of the converter is given in [33].

In the power system, inertia is provided by kinetic energy stored in a rotor of synchronous generator. The inertia coefficient of a synchronous generator is given as:

\[
H = \frac{J\omega^2}{2VA_{rated}}
\]  

(7)

In the synchronous machine-based controller, the inertia is emulated by energy storage. In this paper, the inertia is provided by dc-link capacitor [33]. The inertia provided by dc-link capacitor is expressed as:

\[
H = \frac{C_{dc}V_{dc}^2}{2VA_{rated}}
\]  

(8)

The close mapping between inertia coefficient equations of generator and dc-link capacitor is observed and clearly identified from equation (7) and (8). The \(\omega\) and \(J\) plays a similar role as \(V_{dc}\) and \(C_{dc}\) respectively. The detailed derivation for calculating equivalent inertia coefficient of the converter is given in [33].

The VSI is used for converting DC solar power to AC, which causes harmonics in output voltage and current due to switching frequency [32]. VSI frequency is generally chosen from 2 kHz to 15 kHz. These harmonics not only disturb the voltage and current but also disturb the equipment’s. If same voltage and current are directly fed to the grid, it will distort the PCC voltage and current. To overcome this issue, the filter circuit is connected between VSI and grid, removing harmonics and injecting a nearly fundamental wave into the grid. The filter parameters are determined as a tradeoff between the harmonics injection and operation range of the controller. The most common filters for grid-connected application of the VSI are LC and LCL filters [34]. LC filter is a second order filter, whereas LCL filter is a third order filter. In comparison with LC filter, LCL filter has better performance in removing the harmonics. However, due to more poles and zeroes, the LCL filter makes the control plant more complicated [35]. To mitigate the resonance problem of LC and LCL filters, a resistor is connected in series with a filter capacitor [36].

Fig.1. shows the LCL filter for grid-connected VSI. In the modeling \(R_f\) represents the sum of IGBT on-state resistance and internal resistance of filter inductors \(L_f\). The coupling transformer is modeled as an ideal transformer in series with leakage inductance \(L_s\).

The filter parameters are determined based on several factors such as the harmonics of output current, the resonance frequency of LCL filter, voltage drop of filter inductance and reactive power compensation provided by the filter capacitor. Generally, to limit the VSI current ripple, the reactance of the filter inductor is selected between 0.1 to 0.25 pu [6]. The typical value of the current ripple is 10%-20% of the inverter current peak [37]. The voltage drop across the filter inductor can limit the voltage control by the VSI. Therefore, the voltage drop across the filter inductor should not exceed 0.3 pu. Otherwise, a higher dc-link voltage is needed to produce a specific AC voltage. Also, the amount of reactive power generated by the filter capacitor influences the reactive power compensation by the VSI. Hence, the filter capacitor value is designed to limit the reactive power exchange below 0.05 pu of the inverter power rate [37]. To avoid resonance between filter capacitor and inductor, a damping resistor is added to filter capacitor in series [36].

The values of filter inductance \(L_f\) and filter capacitance \(C_f\) are designed based on the following criteria:

1) The total harmonic distortion (THD) of voltage and current injected into the distribution network should be less than 5% [38].

2) In order to improve the ability of current for tracking and the speed of system response, \(L_f\) should be small, but a better filter effect is achieved if \(L_f\) is large. Hence a suitable value of \(L_f\) should be chosen considering these factors. The value of inductance is chosen such that the ripple of the output current is not more than
10% to 20% [37]. The following equation governs this:

\[
V_{dc} = 4\sqrt{3}v_{ripple}f_{sw} < L_f \leq \sqrt{\frac{V_{dc}}{\omega I_m}} - \frac{V_m}{2} (9)
\]

where, \(V_m\) is peak phase voltage, \(I_m\) is peak current, \(f_{sw}\) is switching frequency and \(v_{ripple}\) is a current ripple.

3) To avoid the lower power factor; generally, the reactive power absorbed from the capacitor filter \(C_f\) should be less than 5% of the nominal power of the system [37].

\[
C_f \leq L_f \leq \frac{0.05Q_n}{3\omega V^2} (10)
\]

where, \(Q_n\) in rated reactive power of inverter and \(V_m\) is a peak value of phase voltage.

4) The resonant frequency of the LCL filter should be in the range between 10 times the line frequency and one half the switching frequency of VSC [37].

\[
10f_o \geq f_{res} \geq 0.5f_{sw} (11)
\]

where, \(f_o\) is a system frequency and \(f_{res}\) is resonance frequency. The resonance frequency can be obtained as:

\[
f_{res} = \frac{1}{2\pi} L_f + \frac{1}{L_f L_r C_f} (12)
\]

A proper resistance \(R_d\) should be added in series with filter capacitor, such that there is sufficient damping of the resonant peak at the resonant frequency.

A coupling transformer brings the VSI output ac voltage to the PCC voltage level. Generally, it is a step-up transformer. The low voltage winding is \(Δ\) connected to avoid voltage disturbance due to the triple-n harmonics and high voltage winding is grounded star connected.

### III. CONTROLLERS FOR PV SYSTEM

The overall control scheme consists of four different controllers like 1) synchronverter control, 2) dc-link voltage control, 3) ac voltage control, and 4) maximum power point tracking (MPPT). The controller schemes are discussed in the following subsection.

#### A. SYNCHRONVERTER CONTROL

Synchronverter emulates the characteristics of a synchronous generator (SG) and hence its response to disturbance is same as SG [17]. It mimics its mathematical equation to control active and reactive power by providing virtual inertia. Fig. 4 shows the synchronverter controller block diagram, which can be broadly divided into two parts, namely 1) Active power loop and 2) Reactive power loop.

1) **ACTIVE POWER LOOP**

When the disturbance occurs, synchronverter maintains the stability of system by controlling angular frequency of reference voltage by providing virtual inertia. The active power loop regulates the angular frequency \(\omega_s\) and power angle \(δ_s\) and this is done by emulating the swing equation given in (13).

\[
\frac{d\omega_s}{dt} = \frac{1}{J} (T_m - T_e + D_p(ω_r - ω_s)) (13)
\]

\[
\frac{dδ_s}{dt} = ω_s (14)
\]

where \(J\) is inertia constant. \(T_m\) and \(T_e\) are mechanical and electrical torque, respectively; \(D_p\) is a damping coefficient. \(ω_s\) is a virtual speed of a synchronverter. \(ω_r\) is a reference value for \(ω_s\). \(T_e\) is a filtered output of \(T_e\). The mechanical torque is computed as \(T_m = P_{sref}/ω_r\) where \(P_{sref}\) is the reference active power. The electrical torque is then evaluated as:

\[
T_e = 1.5\psi_{ff}i_{sd} (15)
\]

The \(ψ_{ff}\) is the filtered output of excitation flux \(ψ_f\), which is obtained from the synchronverter reactive power loop.

For controller design purposes, the small-signal model of the active power loop is shown in Fig. 5. \(ΔP_s/Δδ_s\) is the small-signal change in active power to change in angle and expression for \(ΔP_s/Δδ_s\) is given in the appendix. From Fig. 5, the transfer function \(G_p(s)\) is given as:

\[
G_p(s) = \frac{ΔP_s}{ΔP_{sref}} = \frac{(τs + 1)(ΔP_s/Δδ_s)}{ω_r(2s^2 + D_p)(τs + 1) + (ΔP_s/Δδ_s)} (16)
\]

\[
\frac{d\omega_s}{dt} = \frac{1}{J} (T_m - \frac{1}{τs+1} + D_p(ω_r - \frac{1}{τs+1})) (13)
\]

\[
\frac{dδ_s}{dt} = ω_s (14)
\]
This transfer function is also required in the dc-link voltage control design, as discussed further in the paper.

2) REACTIVE POWER LOOP

The reactive power loop regulates reactive power \( Q \) by emulating the equation given in (17).

\[
d\psi_f = \frac{Q_{sref} - Q_s + D_q(V_{ref} - V_m)}{K_m} \tag{17}
\]

where, \( Q_{sref} \) is a reactive power signal, \( Q_s \) is the passed through a low pass filter. The reactive power \( Q_s \) is obtained from equation (18) as given below.

\[
Q_s = -1.5\omega_s \psi_f i_{sq} \tag{18}
\]

The reactive power loop regulates reactive power \( Q_s \) by controlling excitation flux \( \psi_f \). The speed of response of this loop is controlled by parameter \( K \) and \( D_q \) is a drooping coefficient for voltage droop. \( V_m \) is a peak value of voltage across the shunt branch of filter and \( V_{ref} \) and \( Q_{sref} \) are reference values of \( V_m \) and \( Q_s \).

The inner voltage generated by the synchronverter is expressed as:

\[
e_s = \omega_s \psi_f \tag{19}
\]

This inner voltage \( e_s \) along with angle \( \delta_s \), is treated as a reference for generating appropriate PWM pulses for VSC.

The controller diagram in Fig. 4 shows that, the reactive power loop is essential in AC voltage control. Hence, further details are discussed in the subsection ac voltage control.

B. DC-LINK VOLTAGE CONTROL

The dc-link voltage controller regulates the dc-link voltage to reference voltage \( V_{dcr} \) which is determined based on MPP or non-MPP mode of operation. It also protects the dc-link capacitor and VSC switches from overvoltage stress. Fig. 6 gives the block diagram of dc-link voltage controller. The dc-link voltage error passes through a compensator \( K_c(s) \). The feedforward compensator is used to mitigate the dependencies of \( P_{pv} \) on \( V_{dc} \), as the \( P_{pv} \) is a nonlinear function of \( V_{dc} \). This generates a reference \( P_{sref} \), which serves as an input to the synchronverter controller.

The dc-link voltage controller ensures that \( V_{dc} \) is maintained at \( V_{dcr} \) so that the corresponding active power gets delivered from the PV system to the grid. The following power balance equation governs this relation:

\[
\frac{1}{2} \frac{dV_{dc}^2}{dt} = P_{pv} - P_s \tag{20}
\]
Assume that the grid impedance is mainly inductive since grid voltage, hence voltage is regulated at the desired value. The controller $K_w(s)$ processes the error and generates the $Q_{sref}$ for the reactive power loop.

In this article, voltage across filter capacitor is taken as grid voltage; hence $V_c$ is regulated by ac voltage controller. Assume that the grid impedance is mainly inductive since $X_f \gg R_f$. Hence, resistance $R_f$ is ignored and the voltage amplitude $V_c$ is given as:

$$V_c = V_{pcc} + \frac{Q_s X_f}{3V_c} \quad (23)$$

where $X_f = \omega_f L_f$. $Q_s$ is the reactive output power of VSC, and $V_{pcc}$ is the voltage amplitude of PCC voltage. Linearizing the equation (23) and after ignoring the $2^{nd}$ order term to get:

$$\Delta V_c = \frac{X_f}{3(2V_c - V_{pcc})} \Delta Q_s \quad (24)$$

The PI controller $K_{wc}(s)$ is designed based on adequate phase margin and bandwidth, which is discussed in the next section. $\Delta Q_s/\Delta e_s$ is the small-signal change in reactive power to change in voltage and expression for $\Delta Q_s/\Delta e_s$ is given in the appendix.

D. MAXIMUM POWER POINT TRACKING (MPPT) SCHEME

The power generated by PV is dependent on terminal voltage $V_{dc}$. From the PV curve, it is observed that the power generated is nonlinear and the peak power from PV array is extracted at optimal voltage. The PV peak power and that optimal voltage point are affected by solar irradiance and temperature. Hence MPPT technique finds the optimal value of voltage at which maximum power from PV array is injected into the grid for each solar irradiance and temperature.

Many MPPT techniques are proposed in the literature [39], [40]. The most widely used methods are perturb and observation (P & O) and incremental conductance (IC). The IC is used in this article to achieve MPP and its algorithm is shown in Fig. 9. Algorithm is divided into two parts, first when change in the voltage $\Delta V_{pv} = 0$ and second when there is a change in voltage $\Delta V_{pv} \neq 0$.

When a change in $\Delta V_{pv}$ is 0, then $\Delta I_{pv}$ is checked. If $\Delta I_{pv}$ is 0, then it is assumed that the PV system is already operating at MPP and no change in voltage step is required. If the change in current is nonzero, then positive or negative voltage step change is applied depending upon the change in current is greater than zero or less than zero. As the voltage step is applied, it results in a change in current and this process continues until $\Delta I_{pv} = 0$. In second part, when $\Delta V_{pv}$ is not equal to 0, then equation $\Delta I_{pv}/\Delta V_{pv} > -I_{pv}/V_{pv}$ is examined. In IC, MPP can be tracked by regulating the difference between $\Delta I_{pv}/\Delta V_{pv}$ and $I_{pv}/V_{pv}$, i.e., instantaneous conductance. If the equation is satisfied, the controller assumes that there is a change in insolation or temperature and PV array is operating at MPP and no change in voltage step is required. However, if the equation is not satisfied, then the PV array is not operating at MPP and a small change in voltage is applied. This process continues until MPP operating condition is reached.

IV. CONTROLLER DESIGN

This section discusses the design of various controllers used in this system. As described above, the PV system rating is chosen as 1.4 MW. Further, the switching frequency of VSC is chosen as 6 kHz. The controllers are tuned using a SISO tool in MATLAB/SIMULINK. The design of synchronverter controller, dc-link voltage control and ac voltage control is discussed in the following subsection.

A. SYNCHRONVERTER CONTROL

1) ACTIVE POWER LOOP

In conventional power generation, loads are shared proportional to SGs ratings, and the real power injected to the grid varies according to grid frequency. This control loop is called as ‘frequency droop’ [8]. A prime mover maintains the rotor speed of the synchronous generator. The same mechanism is used in a synchronverter. The frequency droop mechanism is implemented by comparing $\omega_s$ and $\omega_{ref}$ and adding a difference in $T_m$ after multiplying by gain. From equation (13), it is observed that this gain is damping factor $D_p$. Hence, $D_p$ represents as damping factor as well as frequency droop coefficient. A typical value of frequency droop is based on the change in 100% increase in real power for change in
frequency between 0.2% to 0.5%.
\[
D_p = \frac{\Delta T_m}{\Delta \omega_s} \tag{25}
\]

In this article, \(\Delta \omega_s\) is considered to be 0.5% of \(\omega_r\).

The active power \(T_m\) is obtained from \(P_{sref}\) by dividing it by \(\omega_r\). The frequency droop in synchronverter shares the load variation with another inverter and SG in the grid. A time constant of the frequency droop loop is:
\[
\tau_f = \frac{J}{D_p} \tag{26}
\]

The value of \(\tau_f\) is selected based on the amount of inertia provided by the synchronverter. Because large the \(\tau_f\) leads to larger \(J\) and more energy storage is required to provide more inertia. Here, \(\tau_f\) is chosen as 0.01s.

If a grid angle is considered a reference, then the real power provided by the synchronverter is proportional to \(\delta\). As a result, electromagnetic torque \(T_e\) is proportional to \(\delta\). Suppose the grid frequency decreases, the power angle \(\delta\) and \(T_e\) increases. Hence the input to integral block with gain 1/\(J\) decreases. This results in a decrease in \(\omega_s\). This process continues till \(\omega_s\) is equal to grid frequency and vice-versa when grid frequency increases.

2) REACTIVE POWER LOOP

Reactive power loop regulates the reactive power. A voltage droop controller is also a part of the reactive power loop, which ensures a sharing of the reactive power as per the rating of inverter. \(D_q\) is a voltage droop coefficient. In this article, value of the voltage droop is based on the change in 100% increase in reactive power for change in 10% of voltage. The voltage droop coefficient of voltage droop is calculated as:
\[
D_q = \frac{\Delta Q_{\text{max}}}{\Delta V_s} \tag{27}
\]

The voltage error is multiplied by \(D_q\) and then it is added to the error between \(Q_{sref}\) and \(Q_s\), as shown in Fig. 4. The resulting signal is given to the integrator with a gain \(1/K\) to generate \(\psi_f\). The time constant \(\tau_v\) of the voltage loop is:
\[
\tau_v = \frac{K}{\omega_r D_q} \tag{28}
\]

Time constant \(\tau_v\) is set to be 0.02 s. Then, \(K\) is calculated as:
\[
K = \frac{\omega_r D_q}{\tau_v} \tag{29}
\]

B. DC-LINK VOLTAGE CONTROL

The dc-link voltage varies because of the difference between the VSC ac terminal power \(P_c\) and \(P_{pv}\). The power supplied by the PV source is controlled by dc-link voltage. To regulate the dc-link voltage, the compensator \(K_v(s)\) processes the error \(V_{\text{dc ref}} - V_{\text{dc}}\) to generate \(P_{sref}\) for synchronverter. The structure of the \(K_v(s)\) is given below in equation (30) [32]. This compensator generates enough phase margin for a given bandwidth [22]
\[
K_v(s) = \frac{1}{s} \frac{\beta_1}{(s + \beta_2)^2} \tag{30}
\]

where, \(\beta_1\), \(\beta_2\) and \(\beta_3\) are the parameters of controller \(K_v(s)\).

The control block diagram of dc-link voltage controller is shown in Fig. 7. The dc-link voltage open loop transfer function will be \(l(s) = K_v(s)G_p(s)G_e(s)\), for which \(K_v(s)\) is designed for desired gain margin and phase margin. The open loop transfer function of dc-link controller is as follows:
\[
H_{dc}(s) = K_v(s) \frac{\Delta V_{dc}}{\Delta P_s} = -\frac{2\omega_0}{C_{dc} V_{dc}^2} \frac{1}{s} + 1 \frac{\Delta P_s}{\Delta P_{sref}} \tag{31}
\]

The \(K_v(s)\) is multiplied by -1 to compensate the negative sign of \(G_v(s)\). The controller is designed for the worst case by considering negative \(P_{pv}\). To regulate \(V_{dc}\), \(K_v(s)\) is designed with 50° phase margin at 35 rad/s bandwidth. \(K_v(s)\) consists of an integrator to achieve zero steady state error. Further, the gain is added in \(K_v(s)\) to achieve gain cross over frequency at 35 rad/sec. A lead compensator is added in \(K_v(s)\) to stabilize the uncompensated loop with 50° phase margin at 35 rad/s bandwidth. The bode plot with the compensated loop is shown in Fig. 10.

C. AC VOLTAGE CONTROL

The control block diagram of ac voltage control is shown in Fig. 8. The open loop transfer function of the ac voltage controller is as follows:
\[
H_{ac}(s) = \frac{K_{ac}(s)\omega_0(\Delta Q_s/\Delta e_s)}{K_s(\tau s + 1)(\tau s + 1) + \omega_0(\Delta Q_s/\Delta e_s)} \frac{\Delta V_c}{\Delta Q_s} \tag{32}
\]

where,
\[
K_{ac}(s) = \frac{k_{pvc}s + k_{ive}}{s} \tag{33}
\]

The PI controller \(K_{ac}(s)\) is used to regulate the voltage \(V_c\). \(k_{pvc}\) and \(k_{ive}\) are proportional gain and integral gain of the PI controller, respectively.

The compensated bode plot of the ac voltage controller is shown in Fig. 11. It is noted that the ac voltage control loop includes an inner loop, which is a reactive power loop. Therefore, the dynamics of the outer loop are slower than the inner loop. Hence, the controller is designed for a phase margin of 85° and cross over frequency of 10 rad/s.
V. SIMULATION RESULTS

This section presents the response of a synchronverter based 1.4 MW PV system connected to the North American MV network. The MPP voltage of the PV array is 800V. The PV junction temperature of PV system is considered to be 25°C.

The PV system parameters and controllers are given in Table 1. The North American MV benchmark network parameters are given in [25].

A. CASE I: PV SYSTEM RESPONSE WITHOUT MPPT

This case study shows the PV system response to the stepwise change in solar irradiation \(G\) and dc-link voltage setpoint \(V_{dcr}\) when the MPPT scheme is disabled. Fig. 12 shows the PV system response.

Initially, when the PV system starts, \(V_{dc}\) is regulated to 900V, and \(G\) is taken as 0.6 kW/m\(^2\). At \(t = 6\) s, \(V_{dcr}\) changes from 900V to 950V, resulting in a PV system output power reduction, as shown in Fig. 12. At \(t = 9\) s, \(G\) changes to 1 kW/m\(^2\) from 0.6 kW/m\(^2\), which increases the PV system output power. The case study shows the need of MPPT technique and it is noted that PV power generation is approximately proportional to available solar irradiation.

B. CASE II: PV SYSTEM RESPONSE WITH MPPT

The IC MPPT technique is used to track maximum power for the available irradiance. The response of the system is observed for a step change in solar irradiance \(G\) and PV junction temperature \(T\).

Initially, \(G\) is at 1 kW/m\(^2\), and \(V_{dc}\) is at its MPP, i.e., 800V and PV System output is 1.4 MW. At \(t = 2.5\) s, \(G\) changes.
to 0.8 kW/m², then the output power changes to 1.1 MW. The junction temperature $T$ is then changed to 0°C at 5 s and due to this, constant rise is observed in the dc-link voltage $V_{dc}$ and output power $P_s$ of the inverter. After a change in $T$, $V_{dc}$ becomes 0.88 kV to track the maximum power of 1.22 MW related to that temperature. It is observed that the temperature change has a significant impact on PV system operating points, as shown in Fig. 13.

The performance of PV system for partial shading conditions is shown in Fig. 14. Initially, PV operates in MPPT mode with available rated irradiations $G = 1$ kW/m² and the entire array receives uniform irradiations. Before $t = 2.5s$, $V_{dc}$ is at rated MPP and VSI provide rated power $P_s$ to distribution system. At $t = 2.5s$, sudden change in ambient conditions occurs, which causes partial shading of the array and the insolation level of shaded module decreases. Nonuniform shading of the PV array reduces output current and voltage of the PV system. MPPT technique detects the partial shading, which leads to decrease in voltage $V_{dc}$ and output power $P_s$ of VSI as shown in Fig. 14. $V_{dc}$ settles at new MPP, i.e., 0.74 kV and $P_s$ decreases to 1.2 MW. As per PV curve shown in Fig. 3, the power generated by PV panel at 0.74 kV is 1.36 MW; but because of the partial shading effect, $V_{mpp}$ and $I_{mpp}$ reduce, and $P_s$ decreases to 1.2 MW. Also, it is observed that the system is stable after the partial shading disturbance.

**FIGURE 14. PV system response to partial shading condition.**

C. CASE III: INFLUENCE OF PV-SYNCHRONVERTER ON BENCHMARK SYSTEM

This test is carried out with and without PV system to check the effect of connecting a synchronverter to the benchmark system. In the benchmark system, highest load is connected to bus 1. The test is carried out by disconnecting a load on bus 1. Its effect on PCC frequency is observed on bus 3, where the PV system is connected. Initially, $G$ is set to 1 kW/m² and $Q_{ref} = 0$ VAR. Load at bus 1 is disconnected at $t = 4s$.

Fig. 15 shows the test results without PV system and with PV system. A load is disconnected at $t = 4s$. A current drawn from the grid source decreases when a load is disconnected, as shown in Fig. 15. The effect of connecting synchronverter based PV system is clearly observed from the frequency waveform at PCC. Though overall power increases in the benchmark system, due to inertia provided by the PV system, the overshoot of frequency with PV systm at bus 3 is shown in Fig. 15. is slightly less compared to overshoot in frequency without a PV system.

**FIGURE 15. System response for change in load without PV system and with PV system.**

D. CASE IV: FREQUENCY RESPONSE OF PV SYSTEM AT DIFFERENT $J$

This study investigates the response of PV system frequency $\omega_s$ for different values of $J$ when a load is disconnected from bus1. The load is disconnected at $t = 4s$. It is observed from Fig. 16 that as the inertia increases, the overshoot of frequency $\omega_s$ decreases. Also, the increase in control parameter $J$ reduces the RoCoF, as observed from Fig. 16.

**FIGURE 16. Frequency response for change in load at different value of $J$.**

E. CASE V: PV SYSTEM RESPONSE FOR MPP AND nonMPP MODE

The operation of PV system for change in $G$ with nonMPP mode is given in [22] and it is observed that the PV system provides virtual inertia in nonMPP mode. Following this, this case study will conduct a test with the distribution system. Power generated by the PV system is same for MPP and...
non-MPP modes of operation. Initially, for MPP mode $G = 0.8 \text{ kW/m}^2$ and for non-MPP mode, available irradiation is 1 kW/m$^2$ with regulated dc-link voltage to 900V. A disturbance is created by disconnecting the load at $t = 3s$.

From Fig. 17 (a), it is observed that there is no change in $P_{pv}$ when a disturbance occurs as the PV system is operating at MPP mode. For the non-MPP case, the drop in $P_{pv}$ is observed in response to disturbance, as shown in Fig. 17 (b). This results in less overshoot of frequency $\omega_s$ in case of non-MPP mode compared to MPP mode. Inertia provided by the PV system is based on the PV curve as shown in Fig. 3. As per the PV curve, at MPP, a small change in $V_{dc}$ cannot make more change in the output power of PV. However, when the PV system operates in non-MPP mode (negative slope of PV curve), the small change in $V_{dc}$ affects the PV output power. In this way, the PV system participates in virtual inertia during non-MPP mode.

F. CASE VI: PV SYSTEM RESPONSE WITH AC VOLTAGE REGULATOR

This test observes the response of a synchronverter when exchanging active as well as reactive power for change in total load. Initially, $G$ is set to 1 kW/m$^2$ and reactive power controller is activated with $Q_{sref}$ set to 0 kVAR. The ac voltage controller is activated at $t = 3s$ and the load at bus1 is disconnected at $t = 4s$.

Initially, $Q_{sref}$ is set to 0 kVAR, though some reactive power is injected into the grid; because of the filter capacitor and activated voltage droop as shown in Fig. 18. As the $V_c$ is not equal to $V_{sref}$, some value is added due to voltage droop in reactive power error and that is why reactive power is injected in the grid. At $t = 3s$, ac voltage controller is activated, as the $V_{cref}$ is set to 325.26 V, $V_c$ start tracking $V_{cref}$ and settle at 325.26 V. To increase the voltage, more reactive power is injected into the grid, which is observed from $Q_s$. The change in $V_c$ does not affect the active power output $P_s$ and $P_s$ is same in steady state. The $V_c$ keeps tracking $V_{cref}$ after a load is disconnected. As the total load decreases, less reactive power $Q_s$ is injected into the grid to regulate voltage. Also, overshoot in frequency $\omega_{pcc}$ is less than the test result shown in Fig. 15 due to inertia provided by the dc-link capacitor.
G. CASE VII: PV SYSTEM RESPONSE WITH AC VOLTAGE REGULATOR (THREE PHASE TO GROUND FAULT)

This case studies the response of PV system for symmetric fault. The fault is created at bus 4, as shown in Fig. 1. Initially, $G$ is at 1 kW/m$^2$. A MPPT scheme determines the dc-link voltage. The response of a synchronverter without considering voltage droop mechanism is shown in Fig. 19. A temporary fault is created at $t = 2.5$ s, for the duration 0.1 s. As the fault is symmetric, the magnitude of output current of VSI $i_{abc}$ increases equally and a voltage across capacitor $V_{cabc}$ drops equally. As the PCC voltage drops after fault, output power $P_s$ of VSI decreases and the dc-link voltages $V_{dc}$ increase due to power imbalance between PV and grid. Due to change in voltage $V_{cabc}$, reactive power $Q_s$ is disturbed and its response is same as $V_{cabc}$. After clearing the fault, dc-link voltage is back to its MPP value; hence, $P_s$ also regains its original value. As the fault is symmetric, $V_{cabc}$ and $i_{abc}$ are symmetric during a fault, as shown in Fig. 19. As the fault is only for 0.1 sec, the PV system is still connected to the grid. If a fault is longer than 0.16s, the PV system gets disconnected from the grid as per IEEE 1547-2003 guidelines. A permanent fault is created at 7s and after 0.16s PV system is disconnected from the grid, as shown in Fig. 19.

Fig. 20 shows the response of the system for symmetric fault considering the voltage droop mechanism in the reactive power loop. The initial conditions and operation sequence are same as in the above case. As the magnitude of $V_{cabc}$ drops after fault, due to the presence of voltage droop, to regulate voltage $V_{cabc}$ the output reactive power increases, resulting in increased $i_{abc}$ till the fault is not cleared and it is shown in Fig. 20. It is also observed that, a settling time of $Q_s$ decreases due to voltage droop. Also, a synchronverter tries to maintain the voltage and due to that, less impact on $V_{dc}$ is observed.

H. CASE VIII: PV SYSTEM RESPONSE WITH ASYMMETRIC FAULT

This case demonstrates the response of two asymmetric faults 1) single phase to ground fault 2) line to line fault. For both the cases, initially, PV is operating in MPPT mode, and the power provided by PV corresponds to $G = 0.8$ kW/m$^2$. Also, the voltage droop mechanism is active in the reactive power loop with $Q_{sref}$ set to 0.
Fig. 21 shows the response of PV system for single phase to ground fault. The permanent fault occurs at phase A on bus 4 at $t = 3$ s. Due to the voltage source nature of the PV system, the unbalance form of inverter output current $i_{abc}$ is observed, as shown in Fig. 21. Also, a drop in the inverter output voltage $V_{abc}$ is observed, and this drop is in $a$ and $b$ phase due to delta connection on the low voltage side of a transformer. Such faults result in double frequency pulsation in PV system output power $P_s$. These pulsations are also observed in dc-link voltage $V_d$, $P_s$ and $Q_s$. After 0.16s as the fault is not cleared, hence the PV system is disconnected from the grid.

Fig. 22 shows the response of PV system for line-to-line fault. The other condition for this case is same as in single phase to ground fault. Fig. 22 shows same nature of response as shown in the previous case. It is observed that during a fault, increase in current is more than single phase to a ground fault; hence, this fault is more severe than single phase to ground fault. These faults also result in double frequency pulsation in the PV system.

VI. CHIL RESULTS
This section validates the simulation results with CHIL results. The CHIL implementation test setup contains RTDS [41] and controller TMS320F28377s, as shown in Fig 23. The Real-Time Digital Simulator (RTDS) is a digital power system processing hardware architecture to model the study power system in real-time. The RTDS is utilized with real-time simulation software, RSCAD. The power part is modeled in RSCAD software. The models of inverter and other power components in RTDS are based on the Dommels algorithm [41]. A large portion of power components are simulated in a large time step of 25-50$\mu$s called mainstep. The power electronics component operate at higher frequencies.
are run in a substep environment, having time step 1-4μs. The CHIL tests are conducted considering the minimum time step. The control part is programmed in digital signal processing (DSP) based unit TMS320D28377s. The sampling time of Analog-to-digital converter of microprocessor is considered 0.1ms. System parameters used to carry out tests are same as simulation results and are given in Table 1.

The CHIL tests are carried out for MPP and nonMPP modes, as shown in Fig. 24. The initial conditions and disturbance created by a change in load are same as given in simulation of case V (Fig. 17). From the $P_{pv}$, it is observed that during nonMPP mode with ES, PV also participates in providing inertia, which is not observed in the MPP mode of operation.

The PV system response for ac voltage regulation control is validated with CHIL results, as shown in Fig. 25. The initial conditions and tripping sequence of the test are same as that of simulation of case VI (Fig. 18). Initially, the PV system is operating in reactive power mode. When ac voltage regulation mode is activated, $V_c$ starts tracking $V_{cref}$, which is 325.26 V by operating the PV system in capacitive mode. The active power injected by the PV system is less as the available solar irradiation is less; hence the remaining capacity of PV system can be used for injecting/absorbing reactive power to increase the efficiency of PV system. As the load connected at bus 1 is disconnected, the voltage drop is reduced and hence the reactive power injected to regulate the voltage is reduced.

Response of the PV system for change in $D_p$ is shown in Fig. 26. Initially $G = 8 \text{ kW/m}^2$, $Q_{sref}$ is set to 0 MVAR and disturbance is created by disconnecting the load on bus 1. As mentioned in the literature, as $D_p$ increases, the damping of the system increases. For $D_p = 5674$, systems damping is more than $D_p = 1418$, as observed from Fig. 26. The impact is also observed on $Q_s$ due to the coupling of active and reactive power loops.

The reactive power loop parameter $K$ affects the system response, and it is observed from Fig. 27. Initially, $G = 1 \text{ kW/m}^2$, and the reactive power loop is activated with $Q_{sref} = 0 \text{ MVAR}$. The disturbance is created by disconnecting load on bus 1. Increase in response of the system is observed for higher value of $K$ and its little impact is also observed on $P_s$. 

Response of the PV system for change in $K$ with reactive power control is shown in Fig. 28. Initially, $G = 8 \text{ kW/m}^2$, $Q_{sref}$ is set to 0 MVAR and disturbance is created by disconnecting the load on bus 1. As mentioned in the literature, as $K$ increases, the damping of the system increases. For $K = 76710$, systems damping is more than $K = 1352203$, as observed from Fig. 28. The impact is also observed on $Q_s$ due to the coupling of active and reactive power loops.


\[
\frac{\Delta P_S}{\Delta \delta_s} = \frac{3(-e_s^3 R f \sin(2\delta_s) + e_s V_{cd} R f \sin(\delta_s) + e_s^2 X_f \cos(2\delta_s) + e_s V_{qf} R f \sin(\delta_s))}{2(R_f^2 + X_f^2)}
\]

\[
\frac{\Delta Q_s}{\Delta e_s} = \frac{3(e_s^2 R_f^2 \sin(2\delta_s) - 2e_s V_{cd} R_f^3 \sin(\delta_s) - e_s^2 R_f^2 X_f \cos(2\delta_s) - e_s V_{qf} R_f^2 X_f \sin(\delta_s)) + e_s^2 R_f^2 X_f^2 \sin(2\delta_s) - 2e_s V_{cd} R_f^2 X_f^2 \sin(\delta_s) - e_s^2 R_f^2 \cos(2\delta_s) - e_s V_{qf} R_f X_f^2 \sin(\delta_s) + e_s V_{cd} R_f X_f^2 \cos(\delta_s))}{2(R_f^2 + X_f^2)^2}
\]

\[
\frac{\Delta Q_s}{\Delta e_s} = \frac{3(-2e_s R_f^2 X_f \cos(\delta_s^2) + 2V_{cd} R_f^2 X_f \cos(\delta_s) + 2e_s R_f^2 \cos(\delta_s) - V_f^2 X_f \cos(\delta_s) - V_{qf} R_f^2 X_f \sin(\delta_s) - V_f^2 R_f \sin(\delta_s)) + 2e_s R_f^2 \sin(\delta_s) \cos(\delta_s) - V_{cd} R_f^2 \sin(\delta_s) - V_f^2 R_f \cos(\delta_s) - 2e_s^2 X_f^2 \cos(\delta_s^2) + 2V_{cd} X_f^2 \cos(\delta_s))}{2(R_f^2 + X_f^2)^2}
\]

Response of the system for change in \( K \) is observed when the ac voltage regulation loop is activated, as shown in Fig. 28. Initially, \( G \) is set to 0.5 kW/m² and disturbance is created same as above test. As the \( K \) increases, the time constant \( \tau_v \) increases and for \( K = 1352203 \), the \( \tau_v \) is near to bandwidth of ac voltage regulation controller. Hence, the response for a lower value of \( K \) is smooth compared to a higher value of \( K \).

VII. POSSIBLE FUTURE EXTENSIONS OF THE PRESENT WORK

It is clearly evident from the literature that the grid forming control approach will be a promising solution as the share of renewable energy increases in the existing power system. Therefore, a preliminary simulation study on synchronverter controlled PV inverter connected to MV benchmark system is carried out in this paper. As discussed earlier, Synchronverter is one of the various grid forming techniques. However, there are several techniques like droop control, VSM, EDPC, VOC, SPC. Along with the development of grid forming techniques, it is important to study these techniques on different benchmark systems. A study should be carried out from the point of view of frequency regulation, amount of PV power penetration, how effectively it contributes to system strength, etc. Also, a study of control techniques from steady-state and dynamic stability perspectives will be a significant study along with the comparison of control techniques from different aspects.

VIII. CONCLUSION

This article presented the performance of a PV synchronverter with a North American MV benchmark system. The controllers like synchronverter, dc-link voltage control and ac voltage control are described in detail. The design and tuning of these controllers are presented. The results revealed that for the load change disturbance, PCC frequency overshoot is observed to be marginally lesser with the PV system as compared to the system without PV. The PV system response for grid side disturbances during MPP and non-MPP mode was studied. It is observed that the inverter frequency overshoot is slightly less in non-MPP mode compared to MPP mode. The voltage profile of distribution system is improved when the PV system is operated in ac voltage regulation mode and regulates voltage with a fast dynamic response. Furthermore, the response of synchronverter for fault analysis was studied in detail along with the voltage droop mechanism. It is observed that the overall response reaches quite faster to steady state with active voltage droop mechanism. Simulation of the nonlinear model is performed in PSCAD/EMTDC. The CHIL carried out with RTDS validates the simulation results, which are consistent with the simulation results.

APPENDIX

The detailed derivation of \( \Delta P_s/\Delta \delta_s \) and \( \Delta Q_s/\Delta e_s \) is given in [22]. Equation of \( \Delta P_s/\Delta \delta_s \) and \( \Delta Q_s/\Delta e_s \) are given in (34) and (35), as shown at the top of the page.

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