NINE SWITCH INVERTER TO RECOVER VOLTAGE DISTURBANCES OF SENSITIVE LOADS WHILE FEEDING SOLAR ENERGY TO THE GRID

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DECLARATION OF THE CANDIDATE & SUPERVISOR

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Prof. K.T.M.U. Hemapala

ABSTRACT

Electricity consumers have to mitigate voltage disturbance to ensure proper functionality of their sensitive electrical loads. Dynamic Voltage Restorer (DVR) has recognized as an effective and comprehensive power electronic based device which can be used to mitigate voltage sags and swells. Utilization factor of DVR is relatively low because voltage sag/swell is not a frequent event.

Grid connected roof top solar power plants are rapidly growing all over the world and solar DC energy storage is a common resource for electricity consumers. Utilization factor of Solar Inverter is relatively high because it functions every time when solar power is available.

Nine Switch Inverter has shown good performance when it is connected in shunt-series combination of its two inverter outputs as shunt connection has high utilization factor and series connection has low utilization factor.

This project pilots the possibility of mitigating voltage sags and swells of sensitive loads while feeding solar energy to the grid. A new system has proposed using a Nine Switch Inverter by combining a grid-connected roof top solar power plant with a dynamic voltage restorer. This system has the every feature of separate grid connected solar inverter and DVR system but it has given the same performance under reduced switch count. Proposed nine switch inverter system has simulated using Matlab Simulation software and it has successfully validated using the case studies.

ACKNOWLEDGEMENT

It is my great pleasures to express gratitude to all those who have helped me in completing my research project.

First I would like to express my sincere gratitude to my supervisor Prof. K.T.M.U. Hemapala for providing the concept and for his continuous guidance and support throughout the period.

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CHAPTER 1

1. INTRODUCTION

1.1 BACKGROUND

The voltage disturbance has become a critical problem because of the high sensitivity of the modern electrical loads. Some modern electrical equipment had been returned back to their manufacturing countries because of mal operation under voltage disturbance. Due to the incapability of the national grid to keep the voltage level with in required limits in lot of areas, consumers have to get measures to mitigate voltage disturbance. Most common voltage disturbance faced by the sensitive loads is the voltage sag and then the voltage swell. Power electronic based devices can be added to keep the relevant voltage level in the input terminals of the electrical loads. Some of them are Distribution Static Synchronous Compensator (DSTATCOM), Unified Power Quality Conditioner (UPQC) and Dynamic Voltage Restorer (DVR). Among these DVR is more effective and comprehensive.

Sri Lankan government has given attractive rates for renewable energy resources such as solar and wind power. Therefore roof top solar power plants are being installed everywhere and 100MW milestone for grid connected solar power capacity, passed in recent past. Photo voltaic solar module is a DC source and solar array is prepared by connecting solar modules in series and parallel way for receiving required voltage output and power capacity. Three phase current source inverter (CSI) is the predominant part of the solar plant which connected to the power system. But the voltage source inverter (VSI) can be used for this purpose by proper controlling of input DC voltage. Maximum power point tracking (MPPT) regulator for solar plant is utilized to catch maximum energy from the solar panels.

1.2 VOLTAGE DISTURBANCE AND EFFECTS

Voltage disturbance events can be shown as Figure 1.1 [2]. Voltage sags are the voltage events which has 0.9 pu to 0.1 pu voltage and occurs below 1 second time. Voltage swells are the voltage events which has more than 1.1 pu voltage and occurs below 1 second time. Voltage fluctuations are the voltage events which has 0.9 pu to 1.1 pu voltage and they are also badly effect for modern sensitive loads. But voltage fluctuations are also categorized as voltage sags and swells in different occasions in the electrical sector.

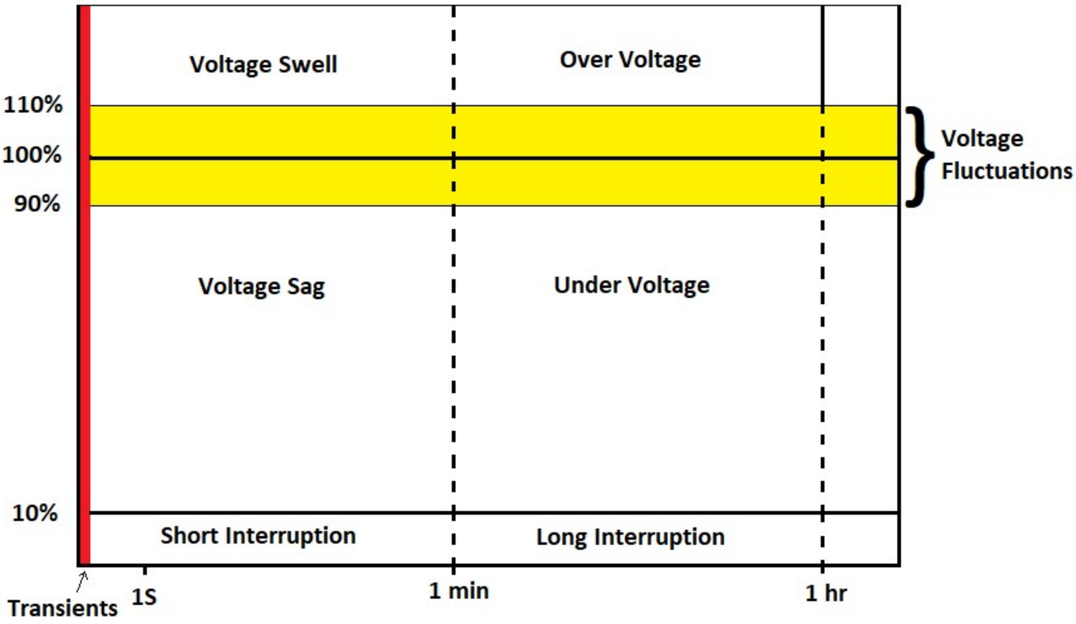


Figure 1.1: Voltage Events

Voltage sag and swell situations can be created by following reasons.

- Sudden connection or disconnection of large loads
- Faults on feeders
- Line capacitor switching

Voltage disturbance badly effect to industries and commercial sector. Some of them are as follows.

- Loss of productivity
- Idle people and equipment
- Customer Dissatisfaction

1.3 EXISTING GRID CONNECTED SOLAR PLANT AND DVR SYSTEM

As shown in Figure 1.2 there are separate systems for grid feeding of solar energy and mitigation of voltage disturbances of sensitive loads. A six switch inverter is connected to the DC bus of solar array and three phase AC output is connected to the grid via coupling inductor. DC capacitors and harmonic filters are also included in this system. The capacity of the solar inverter is designed according to the capacity of solar array. Utilization of solar inverter is limited to the time interval of day time having sunlight well.

Then a separate six switch inverter is connected to the three phase line before the sensitive load for the purpose of DVR. Normally a DC capacitor or a battery bank is connected to supply DC power to the inverter. Series transformer is used for voltage compensation and harmonic filter is also included to the system. Normally active power is fed to the grid by solar inverter and both active and reactive power are fed to the system through DVR according to the severity of voltage sag and swell. Capacity of DVR inverter is designed considering the factors such as required extent of sag/swell mitigation and voltage profile of the power system. Any way the utilization factor of DVR inverter is low because the voltage sag/swell is not a frequent event. Normally 30 % capacity from capacity of sensitive load is adequate for the DVR inverter.

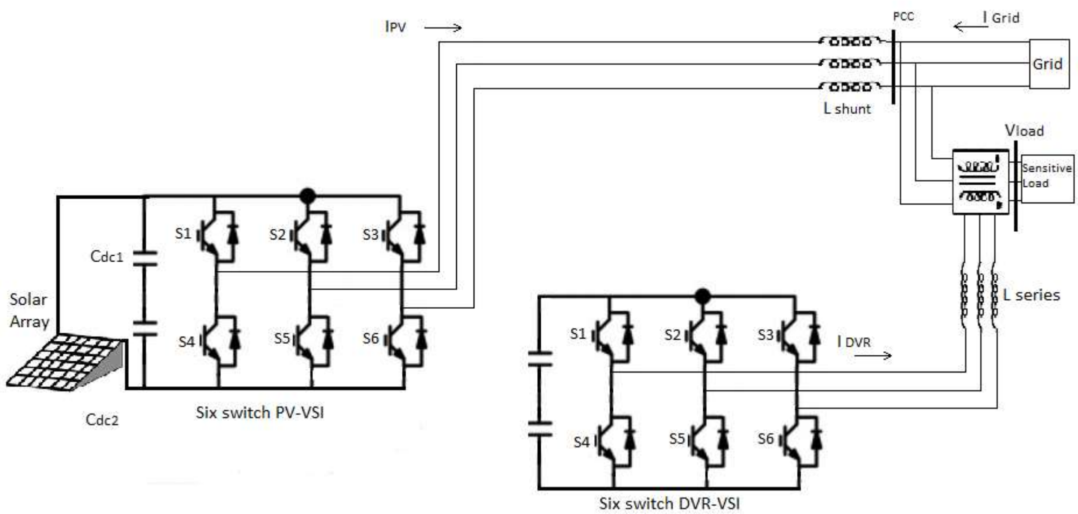


Figure 1.2: Conventional Solar Inverter and DVR Systems (Separate Systems)

CHAPTER 2

2. PROJECT OVERVIEW

2.1 SCOPE OF THE PROJECT

By adding a dynamic voltage restorer to a grid connected solar inverter, a new system model is created using nine switch inverter for doing the grid feeding of solar energy and mitigation of voltage disturbance of sensitive loads simultaneously as shown in Fig. 2.1. Then couple of distinct inverters to above both applications are not required and the switch count also has been reduced. This system can be successfully used by the consumers who have roof top grid connected solar energy plant and have sensitive electrical loads which are required the voltage without sag or swells. Energy of the solar power plant can be shared intelligently between grid connected solar inverter and the DVR, giving priority to DVR for mitigation of voltage sags and swells of sensitive load.

2.2 OBJECTIVES OF THE STUDY

Main objectives of the Research Project are as follows.

1. Find the possibility of using Nine Switch Inverter as Solar Inverter and DVR inverter with Solar Photovoltaic Panels to mitigate voltage sags and swells of sensitive loads while feeding solar electrical energy to the grid.
2. Develop a model with a controller using Matlab Simulink to verify.

2.3 METHODOLOGY

Steps of the Research Project are as follows.

- Analyze the grid feeding methods of solar energy and mitigation methods of voltage disturbance of sensitive loads
- Study the applications of nine switch inverter (NSI) and compatibility of NSI for similar projects
- Calculate the parameters for the project such like load parameters, grid parameters and voltage disturbance levels
- Design a suitable model architecture for Nine Switch Inverter
- Simulate the model and troubleshooting

- Run the simulation under different case studies and present the results with discussion

CHAPTER 3

3. NINE SWITCH INVERTER MODEL

3.1 LITERATURE SURVEY

Digi K Dileep , Bharath K R have presented in their research paper [4], the inverter topologies that are used commonly for grid connected solar power applications are either Voltage Source Inverter(VSI) and Current Source Inverter(CSI). A constant current is applied to the CSI input terminals and the DC link capacitor is small because a DC link inductor is applied to control the current ripple. In VSI a voltage source or a constant voltage is applied as the input to the inverter system and a large capacitor is required.

Fehmi Sevilmis, Hulusi Karaca have presented in their research paper [7], CSI can block reverse voltage well and it has high impedance to short circuits. Also VSI can be controlled easily and it has low conduction losses. The Sinusoidal Pulse Width Modulation (SPWM) technique is very easy to implement, it requires carrier and reference signals but it has the drawbacks like higher switching losses and low DC bus voltage utilization compared to Space Vector Pulse Width Modulation (SPWM) technique. It is required to synchronize the output voltages of the grid connected solar inverter with grid side voltage and synchronization with the grid plays a major role in grid connection of solar inverters. For this purpose, the phase angle and amplitude of the grid side voltage shall be measured accurately and quickly. Phase locked loop (PLL) method is generally used to synchronize the solar inverter with the grid and various PLL methods have been shown better response to many disturbing effects such as harmonics, unbalances, frequency variation, and sags and swells.

Trishan Esram, Jonathan W. Kimball, Philip T. Krein, Patrick L. Chapman, Pallab Midya, have presented in their research paper [8], Ripple Correlation Control(RCC) that effort to feed the solar power to the MPP by reaching gradients dP/dI or dP/dV to zero. RCC correlates the time derivative of power with the time derivative of current or voltage. It has been shown that this comes the power gradient to zero, though the obvious power gradient is not calculated. The derivatives are nonzero due to the natural ripple that occurs due to converter high switching frequency, thus the name "ripple correlation" control.

Tsutomu Kominami, Yasutaka Fujimoto, have presented in their research paper [8], a nine-switch inverter can be used to independently control two three-phase loads. SPWM has used to control both the amplitude and the frequency of two three phase loads. However, there are some ripple amplitude and a little interference between inverter 1 and inverter 2. In addition a 3N+3 switch inverter, which can independently control N three-phase loads is proposed. However, the dc-bus voltage is underutilized when the number of loads is increased.

Wei Du, Qirong Jiang, Micah J. Erickson, Robert H. Lasseter, have presented in their research paper [10] about Vdc-min regulator and MPPT regulator. The Vdc-min regulator is preventing the happening of dc voltage collapse. As revealed by solar array dc bus voltage stability analysis, the V_{dc} shall operate above the MPP voltage in steady state condition. Apart from that, the V_{dc} shall be greater than Vdc-min-reference, which is the minimum dc bus voltage required by the inverter to produce the rated ac voltage. When the output power at ac side is higher than the power from solar array, which causes the drop of V_{dc}, the controller will instantly deduct the frequency, so the power angle of solar array can be adjusted, and the extra ac power can be transferred to the other micro sources which have marginal capacities. By doing this, the power from the solar array and the power at the ac side of the inverter can be balanced again, and the V_{dc} works as Vdc-min. The MPP changes with the variation of environmental conditions. By regulating, Vdc-min, the solar array could catch maximum power. The popular perturb and observe algorithm is used as an external loop of the Vdc-min controller and it increases a small step in Vdc-min , and waits for the V_{dc} to converge to Vdc-min. Once the V_{dc} converges to Vdc-min, the MPPT measures the power from the solar array and compares it with the power measured before the changes in Vdc-min, and decides to increase or decrease the Vdc-min. The Vdc-min will finally be the MPP voltage, which is also the minimum voltage that V_{dc} shall work in steady state condition.

Lei Zhang, Poh Chiang Loh, in their research paper [1] have evaluated shortcomings experienced by previous applications of the nine-switch converter. According to that the nine-switch converter is not an attractive alternative for replacing back-to-back converter with two shunt inverters. Instead, the nine-switch converter is more suitable for replacing back-to-back converter in one shunt inverter and one series inverter systems, where one good example is the Unified Power Quality Conditioner (UPQC). UPQC consist of a shunt inverter and a series inverter where shunt inverter is linked in parallel at the common coupling point, and a series inverter is linked in series with the power line through a series transformer. The shunt inverter is generally governed to compensate for load harmonics, unbalance and reactive power flow, so that a sinusoidal fundamental current is always drawn from the utility grid, regardless of the extent of load nonlinearity. Complementing, the series inverter is controlled to block grid harmonics, voltage sags and swells so that a set of three-phase fundamental voltages always appear across the load terminals. The performance has been increased by adding a modified 120^0-discontinuous modulation scheme for reducing the overall commutation count by 33%. Harmonics, reactive power, and voltage sags are compensated promptly using proper shunt and series control showing better performance. The nine-switch inverter based UPQC was therefore proved to be effective, while yet using lesser semiconductor switches. Experimental results for confirming its better performance have already been shown through intensive laboratory testing.

Feng Gao, Lei Zhang, Ding Li, Poh Chiang Loh, Yi Tang, Houlei Gao, in their research paper, [1] have assessed physical constraints experienced by the nine-switch converter, before proposing modulation schemes for optimizing its performance. It is proposed two modulation methods named Common Frequency (CF) mode and Different Frequency (DF) mode. Also proposed 120^0 discontinuous scheme can be applied for above two modes, as proved using a simulation and experimentally.

Ankit Pandey, Rajlakshmi, have presented in their research paper [11] the study of a DVR and its application for the compensation of voltage sag for sensitive loads. This paper explains the types of DVR, LV-Level rated for 10kVA and MV-Level rated for

200kVA and their comparative applications at both these two levels. The calculation for voltage sag with consideration of fault and no-fault conditions are done with reference to application of DVR. According to that DVR has a tremendous application for voltage sag mitigation of critical loads. The paper also explains the various advantages, limitations related to the DVR along with its features. A general study of how a DVR can be such useful for mitigation of voltage disturbance of the sensitive loads has been done in this paper.

3.2 PROPOSED NINE SWITCH INVERTER SYSTEM

As shown in Figure 3.1, Nine Switch Inverter system has nine IGBTs named S1 to S9. NSI consists of three legs and each leg has three semiconductor switches. Two inverter outputs can be given from NSI. Six switches named S1-S6 represent first inverter and it is used as the solar inverter. Six switches named S4-S9 represent the second inverter and it is used as the DVR inverter. Then the three switches named S4-S6 are common for the both solar and DVR inverters. Therefore some limitations are created compared to using two separate inverters and special modulation technique is required to compatible with those limitations.

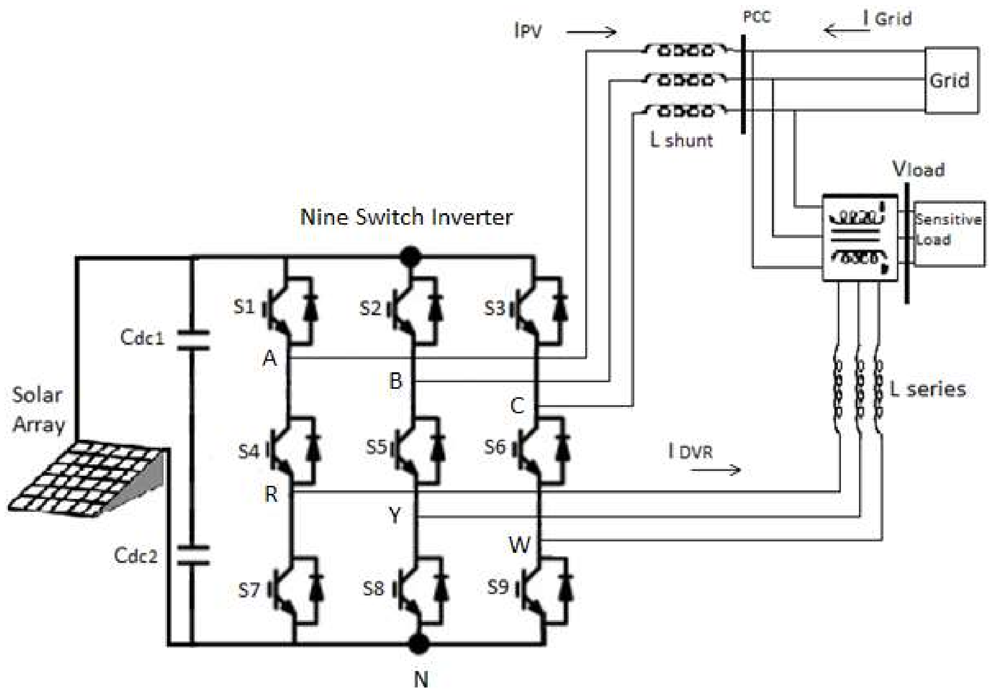


Figure 3.1: Proposed Nine Switch Inverter System

3.3 OPERATION OF THE NINE SWITCH INVERTER SYSTEM

When the power system is in healthy condition there is no voltage sag or swell at the point of common coupling. Then solar inverter feed active power to the grid using almost full DC energy produced by solar array. DVR inverter feeds lesser amount of DC energy to compensate for marginal difference between reference load voltage and healthy PCC voltage. All nine switches are in PWM operation and reference signals for nine switches are derived using different control blocks as discussed later in this Chapter.

When a voltage sag or swell create, DVR inverter consumes more DC energy to compensate the same and both active and reactive power are fed to the load through series compensation transformer. If the voltage sag or swell level is within the limitations for solar grid connection parameters of the grid, remaining DC energy is fed to the grid through solar inverter. According to the sag/swell depth, DC power is shared between the solar inverter and DVR inverter giving priority to DVR for sag/swell mitigation. All nine switches are in PWM operation and reference signals for both inverters are produced using relevant controllers as discussed later in this chapter.

3.4 SELECTION OF THE SYSTEM PARAMETERS

In this project both solar power plant and sensitive load were connected to low voltage network. System voltage (line to line) of low voltage system in Sri Lanka is 400V. Solar plant capacity was 14 kW and the sensitive load was 10kW with a power factor of 0.5 lagging. Capacity of the DVR was 10kW and capacity of series transformer was 10kW. Solar radiation level was within 400W/m^2 and 1000W/m^2 and the considered temperature was 45^{0}C.

DC voltage was selected as 768.5V (such that peak phase voltage was equal to 85% of DC voltage). Maximum power of a solar panel was 418W and solar array was arranged as 11 series connected modules per string and 3 parallel strings. All system parameters used for simulation are given under Chapter 04.

3.5 NINE SWITCH INVERTER CONTROL

For the controlling purposes direct and quadrature (dq) quantities of current and voltage were considered. The details about different controllers and modulation scheme are given bellow.

3.5.1 PV inverter controlling Method

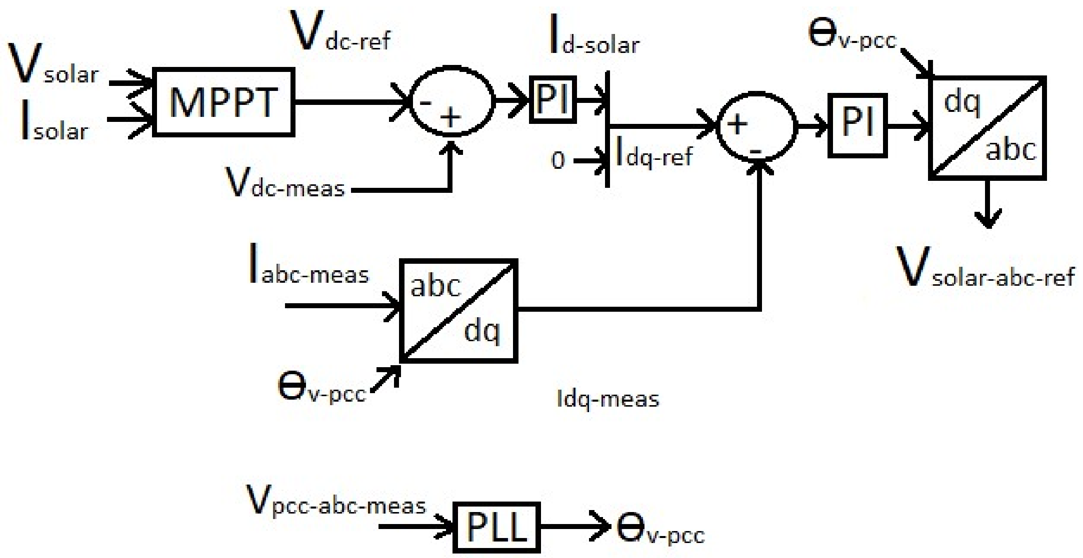


Figure 3.2: Proposed Solar Inverter Control Block Diagram

Figure 3.2 has shown the control block diagram for solar inverter. According to that, it has been used three main controllers for PV inverter controlling. They are

- Maximum power point tracking (MPPT) controller – catch the maximum solar power for grid feeding
- DC voltage regulator- determine the required active current reference for the current regulator according to the DC voltage
- Active current regulator- according to the current reference, determines the required reference voltages for the inverter

a. Maximum power point tracking (MPPT) controller

According to the Current-Voltage and Power- Voltage curves of Figure 3.3 and Figure 3.4, maximum power of the solar plant was around 12.5 kW @ 45 ^{0}C. The DC voltage was around 760 V at the maximum power. According to the Power-Voltage characteristics of solar array, if both voltage and power increasing or decreasing, dc voltage shall be increased to extract maximum power. When voltage increasing and power decreasing or voltage decreasing and power increasing, dc voltage shall be decreased. Purturb and Observe Algorithm was used for MPPT controller, terminal voltage and current of solar array were given as inputs. DC voltage reference was given as the output of the MPPT controller.

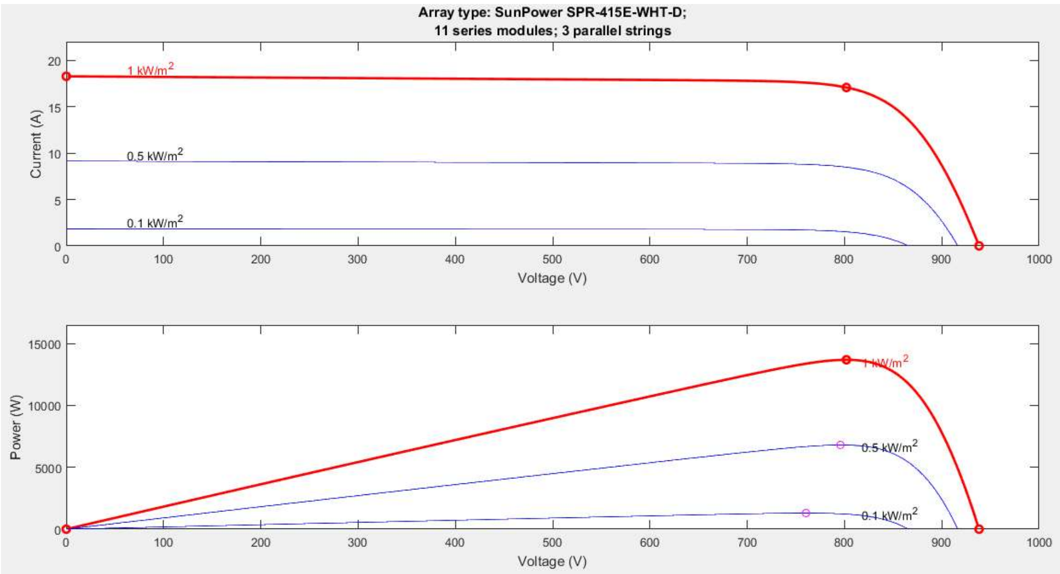


Figure 3.3: I-V and P-V Characteristics of Solar Array @ 45 ^{0}C and 100, 500, 1000 W/m^{2}

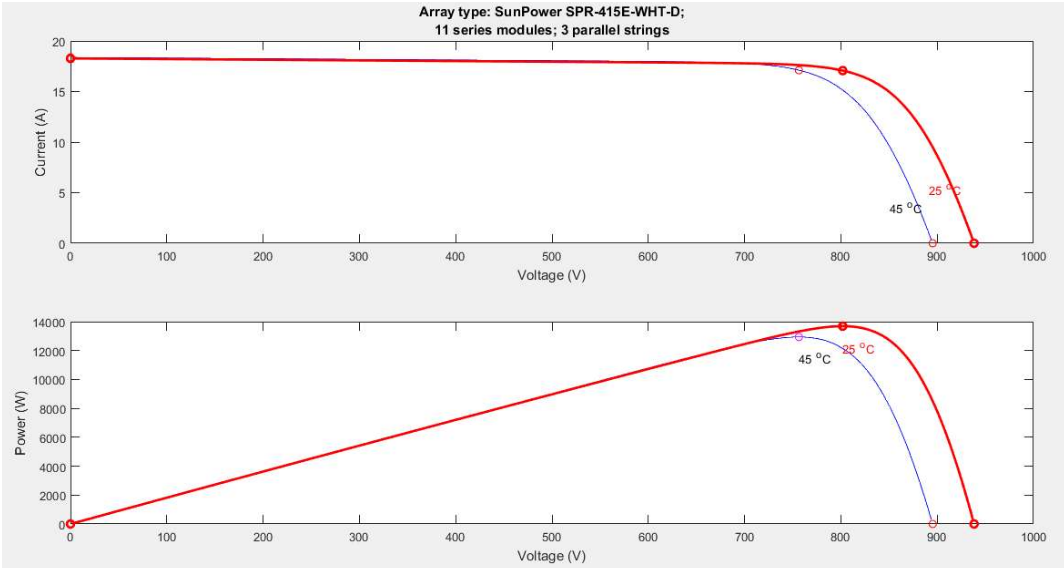


Figure 3.4: I-V and P-V Characteristics of Solar Array @ 1000 W/m2 and 25 ^{0}C- 45 ^{0}C

b. DC voltage regulator

As shown in Figure 3.2, DC voltage reference given by MPPT controller was compared with the measured DC voltage of the solar array. The error was given to a PI controller and output of the PI controller was received as the active current reference (I_d). PV array supply only active power to the system and according to IEEE 1547 reactive current reference (I_q) was kept as 0 initially.

c. Current regulator

As shown in Figure 3.2, AC current fed to the grid by solar plant at point of common coupling was converted to dq quantities in synchronous reference frame. Then active current reference (I_d) and reactive current reference (I_q) were compared with the above measured I_d and I_q values at point of common coupling. Then the error was given to a PI controller and output of PI controller was received as the reference signal of Solar Inverter.

3.5.2 DVR inverter controlling Method

In DVR controller, as shown in Figure 3.5, both required load voltage reference and measured load voltage were compared with point of common coupling voltage and the error was given to the PI controller. The output of PI controller was received as the reference signal of DVR Inverter.

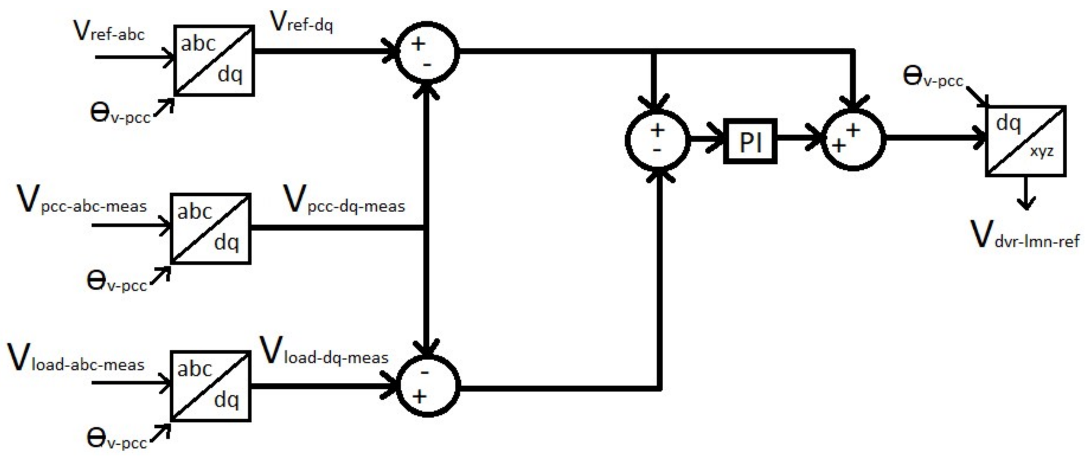


Figure 3.5: DVR Inverter Controller

3.5.3 Modulation scheme of Nine Switch Inverter

As discussed under operation of NSI, it has three shared switches between two inverters. According to Figure 3.1, the left handed leg of NSI has three switches named S1, S4 and S7. The output voltages of two inverters of this leg are as V_{AN} for solar inverter and V_{YN} for DVR inverter. Possible output voltage values of V_{AN} and V_{YN} shall be solar array DC voltage (V_{dc}) or 0. According to the switching conditions of NSI following combinations are possible as in Table 3.1. [1]

S1	S4	S7	V_{AN}	V_{RN}
ON	ON	OFF	V_{dc}	V_{dc}
ON	OFF	ON	V_{dc}	0
OFF	ON	ON	0	0

Table 3.1: Switching Status and Output Voltage per Phase

Here the combination of V_{AN}=0 and V_{RN}=V_{dc} cannot be achieved because of DC voltage short circuiting. If the V_{RN} equals to V_{dc} then V_{AN} shall be intentionally V_{dc}. To achieve this condition, voltage reference signal of solar inverter shall be always above the voltage reference signal of DVR inverter. Both references were modulated using a single carrier signal to achieve above requirement. As shown in Figure 3.6, modified discontinuous offset signal method has used to keep solar inverter reference signal above the DVR inverter reference signal.

Two modulation methods are used for NSI as Equal Frequency Modulation (EF) and Different Frequency Modulation (DF). Figure 3.6 has shown equal frequency modulation and here there are equal frequency reference signals and small phase difference between them. Figure 3.7 has shown different frequency modulation and here there are different frequency reference signals and DC voltage shall be doubled.

When there is no voltage sag/swell in the PCC, the reference voltage signal of solar inverter reaches one and feed maximum energy to the grid. DVR inverter reference signal reaches zero and it only compensate the marginal difference of reference load voltage and PCC voltage. When there is a voltage sag in PCC, the reference voltage signal of DVR inverter increases and DVR feeds active power also reactive power to the load accordingly. Then the reference signal of solar inverter reduces and feed the remaining solar energy to the grid via solar inverter. For a sag condition, when the DVR inverter reference signal increases, solar inverter reference decreases naturally and avoid the reference cross over. But for a swell condition both reference signals increase as discussed under case studies in Chapter 5.

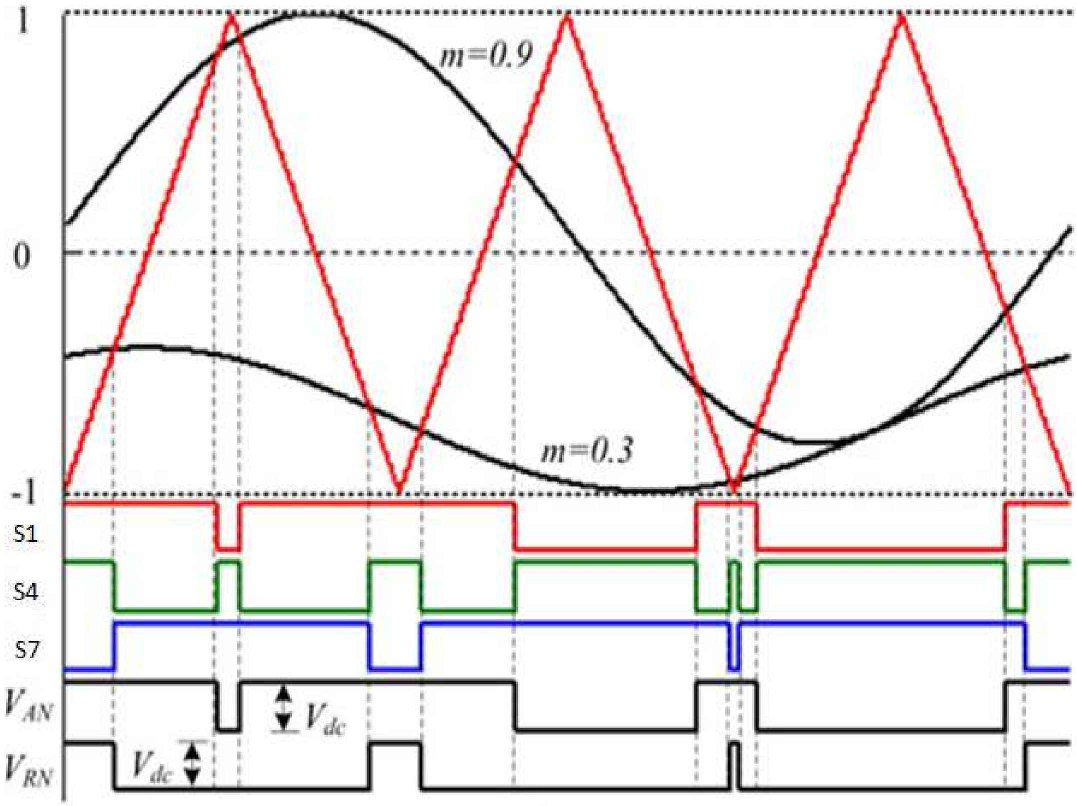


Figure 3.6: Equal Frequency Modulation of NSI [1]

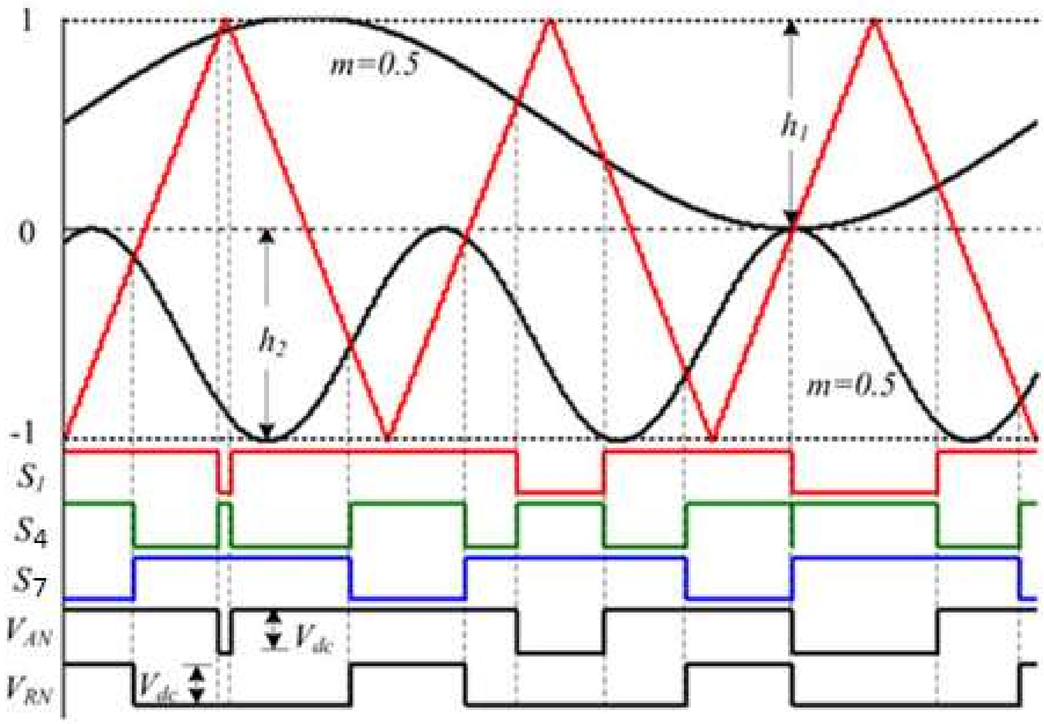


Figure 3.7: Different Frequency Modulation of NSI [1]

The procedure for generating nine gate pulses are presented below. Two sets of three phase voltage reference signals for solar inverter and DVR inverter were generated by the controllers and they can be represented as follows.

$V_{solar\text{-}a\text{-}ref} = M_{solar\text{-}ref} \cos (w_{solar\text{-}ref}t + \emptyset_{solar\text{-}ref})$

$V_{solar\text{-}b\text{-}ref} = M_{solar\text{-}ref} \cos (w_{solar\text{-}ref}t - 120^0 + \emptyset_{solar\text{-}ref})$

$V_{solar\text{-}c\text{-}ref} = M_{solar\text{-}ref} \cos (w_{solar\text{-}ref}t - 240^0 + \emptyset_{solar\text{-}ref})$

$V_{dvr\text{-}l\text{-}ref} = M_{dvr\text{-}ref} \cos (w_{dvr\text{-}ref}t + \emptyset_{dvr\text{-}ref})$

$V_{dvr\text{-}m\text{-}ref} = M_{dvr\text{-}ref} \cos (w_{dvr\text{-}ref}t - 120^0 + \emptyset_{dvr\text{-}ref})$

$V_{dvr\text{-}n\text{-}ref} = M_{dvr\text{-}ref} \cos (w_{dvr\text{-}ref}t - 240^0 + \emptyset_{dvr\text{-}ref})$

Here $V_{solar\text{-}abc\text{-}ref}$ and $V_{dvr\text{-}lmn\text{-}ref}$ were voltage reference signals for solar and DVR inverters. Then the discontinuous signals were derived as follows.

$V_{offset\text{-}solar} = 1 - [\mathrm{Max}(V_{solar\text{-}abc\text{-}ref})]$

$M_{dis\text{-}abc\text{-}ref} = V_{offset\text{-}solar} + V_{solar\text{-}abc\text{-}ref}$

$V_{offset\text{-}dvr} = -1 - [\mathrm{Min}(V_{dvr\text{-}lmn\text{-}ref})]$

$M_{dis\text{-}lmn\text{-}ref} = V_{offset\text{-}dvr} + V_{dvr\text{-}lmn\text{-}ref}$

where $M_{dis\text{-}abc\text{-}ref}$ and $M_{dis\text{-}lmn\text{-}ref}$ were the generated 120^0 signal offsets of solar inverter and DVR inverter respectively. Those signals were fed to Pulse With Modulation generators of solar and DVR inverters. As shown in Figure 3.8, nine gate signals for NSI were given by as follows.

$S_{solar1-3} = !(S_{solar4-6})' = 1$, if $M_{dis\text{-}abc\text{-}ref} > M_{carrier}$ $M_{carrier}$ = amplitude of carrier signal

$S_{solar1-3} = !(S_{solar4-6})' = 0$, if $M_{dis\text{-}abc\text{-}ref} < M_{carrier}$

$S_{dvr1-3} = !(S_{dvr4-6})' = 1$, if $M_{dis\text{-}lmn\text{-}ref} > M_{carrier}$

$S_{dvr1-3} = !(S_{dvr4-6})' = 0$, if $M_{dis\text{-}lmn\text{-}ref} < M_{carrier}$

Then the reference signal for S4, S5 and S6 switches were obtained through the OR gate operation of the reference signals of $S_{solar,\ 4\text{-}6}$ and $S_{dvr,1\text{-}3}$ as shown in Figure 3.8. Then the nine gate signals for NSI were given by as follows.

$S_{NSI,1-3} = S_{solar,1-3}$

$S_{NSI,7-9} = S_{dvr,4-6}$

$S_{NSI,4\text{-}6} = S_{solar,4-6} + S_{dvr,1-3}$

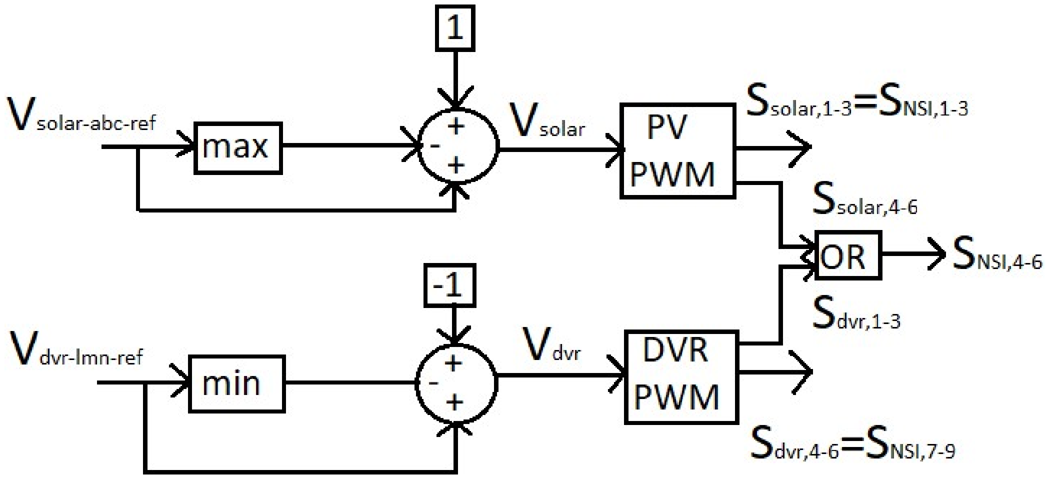


Figure 3.8: Nine Switch Inverter Modulator

4. SIMULATION OF THE NINE SWITCH INVERTER MODEL

4.1 NINE SWITCH INVERTER MODEL SIMULATION

Matlab-Simulink R2016a software package has used for the simulation and simulated model was as shown in Figure 4.1.

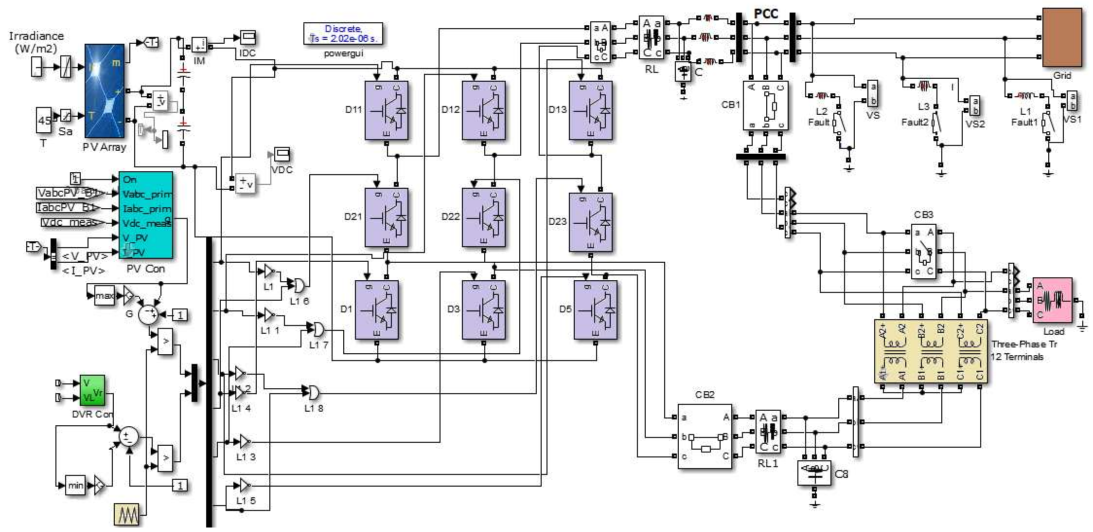


Figure 4.1: Simulated Nine Switch Inverter Model

All simulated system parameters were given in Figure 4.2.

```
% System frequency (Hz):
Fnom=50;
% Simscape Power Systems sample time (s):
Ts_Power=1/(99*Fnom)/100; Ts_Power= 2.0202e-6
% Inverter Control system sample time (s):
Ts_Control=10*Ts_Power; Ts_Control= 2.0202e-5

% ****************************************************************
%                          POWER PARAMETERS
% ****************************************************************

Pnom = 14e3;      % Inverter nominal 3-phase power (VA)
Vnom_dc = 768.5;     % Nominal DC link voltage (V)

% Nominal inverter line-to-line voltage (Vrms):
Vnom= 0.85*Vnom_dc/2/sqrt(2)*sqrt(3); Vnom= 400 V

% Inverter choke RL [Rpu Lpu] in pu
RLchoke=[0.40/100 0.40 ]; RLchoke=[0.004 0.4]
Pbase=Vnom^2/Pnom; Pbase=11.42
RL(1)=RLchoke(1)*Pbase; RL(1)=0.0457
RL(2)=RLchoke(2)*Pbase/(2*pi*Fnom); RL(2)=0.0146

% Filter C Parameters
Qc=0.05*Pnom;  Qc= 700           % Capacitive reactive power (var)
Pc=Qc/50;  Pc= 14      % Active power (W)

% DC link energy for 3/4 cycle of Pnom
Ceq= 3/4 * (Pnom/Fnom*2/Vnom_dc^2);= 7.1115e-4
Clink=Ceq*2;= 0.0014    % Cp & Cn (F)

% Nine Switch IGBT Bridge parameters

Rs=1e6;           % IGBT Snubber (Ohm)
Cs=inf;           % IGBT snubber (F)
Ron=1e-3;         % IGBT conduction resistance
Vf=0;             % IGBT Forward voltage
Vfd=0;            % Diode Forward voltage

% ****************************************************************
%                     CONTROL PARAMETERS
% ****************************************************************

% MPPT Control (Perturb & Observe Algorithm)

Increment_MPPT= 0.01;     % Increment value used to increase/decrease
Vdc_ref
Limits_MPPT= [ 883 650 ]; % Upper & Lower limit for Vdc_ref (V)
```

```
% VDC regulator (VDCreg)

Kp_VDCreg= 2;            % Proportional gain
Ki_VDCreg= 400;          % Integral gain
LimitU_VDCreg= 1.5;      % Output (Idref) Upper limit (pu)
LimitL_VDCreg= -1.5;     % Output (Idref) Lower limit (pu)
%
% Current regulator (Ireg)

RLff(1)= RLchoke(1);=0.0040 % Feedforward values
RLff(2)= RLchoke(2)+ (0.01/Pbase);= 0.4009 % Feedforward values

Kp_Ireg= 0.3;            % Proportional gain
Ki_Ireg= 20;             % Integral gain
LimitU_Ireg= 1.5;        % Output (Vdq_conv) Upper limit (pu)
LimitL_Ireg= -1.5;       % Output (Vdq_conv) Lower limit (pu)

% PWM Modulator Parameters

Fc= 99*Fnom ; % Carrier frequency (Hz)
Solar Inverter Coupling Inductance = 3 mH

% DVR Controller Parameters
Kp_DVR_Vreg = 0.3;
Ki_DVR_Vreg = 20;

% Series Transformer Parameters
Three Phase Rated Power = 10 kVA
Winding 1 Phase Voltage = 100 V
Winding 1 Resistance = 2 x 10^-7 pu
Winding 1 Reactance= 8 x 10^-7 pu
Winding 2 Phase Voltage = 100 V
Winding 2 Resistance = 2 x 10^-7 pu
Winding 2 Reactance= 8 x 10^-7 pu
Magnetizing Resistance = 200 pu
Magnetizing Reactance = 200 pu
```

Figure 4.2: System Parameters used for Simulation

4.2 SOLAR INVERTER CONTROLLER SIMULATION

4.2.1 MPPT Controller Program

Matlab-Simulink program for the MPPT controller has shown in Figure 4.3.

```
function D  = PandO(Param, Enabled, V, I)

% MPPT controller based on the Perturb & Observe algorithm.

% D output = Reference for DC link voltage (Vdc_ref)
% Enabled input = 1 to enable the MPPT controller
% V input = PV array terminal voltage (V)
% I input = PV array current (A)
%
% Param input:
Dinit = Param(1);   %Initial value for Vdc_ref
Dmax = Param(2);    %Maximum value for Vdc_ref
Dmin = Param(3);    %Minimum value for Vdc_ref
deltaD = Param(4); %Increment value used to increase/decrease Vdc_ref
%
persistent Vold Pold Dold;

dataType = 'double';

if isempty(Vold)
    Vold=0;
    Pold=0;
    Dold=Dinit;
end
P= V*I;
dV= V - Vold;
dP= P - Pold;

if dP ~= 0 & Enabled ~=0
    if dP < 0
        if dV < 0
            D = Dold + deltaD;
        else
            D = Dold - deltaD;
        end
    else
        if dV < 0
            D = Dold - deltaD;
        else
            D = Dold + deltaD;
        end
    end
else D=Dold;
end

if D >= Dmax | D<= Dmin
    D=Dold;
end

Dold=D;
Vold=V;
Pold=P;
```

Figure 4.3: MPPT Controller Matlab Simulink Program

4.2.2 DC Voltage Regulator simulation

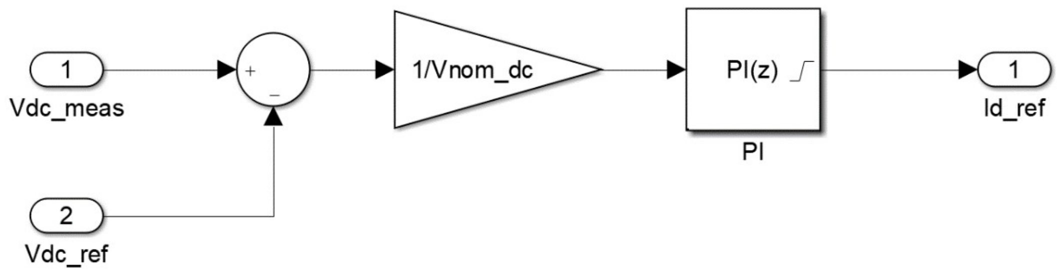


Figure 4.4: DC Voltage Regulator Simulation

As shown in Figure 4.4, DC voltage reference value coming from MPPT controller was compared with measured DC voltage value of solar array and per unit error was given to PI controller. Then the output signal of PI controller was received as active current reference (I_d). PI controller gains, K_P and Ki values were 2 and 400 respectively.

4.2.3 Current Regulator Simulation

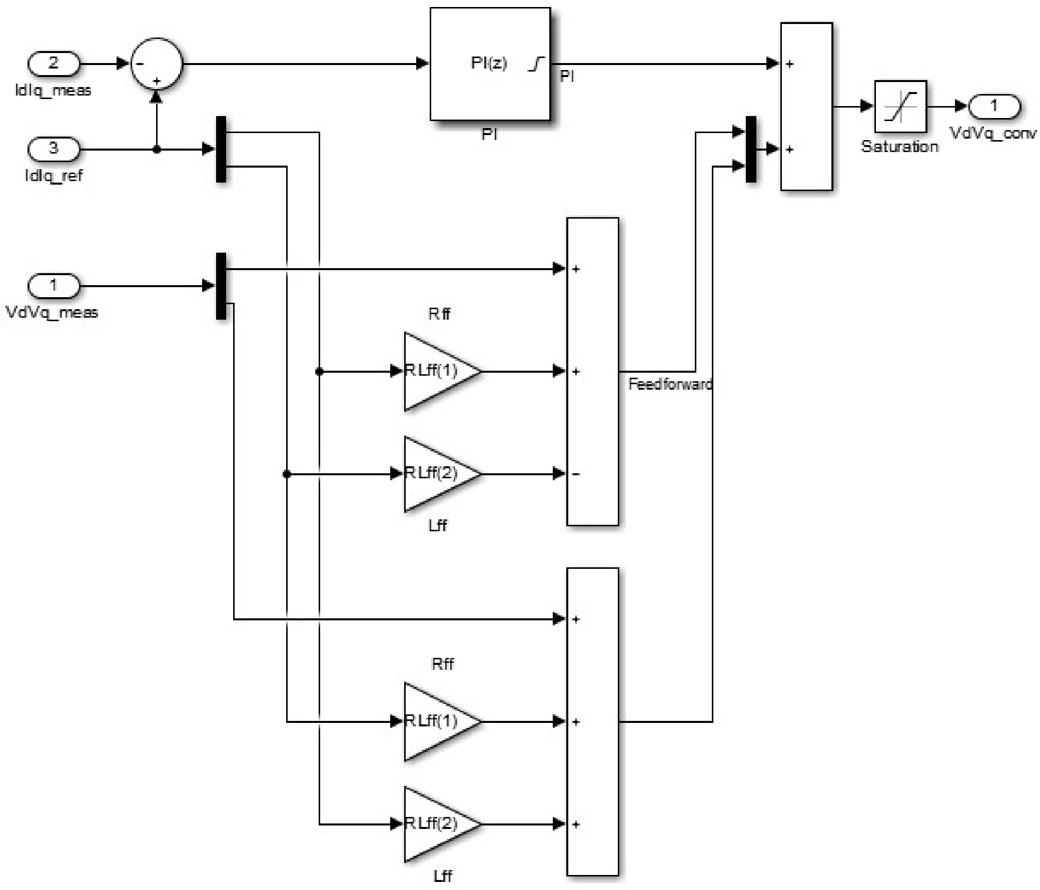


Figure 4.5: Current Regulator Simulation

Injected three phase current by the solar array was measured at point of common coupling (PCC) and it was converted in to I_d, I_q values in synchronous reference frame. As shown in Figure 4.5, these values were subtracted from the reference I_d value received from DC voltage regulator (reference I_q value was set to zero initially) and difference was given to PI controller. Output of PI controller was received as reference voltage signal for Solar Inverter. After converting these V_d, V_q values to three phase sine waves, they were given to PWM converter as V_{abc} reference. Feed forward signal was produced using measured common coupling voltage to compensate the losses created by filters. PI controller gains, K_P and Ki values were 0.3 and 20 respectively.

4.2.4 PLL and dq converter Simulation

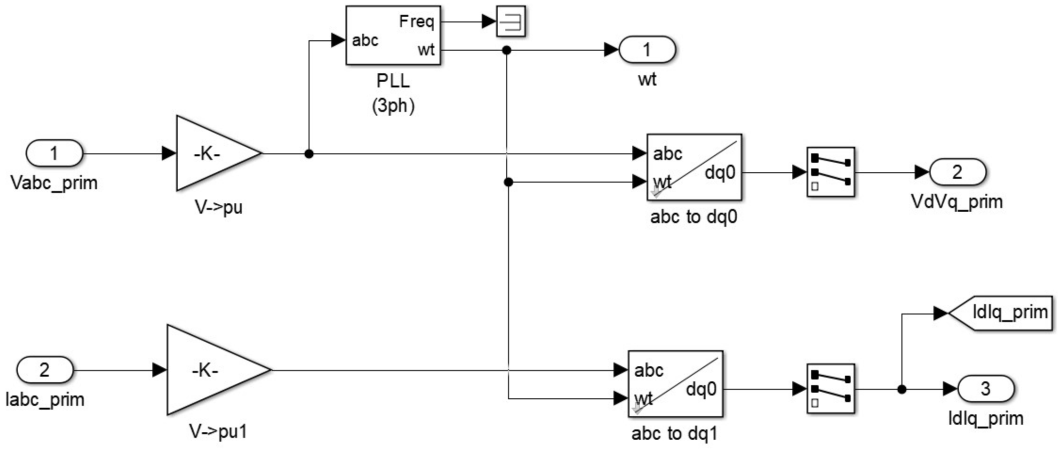


Figure 4.6: PLL and dq converter Simulation

Phase locked Loop (PLL) was used for synchronization purposes and voltage and current control has done in synchronous reference frame using dq converters as shown in Figure 4.6.

4.2.5 DVR Controller Simulation

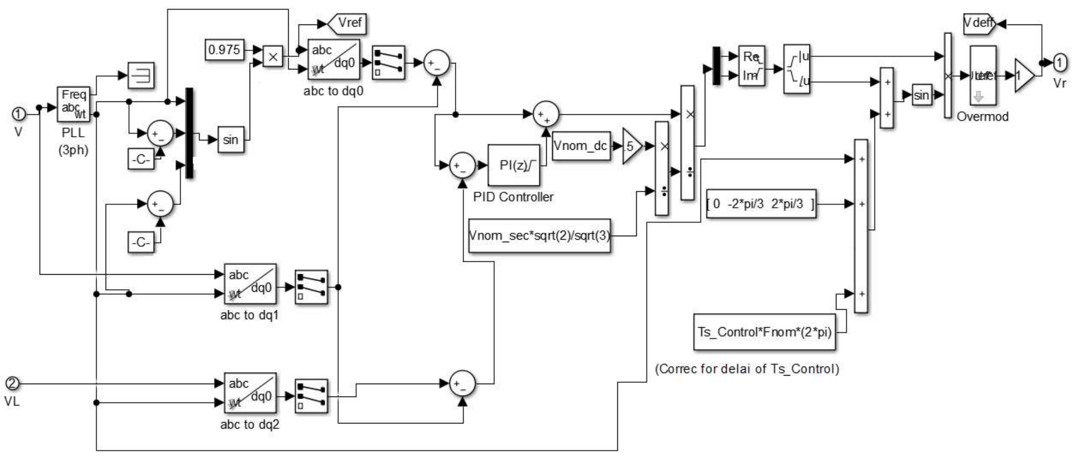


Figure 4.7: DVR Controller Simulation

The error between required load voltage and voltage of point of common coupling (V_{Lref}-V_{PCC}) and the error between measured load voltage and voltage of point of common coupling were compared and error was given to PI controller as shown in Figure 4.7. The output received from PI controller was given to PWM converter of DVR Inverter. PI controller output was received in synchronous reference frame (V_d,V_q) and it was converted to three phase sine waves. PI controller gains, K_P and Ki values were 0.3 and 20 respectively.

5. CASE STUDIES AND RESULTS

5.1 CASE 1 VOLTAGE SAGS

5.1.1 Case 1A 50% three phase balanced sag

At the PCC, 50% three phase balanced sag was created for 200 miliseconds. DC voltage, PCC voltage, DVR compensated voltage, load voltage, solar array AC output, DVR active and reactive power, Load active and reactive power were as follows.

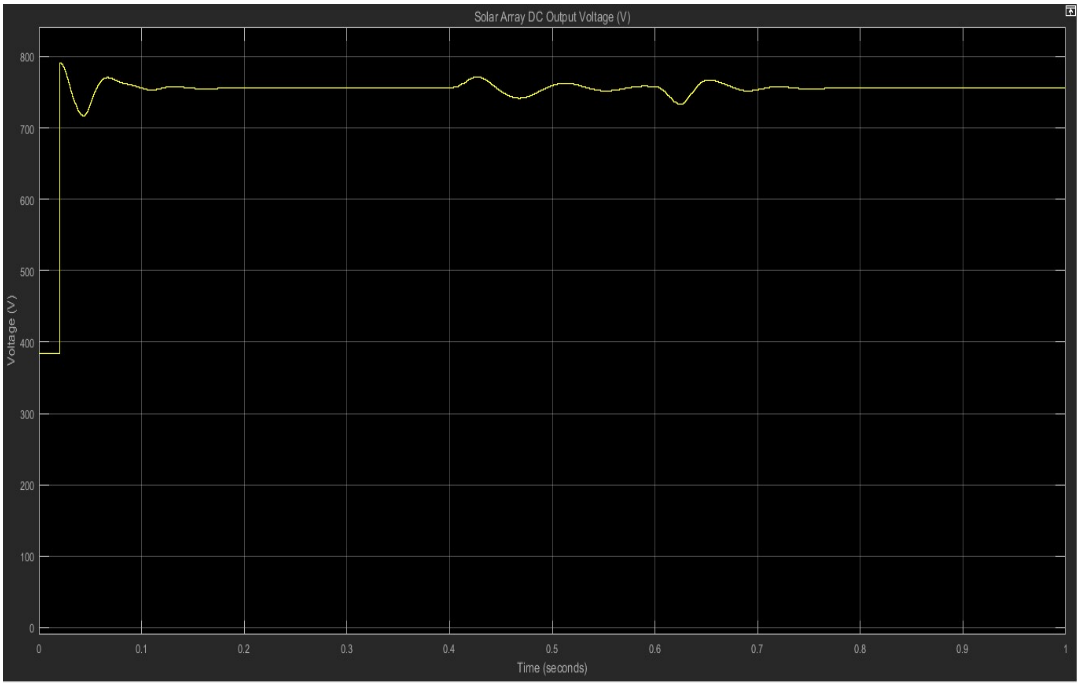


Figure 5.1: Case 1A - Solar Array DC Output Voltage

Figure 5.1 has shown that DC output voltage was almost constant. It has kept as 755 V by MPPT controller at 1000 W/m^2 solar radiance and 45 ^{0}C temperature. In the sag duration DC voltage has increased up to 771V and decreased up to 732 V. The variance was -23 V to 16 V (-3.05% to 2.12%) and it wasn't difficult to drive two voltage source inverters.

Voltage (pu)	Maximum tripping time (ms)
V<0.05	100 ms
0.05<V<0.5	200 ms
0.5<V<0.95	500 ms
0.95<V<1.05	Continuous
V>1.05	100 ms

Table 5.1: CEB Operating Limits of the Solar Inverter

According to the CEB operating limits of solar inverter as shown in Table 5.1, more than 50 % of voltage sag was allowed for 200ms. Therefore 50 % of balanced three phase voltage sag was created at PCC for 200ms time period as shown in Figure 5.2. Voltage sag was created from 0.4 s to 0.6 s.

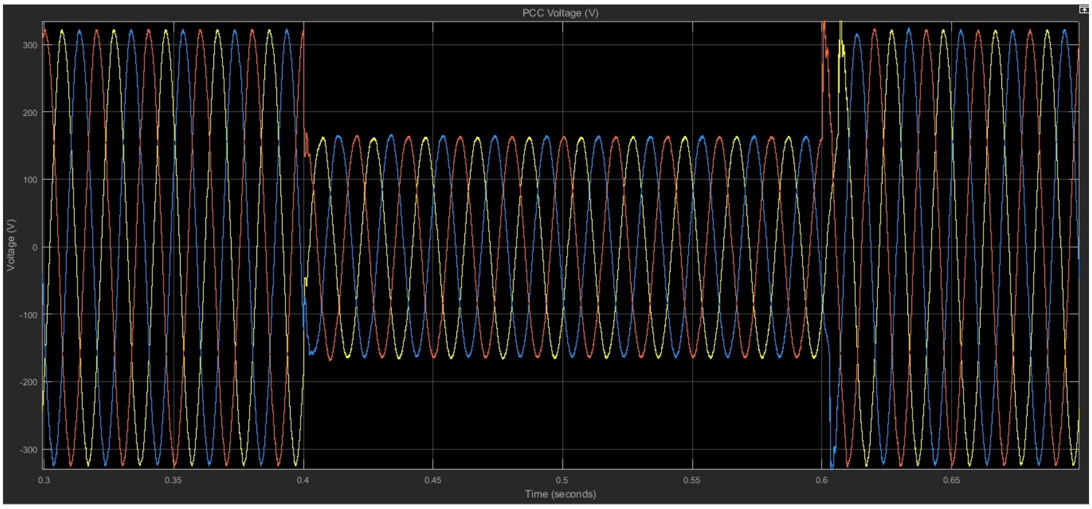


Figure 5.2: Case 1A - PCC Voltage

DVR compensated voltage is shown in Figure 5.3. Because of the special modulation scheme of NSI, the zero level was varied giving a triangular signal between -530 V and -230 V. When the compensated voltage was nearly zero the graph gave a triangular wave and its color was a mixture of colors of three phase voltage waves. In Figure 5.3, up to 0.4 s and after 0.6 s, small amount of yellow color and blue color can be seen because there was a small difference between reference load voltage and nominal PCC voltage. From 0.4 s to 0.6s sag compensation was done by DVR and the compensated voltage waveform was as shown in Figure 5.3.

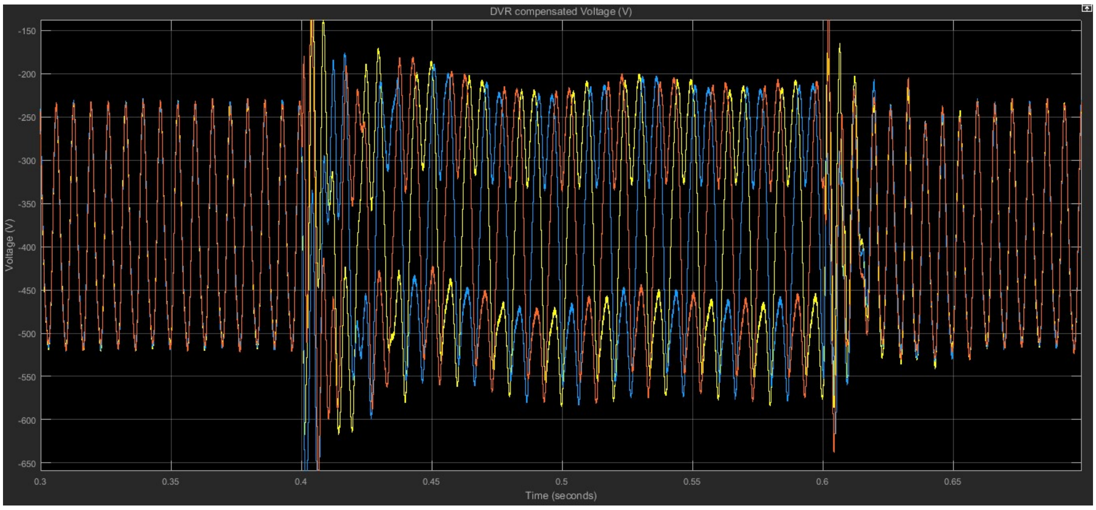


Figure 5.3: Case 1A – DVR Compensated Voltage

Load voltage has shown in Figure 5.4 and sag was compensated successfully. There were small spikes at the beginning and ending of the sag and could be reduced properly by tuning the controllers.

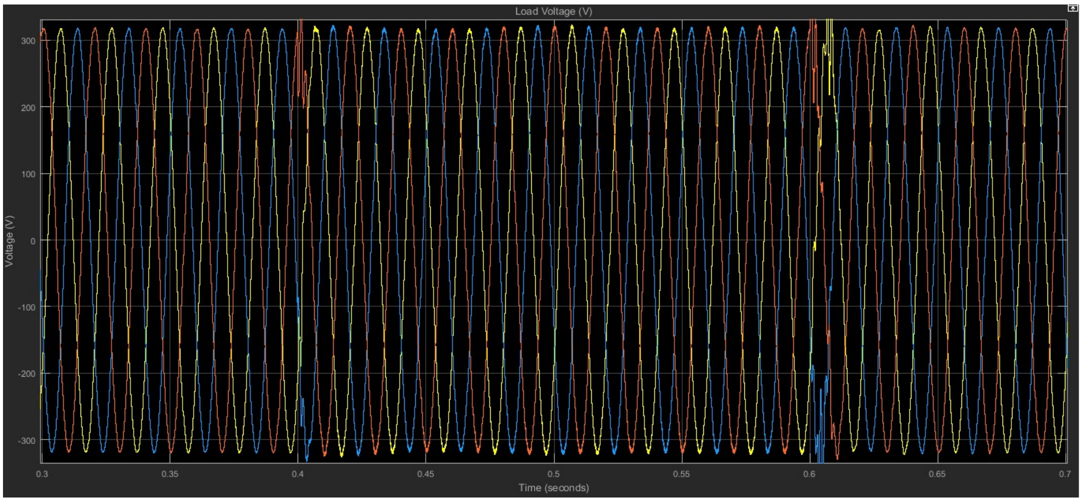


Figure 5.4: Case 1A - Load Voltage

PV inverter generated power at 1000 W/m^2 solar radiance and 45 ^{0}C temperature was 12.8 kW. At 50% three phase balanced sag condition it reduced to 8.4 kW and DVR active power and reactive power were increased to 4.5 kW and 2.2 kvar respectively as shown in Table 5.2. Figure 5.5 has shown active power variation of solar PV inverter and it had some spikes at the beginning and ending of the sag.

Operating condition	Active Power Injected to Grid (kW)	DVR Active Power (kW)	DVR Reactive Power (kvar)
Without sag	12.8	0.02	-0.05
At sag condition	8.4	4.5	2.2

Table 5.2: Case 1A PV Inverter and DVR Inverter Output

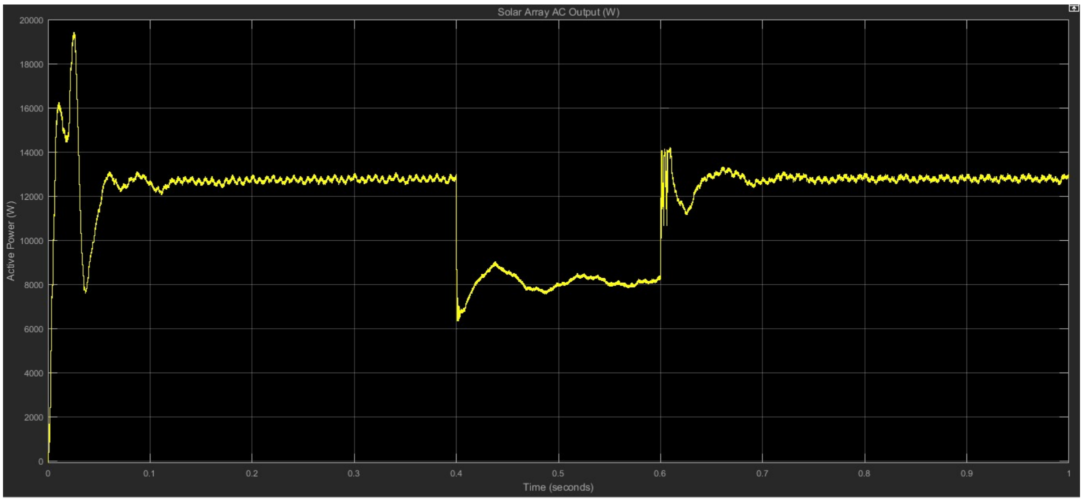


Figure 5.5: Case 1A - Solar Array AC Output (Active Power)

Figure 5.6 and Figure 5.7 have shown the active and reactive power variation of DVR respectively.

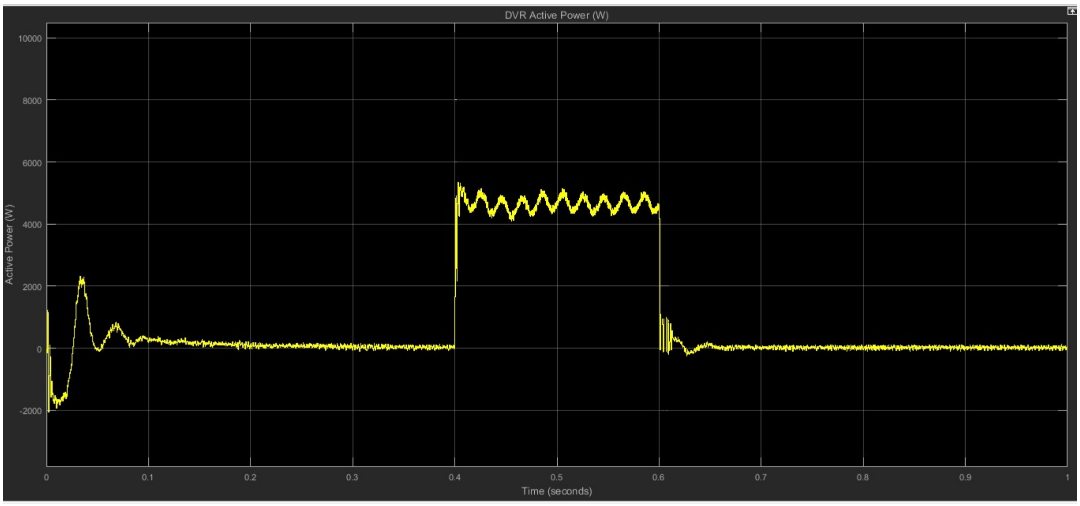


Figure 5.6: Case 1A - DVR Active Power

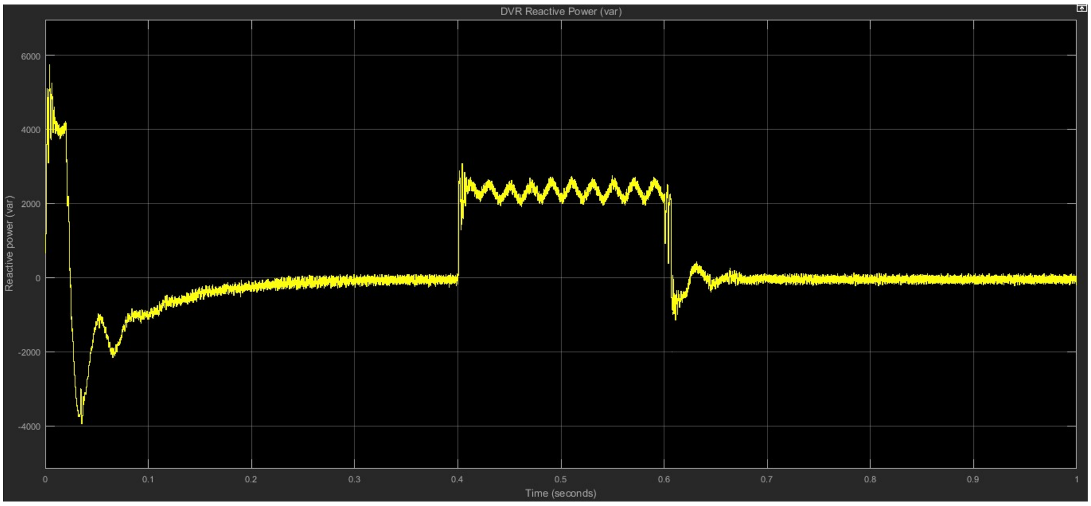


Figure 5.7: Case 1A - DVR Reactive Power

Figure 5.8 and Figure 5.9 have shown the active and reactive power variation of load respectively. Load had a constant power consumption throughout the time and no change at sag duration.

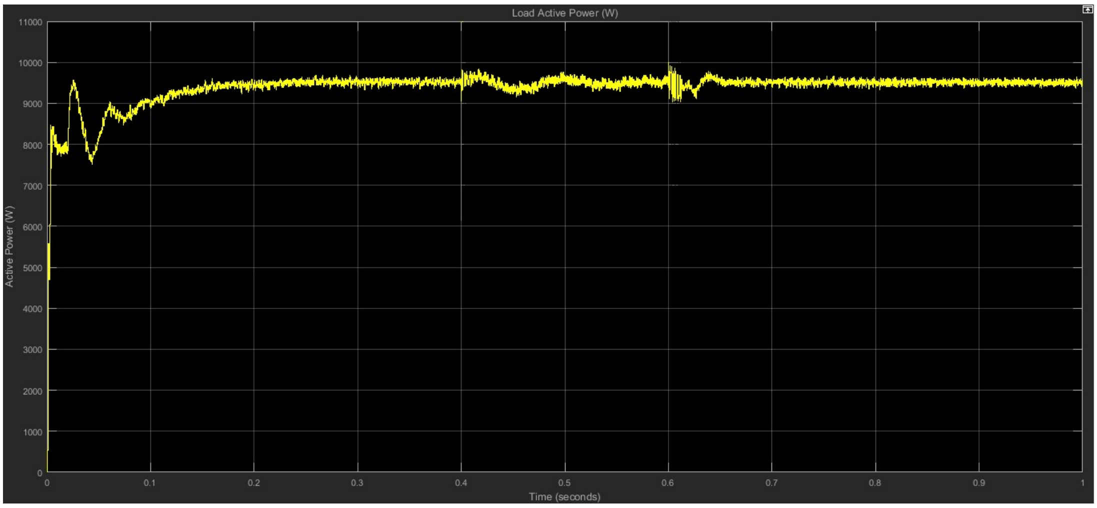


Figure 5.8: Case 1A – Load Active Power

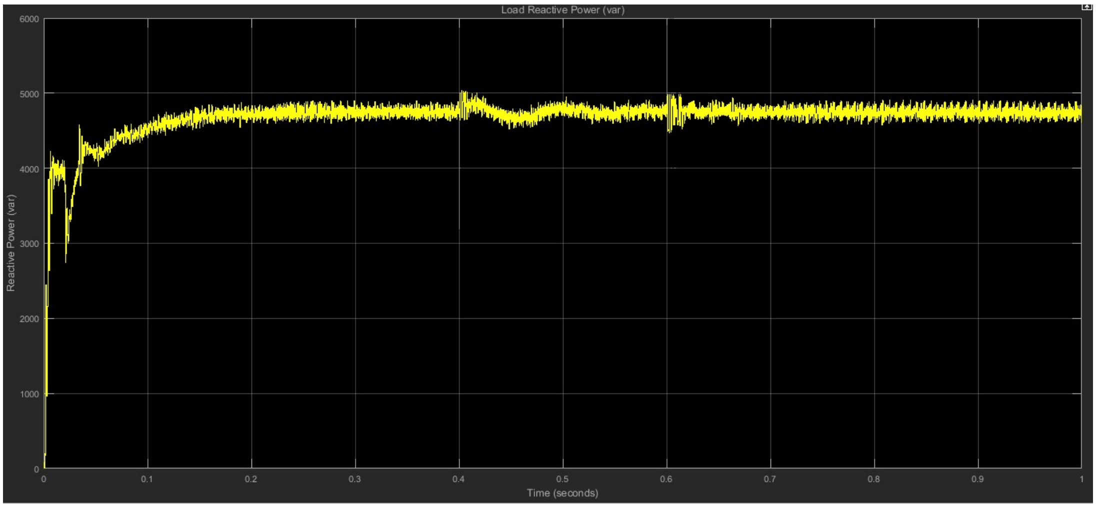


Figure 5.9: Case 1A – Load Reactive Power

5.1.2 Case 1B- 50% three phase unbalanced sag

At the PCC, 50% three phase unbalanced sag was created for 200 miliseconds. PCC voltage, DVR compensated voltage and load voltage were as follows. DC voltage, solar array AC output, DVR active and reactive power, Load active and reactive power were in same pattern like in Case1A.

Figure 5.10 has shown the PCC voltage with unbalanced sag created from 0.4 s to 0.6 s time interval. Figure 5.11 has shown the DVR compensated voltage and Figure 5.12 has shown the load voltage and sag was compensated successfully.

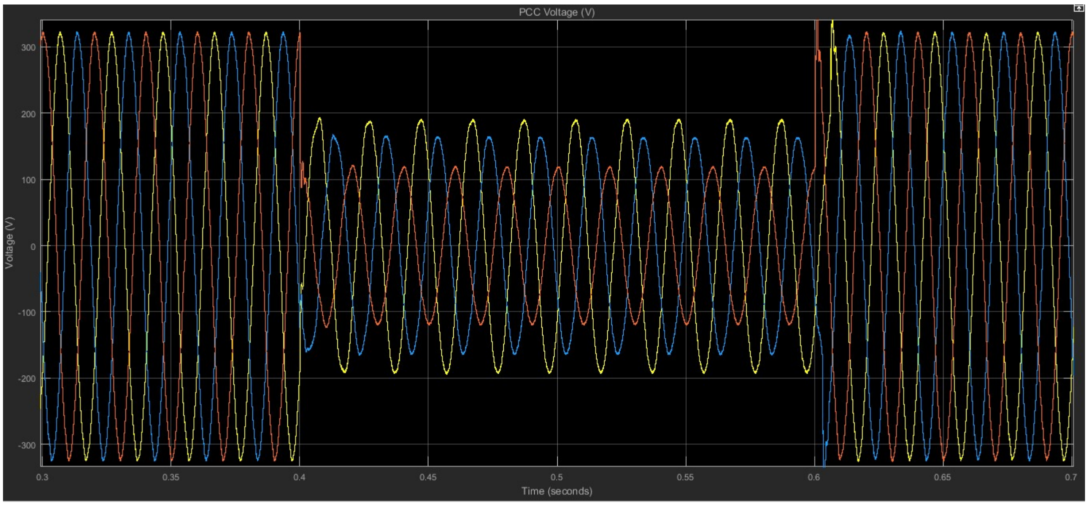


Figure 5.10: Case 1B – PCC Voltage

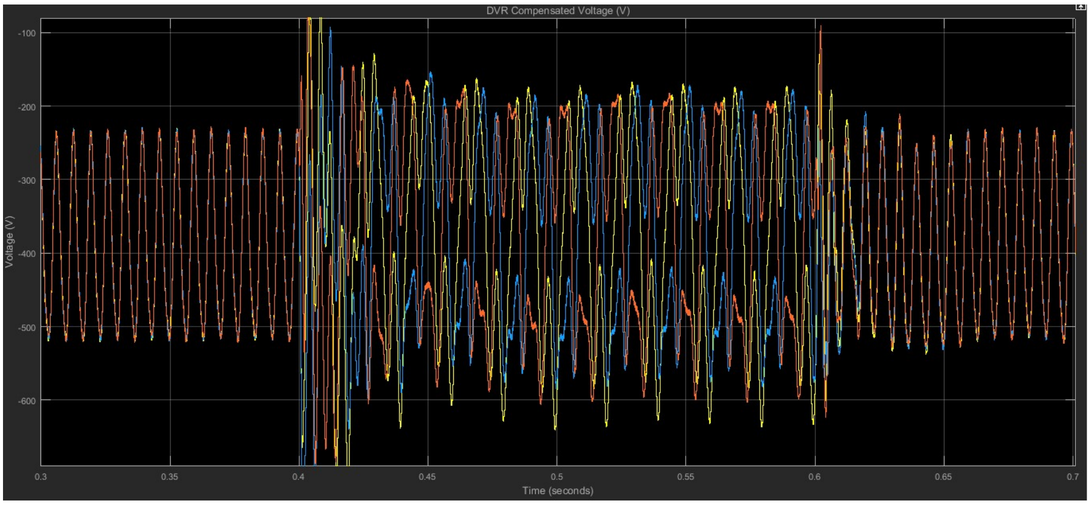


Figure 5.11: Case 1B – DVR Compensated Voltage

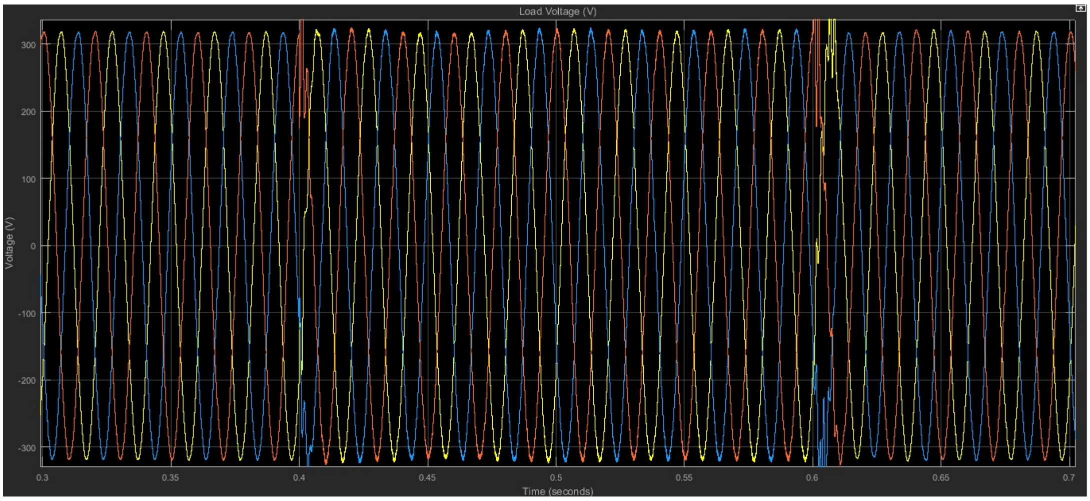


Figure 5.12: Case 1B – Load Voltage

Operating condition	Active Power Injected to Grid (kW)	DVR Active Power (kW)	DVR Reactive Power (kvar)
Without sag	12.8	0.02	-0.05
At sag condition	8.0	4.5	2.2

Table 5.3: Case 1B PV Inverter and DVR Inverter Output

PV inverter generated power at 1000 W/m^2 solar radiance and 45 ^{0}C temperature was 12.8 kW. At 50% three phase unbalanced sag condition it reduced to 8.0 kW and DVR active power and reactive power were increased to 4.5 kW and 2.2 kvar respectively as shown in Table 5.3.

Figure 5.13 has shown the modulated wave forms of the three phases. Solar inverter reference voltage wave form has shown in yellow color and that of DVR has shown in blue color. During the voltage sag, DVR inverter reference signal has increased and solar inverter reference has decreased accordingly and reference cross over has naturally avoided.

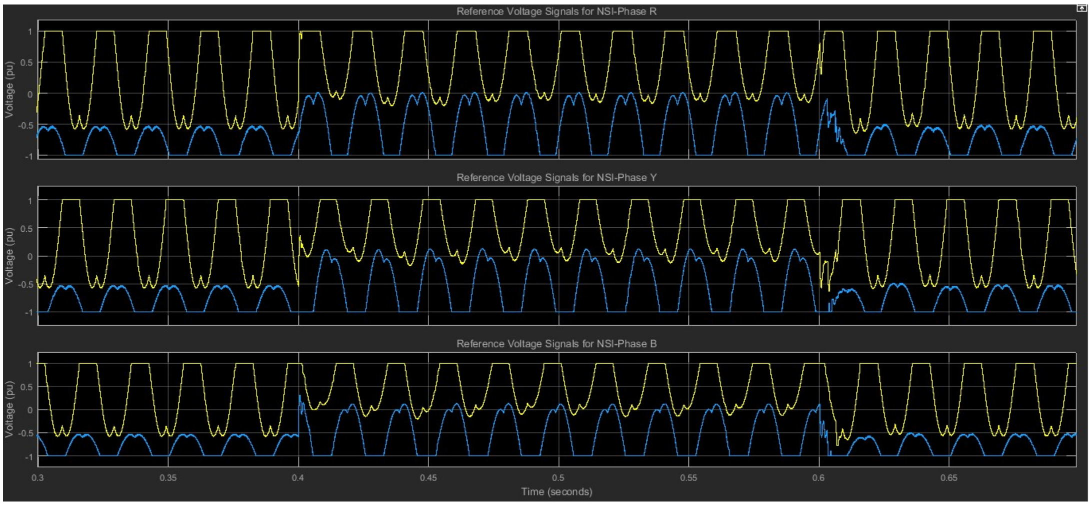


Figure 5.13: Case 1B – Reference Voltage Signals for NSI

As shown in Figure 5.14, IGBT current of Switch No. D22 has slightly increased during the sag interval and it was in tolerable level to the IGBT switch.

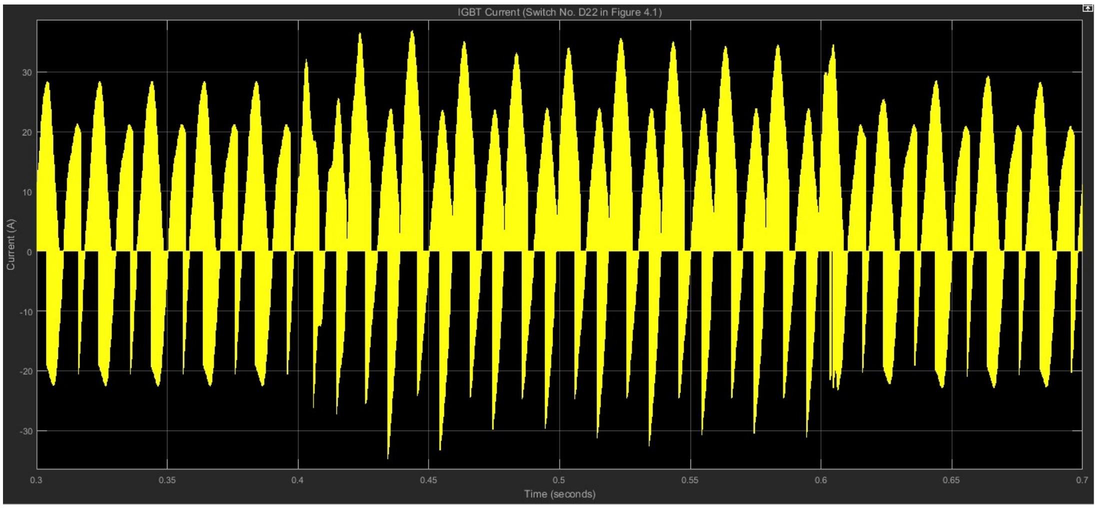


Figure 5.14: Case 1B – IGBT Current (Switch No. D22 in Figure 4.1)

5.2 CASE 2 VOLTAGE SWELLS

5.2.1 Case 2A -10% three phase balanced swell

According to CEB operating limits of solar inverter (Table 5.1) only 5% swell is allowed for 100ms. For the purpose of showing the capability of NSI system 10% three phase balanced swell was created for 200 miliseconds at the PCC. PCC voltage, DVR compensated voltage and load voltage were as follows. DC voltage, solar array AC output, DVR active and reactive power, Load active and reactive power were in same pattern like in Case1A.

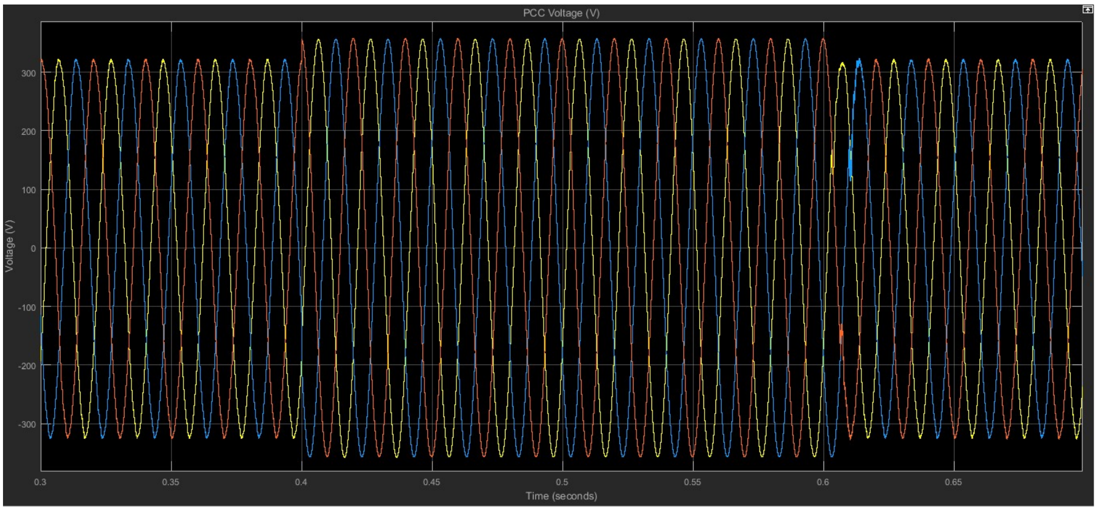
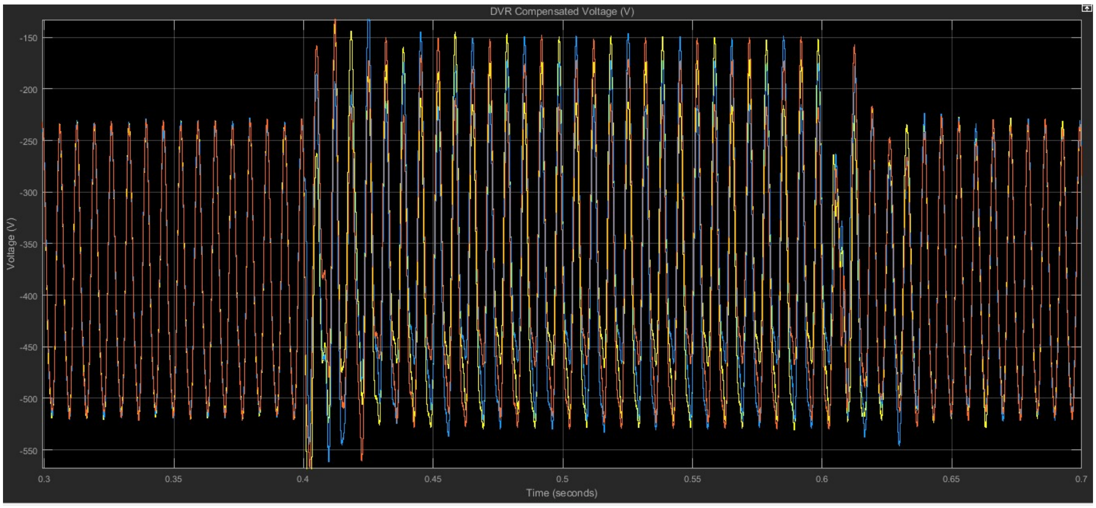
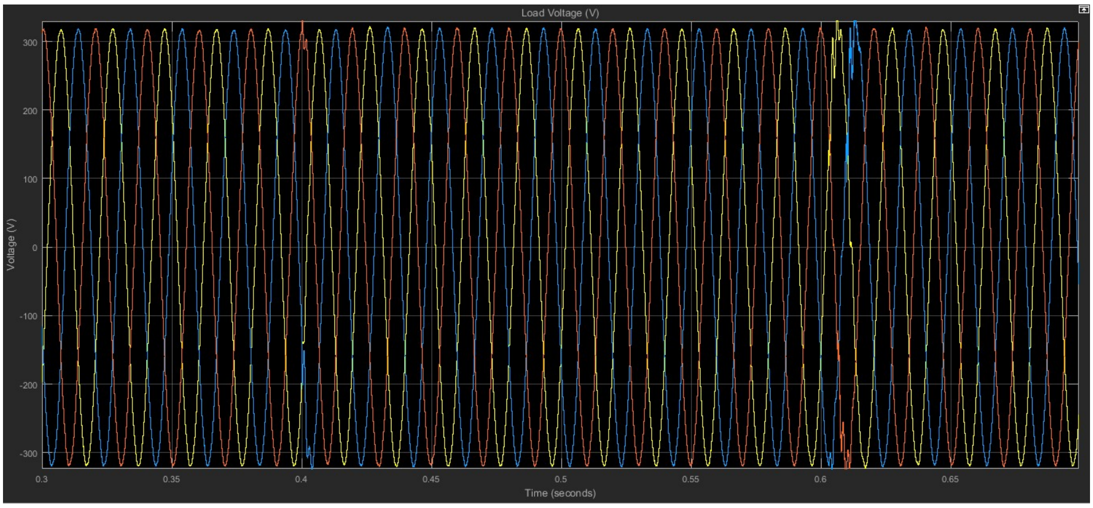


Figure 5.15: Case 2A – PCC Voltage



<u>Figure 5.16: Case 2A – DVR Compensated Voltage</u>



<u>Figure 5.17: Case 2A – Load Voltage</u>

Operating condition	Active Power Injected to Grid (kW)	DVR Active Power (kW)	DVR Reactive Power (kvar)
Without sag	12.8	0.02	-0.05
At sag condition	13.5	-1.2	-0.6

Table 5.4: Case 2A PV Inverter and DVR Inverter Output

PV inverter generated power at 1000 W/m^2 solar radiance and 45 ^{0}C temperature was 12.8 kW. At 10% three phase balanced swell condition it increased to 13.5 kW and DVR active power and reactive power were -1.2 kW and -0.6 kvar respectively as shown in Table 5.4.

5.2.2 Case 2B-10% three phase unbalanced swell

At grid side, 10% three phase unbalanced swell was created for 200 miliseconds at the PCC. PCC voltage, DVR compensated voltage and load voltage were as follows. DC voltage, solar array AC output, DVR active and reactive power, Load active and reactive power were in same pattern like in Case1A.

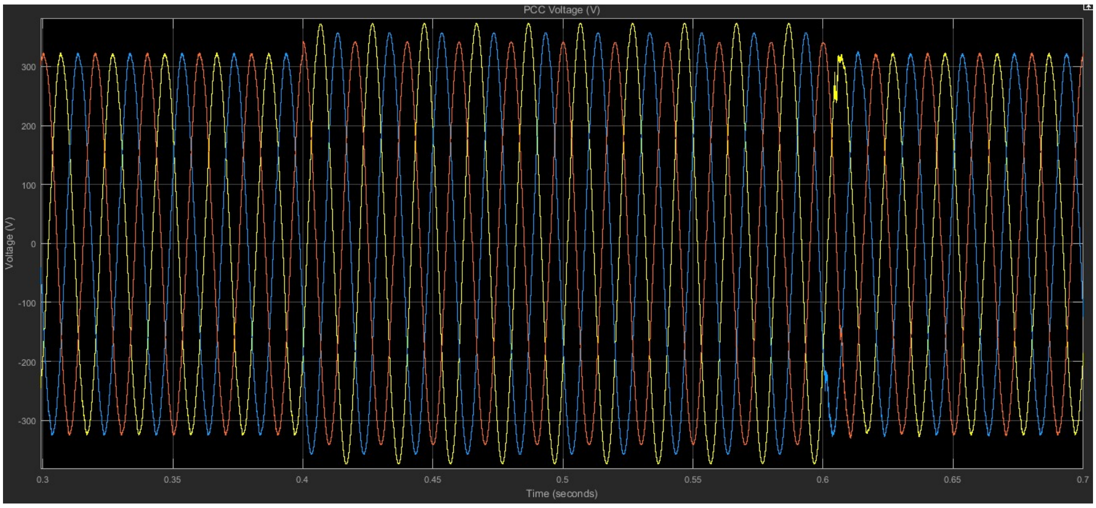


Figure 5.18: Case 2B – PCC Voltage

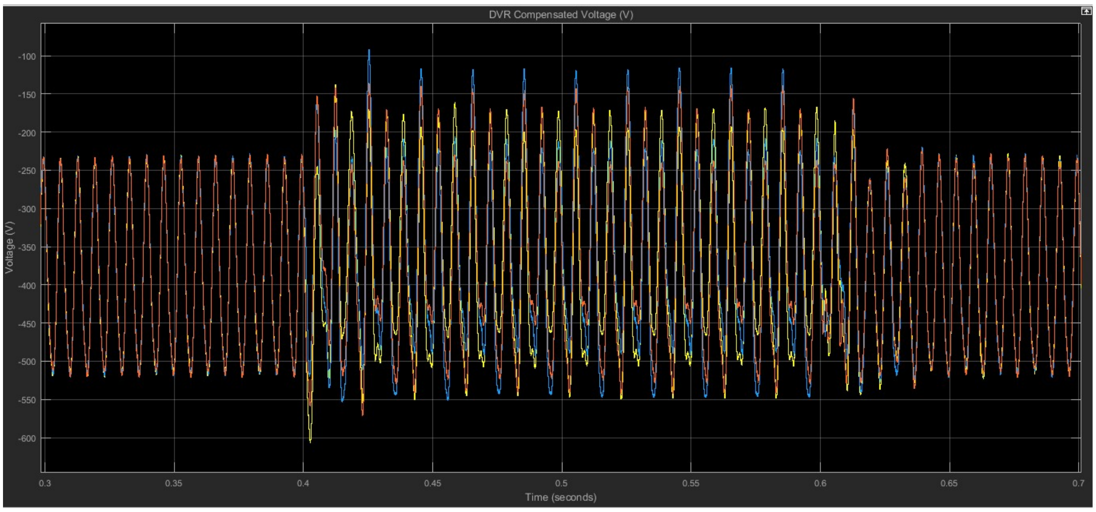


Figure 5.19: Case 2B – DVR Compensated Voltage

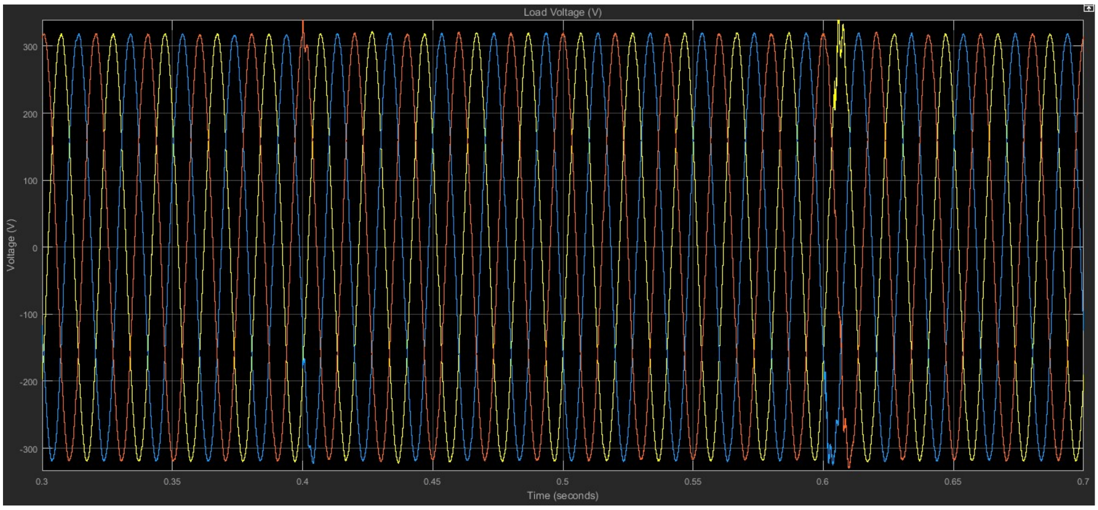


Figure 5.20: Case 2B – Load Voltage

Operating condition	Active Power Injected to Grid (kW)	DVR Active Power (kW)	DVR Reactive Power (kvar)
Without sag	12.8	0.02	-0.05
At sag condition	13.7	-1.2	-0.6

Table 5.5: Case 2B PV Inverter and DVR Inverter Output

PV inverter generated power at 1000 W/m^2 solar radiance and 45 ^{0}C temperature was 12.8 kW. At 10% three phase unbalanced swell condition it increased to 13.7 kW and DVR active power and reactive power were -1.2 kW and -0.6 kvar respectively as shown in Table 5.5.

Figure 5.21 has shown the modulated wave forms of the three phases. Solar inverter reference voltage wave form has shown in yellow color and that of DVR has shown in blue color. During the voltage swell, both DVR and solar inverter reference signals have increased and reference cross over has marginally avoided. Therefore maximum possible swell compensation by the proposed NSI system was around 10% unbalanced swell.

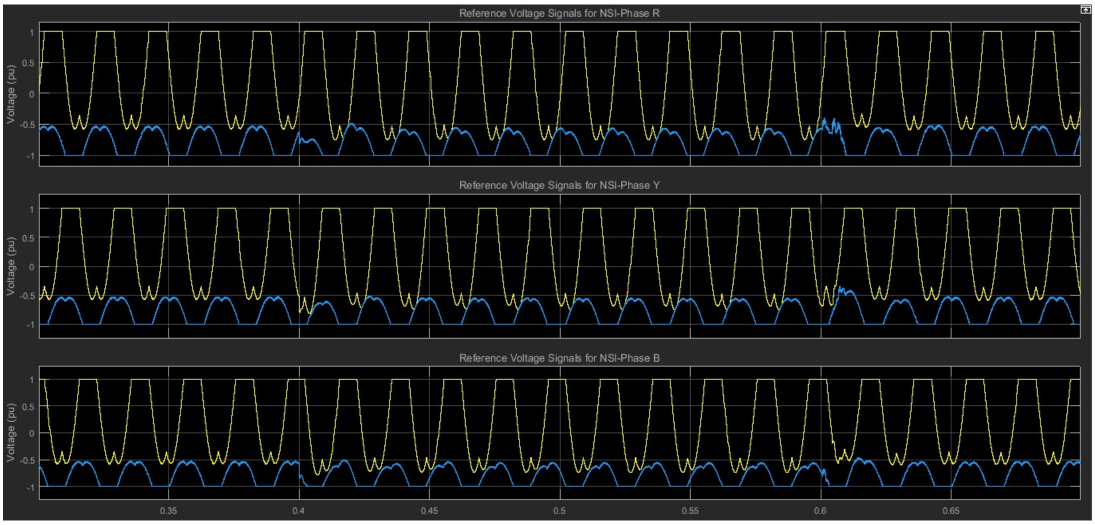


Figure 5.21: Case 2B – Reference Voltage Signals for NSI

As shown in Figure 5.22, IGBT current of Switch No. D22 has slightly increased during the swell interval and it was in tolerable level to the IGBT switch.

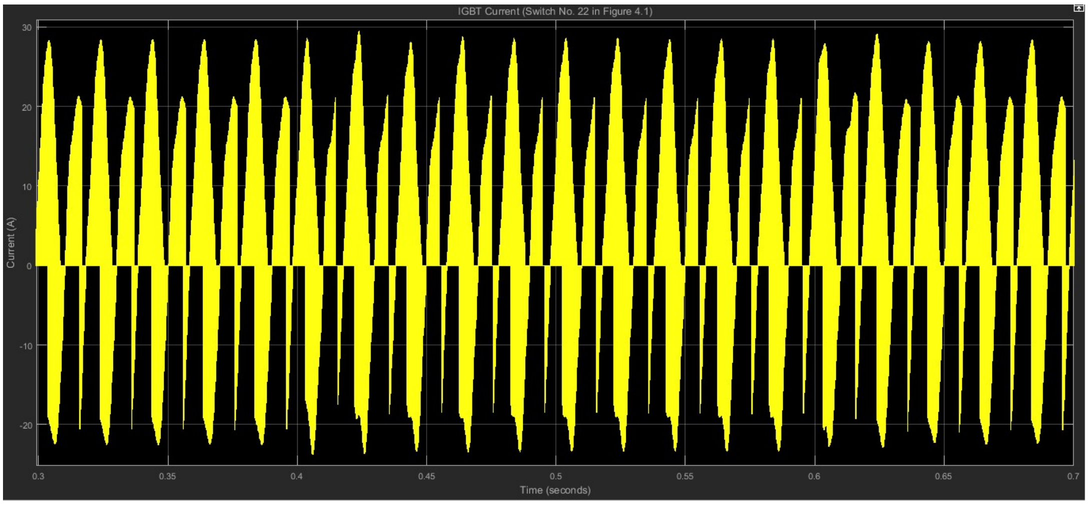


Figure 5.22: Case 2B – IGBT Current (Switch No. D22 in Figure 4.1)

5.3 CASE 3-SYSTEM RESPONSE AFTER SOLAR INVERTER TRIPPING

When the sag or swell duration is higher than the allowable limit for solar inverter, it shall trip and no solar power feeds to the grid. At that time DVR inverter shall have the capability to mitigate voltage sag or swell continuously. As in Case 1A, 50% balanced sag was created from 0.4s to 0.6s. It was arranged to trip solar inverter at 0.5s and PCC Voltage, Load Voltage, Solar array DC output voltage and Solar array AC output were as follows.

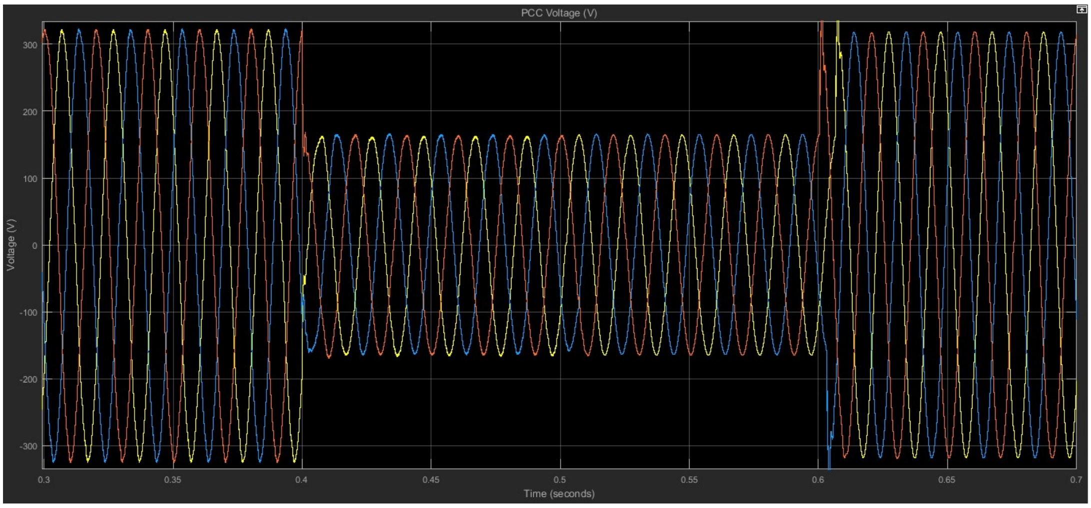


Figure 5.23: Case 3 – PCC Voltage

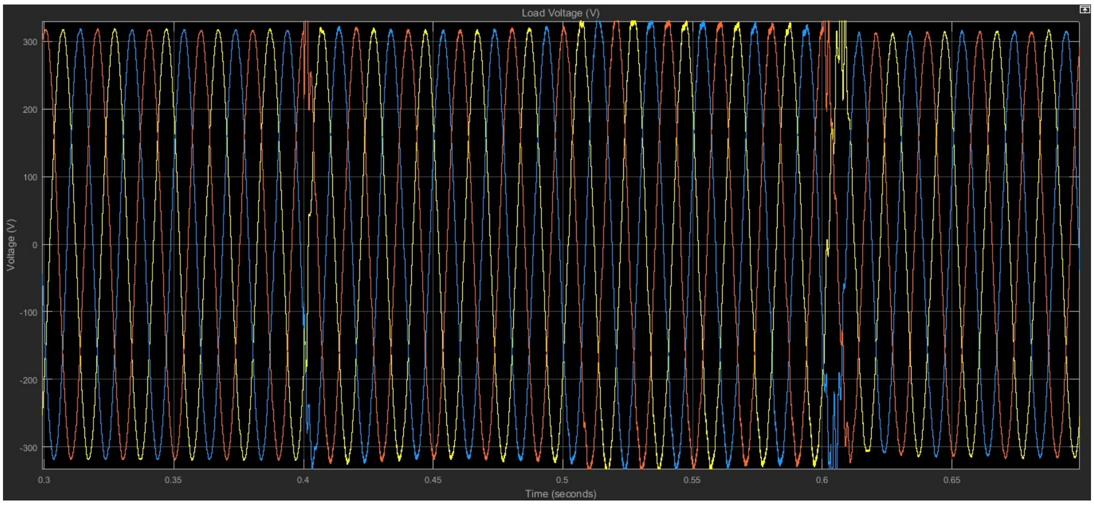


Figure 5.24: Case 3 – Load Voltage

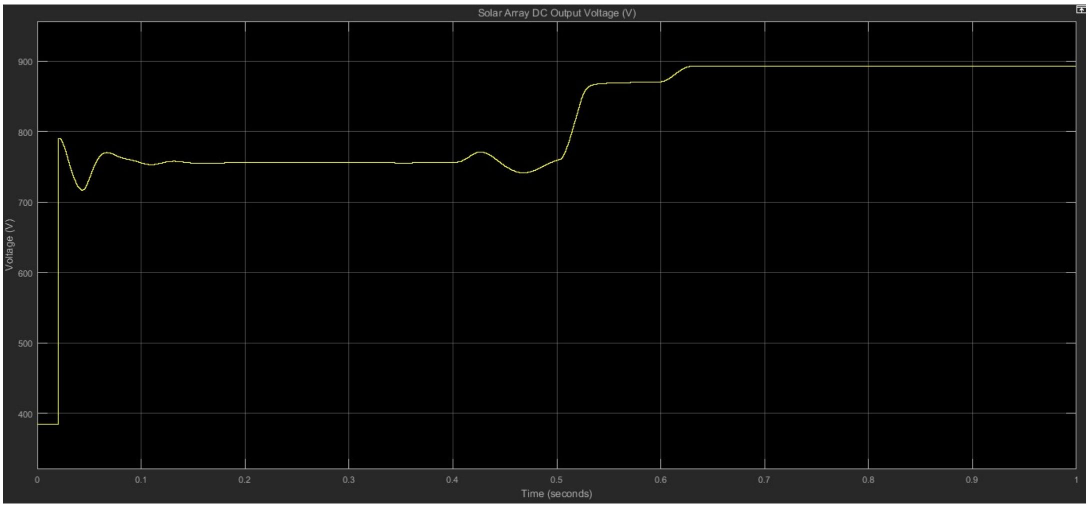


Figure 5.25: Case 3 – Solar Array DC Output Voltage

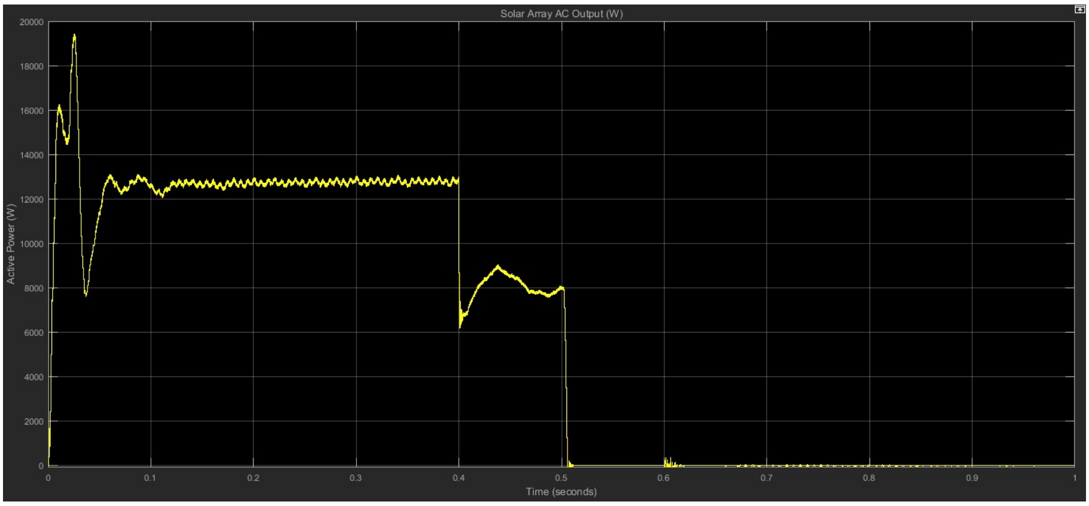


Figure 5.26: Case 3 – Solar Array AC Output

After tripping the solar inverter, the DC voltage has increased then stabilized and sag has compensated successfully. The NSI system has shown that it was capable to mitigate voltage sag and swells continuously using the solar energy after tripping solar inverter. Then the generated solar energy was not wasted and fed to load via DVR inverter.

6. CONCLUSION

Dynamic Voltage Restorer (DVR) has used as a custom power device to mitigate voltage sags and swells in critical loads. Nine Switch Inverter (NSI) was suitable to use as its one inverter output in parallel connection for continuous usage or high power consumption and remaining inverter output in series connection for short time usage or low power consumption. Some consumers had grid connected solar panel systems and they wanted to mitigate voltage sags and swells in their sensitive loads. Incorporating a NSI with the grid connected solar panel system was one proposed solution to this situation.

A NSI model was simulated using Matlab Simulation software package. Electricity consumer had a 14 kW grid connected solar power plant and there was a 10 kW sensitive load which was required terminal voltage free of sags and swells. Voltage sag and swell events have created using fault conditions and higher rated voltage sources respectively. Two cases were run using the simulation under balanced and unbalanced sag and swell conditions.

Operating limits of the solar inverter allowed by CEB, are 200 ms for sags up to 0.5 per unit and 100 ms for swells up to 1.05 per unit. If the sag or swell levels exceed above time intervals, solar power plant is disconnected from the grid and shut off. Therefore mitigation of above sag and swell levels through the DVR while feeding solar energy to the grid is adequate. The results of Case1A and Case1B have shown that NSI model could mitigate the above sag level by reducing the grid fed solar energy output. Also the results of Case 1B and Case 2B have shown that the NSI model could mitigate swell levels more than above limitations. Separate case; Case 3 was run to show the DC voltage stability after tripping the Solar power plant. After tripping the solar plant, DC voltage has increased and stabilized then DVR has properly functioned continuously. Therefore the solar energy was not wasted and fed to the load via DVR inverter.

Voltage reference signal of solar inverter shall be above the reference signal of DVR inverter to avoid reference crossover for the purpose of avoiding DC voltage short circuit. Regarding this, Case 1B and Case 2B were worst compared to other two and it has shown using those cases that modulation signals of the Solar Inverter and DVR Inverter were not over lapped and NSI was capable to mitigate voltage sags and swells up to the required extent. Also when sag compensation, reference signal of solar inverter has decreased and the same of DVR has increased accordingly. Then the reference cross over has naturally avoided. But when swell compensation, both reference signals of solar inverter and DVR inverter have increased simultaneously and reference cross over marginally avoided. Therefore proposed NSI model was more suitable for sag compensation than swell compensation while feeding solar energy to the grid. Anyway it has compensated voltage swells up to the required extent according to CEB limits.

When consider the IGBT currents of NSI, three common switches of solar inverter and DVR inverter were critical compared to other six switches. It was revealed that the IGBT currents have slightly increased when voltage sag compensation and those currents were also in tolerable level of the IGBTs.

Two separate inverters can be used for this purpose as solar inverter for solar power grid feeding and DVR inverter for mitigation of voltage disturbances of sensitive loads. Because mitigation of voltage sag/swell is not a frequent event, using a separate inverter for DVR function is not economical. Then the NSI is adequate for the above two applications and, number of IGBT switches could be reduced with gate drives compared to separate Solar Inverter and DVR systems. Also solar energy can be optimally used for continuous grid feeding and short time voltage sag/swell mitigation.

Every time, point of common coupling voltage may slightly differ from reference load voltage but that sag and swell levels may not be harmful to the sensitive load. So reference voltage of DVR inverter is always nonzero and IGBT switches of DVR are operating continuously. For the prevention of unnecessary switching of IGBT switches, the system can be configured as DVR inverter is idle below a threshold sag or swell level.

DC power can be given by solar power plant only on sunny days and DVR inverter can be operated at those times. Then suitable modification can be applied to NSI to use solar inverter as a charger when there is no solar energy, to charge DC capacitor using the grid power. Then voltage disturbance of sensitive load can be mitigated without solar power also. Alternatively a suitable battery bank can be added to this purpose.

Finally, it can be concluded that the proposed NSI model can be successfully used for mitigation of voltage sag/swell of sensitive loads while feeding solar energy to the grid.

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