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Simulation of VSI FED Grid-Connected System using Decoupled Active and Reactive Power Control

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ABSTRACT
This report presents a small scale three-phase grid connected photovoltaic system with active and reactive power control scheme for improvement in voltage stability. The proposed system consists of a 100 kW PV panel with a DC-DC boost converter with controller for Maximum Power Point Tracking using perturb and observe algorithm and DC-AC 3-phase voltage source inverter with decoupled reactive power controller supplying the load. The VSI (voltage source inverter) is synchronized with the grid using a phase locked loop. A special Perturb and Observe algorithm has been developed and applied to the boost converter, in such a way that a controlled active power is produced by it. The VSI controller is used for independent control over reactive power injected by the voltage source inverter into the system, and maintains constant DC point of coupling voltage. This method improves the system stability by producing or absorbing reactive power at sudden voltage increase or decrease due to change in loads, instantaneously. The simulation of the proposed model is carried out to show its effectiveness and robustness in enhancing the capabilities of grid-connected photovoltaic systems.

Keywords: *Grid connected PV system, Boost converter, VSI, MPPT, P&O algorithm.*

INTRODUCTION

Grid connected PV systems in the world account for about 94% of the current installed capacity around the world in grid connected systems, in comparison to off-grid systems, which makes use of batteries. Battery-less grid connected PV are cost effective and require less maintenance, and can be used as instantaneous energy supply, as there is no problem of storing energy. But, the PV system with different technologies till now can supply active power only to the grid, reactive power generation using present topologies, is impossible. Hence, the grid is responsible for supplying the majority of reactive power to the load, and this can cause many problems in the future, as the conventional generation will cease to exist due to degradation fossil fuels and pollution in the environment, at that time more energy will be generated by the renewable generating stations than conventional systems. What we need is technology that can produce reactive power, without changing the running equipment/ sources of reactive power. In this project, we have designed a controller circuit for a PV system, which converts this old system into a DEG which can supply not only active power, but also reactive power, into the electrical power system.[9] The generalized block diagram in the form of a single line diagram, of the proposed project is given below. The concept of negative feedback is used in the network, to get required active power and reactive power supplied as per the set reference active and reactive power.

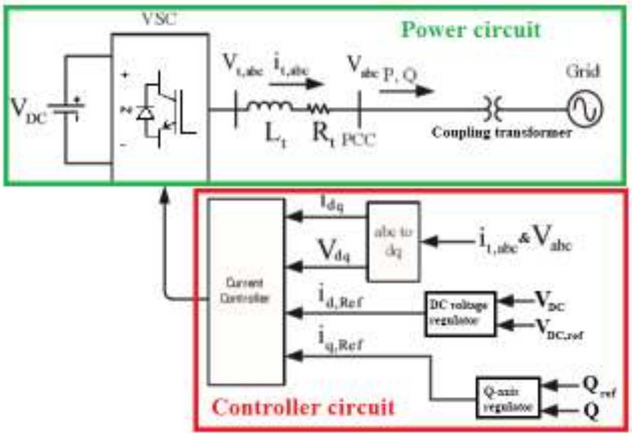

Fig. 1: *Basic Block Diagram of Proposed Project.*

In this project we have selected a PV array, with a rating of 100kW. PV array through boost converter is fed to VSI (2-stage power conversion).[3] Thus, the Active power of 100kW can be extracted from the VSI. If a voltage-oriented control (VOC) method is used to control the inverter, reactive power can be controlled by controlling the q-axis current. Using a suitable PQ controller, Reactive power ranging from +100kVAR (lead) to -100kVAR (lag) can also be generated by the VSI, along with 100kW active power.[4] The DC-DC converter will perform the MPPT technique to extract maximum power from the PV array. The VSI in our project is mainly used to maintain a constant DC PCC voltage, which will in-turn maintain a constant terminal 3-phase voltage at the output. The design and simulation of the proposed project is done in MATLAB R2015a/SIMULINK 8.5.[8]

PV PANEL WITH MPPT, BOOST CONVERTER, VSI, LOADS CONNECTED TO TRANSMISSION LINE[7]

PV Array

The PV array has been designed to produce an active power of 100kW. To achieve this, PV modules are connected in series and parallel to supply sufficient power to the grid.

Table 1: *Parameters of PV Module.*

Parameters	Ratings
Open Circuit Voltage(Voc)	64.2V
Short circuit current(Isc)	5.96
Voltage at MPP(Vmp)	54.7V
Current at MPP(Imp)	5.58A
Maximum power	305.226 W
Number of cells per module	96

Table 2: *Parameters of PV Array.*

Parameters	Ratings
No. of strings	66
No. of modules in string	5
Total current from all strings	66×5.58=368.28A
Total voltage from all modules	5×54.7=273.5V
Total power PV array	368.28×273.5= 100.724kW

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In this project we have selected standard irradiation ($1kW/m^2$) and temperature (25°C) for the PV array design. The VSI (voltage source inverter) controller designed for the proposed project, can control the input DC voltage at PCC (point of common coupling), and reactive power injected by the VSI. Thus, Active power of 100kW can be extracted from the VSI, as active power cannot be controlled in the VSI.

Maximum Power Point Tracking

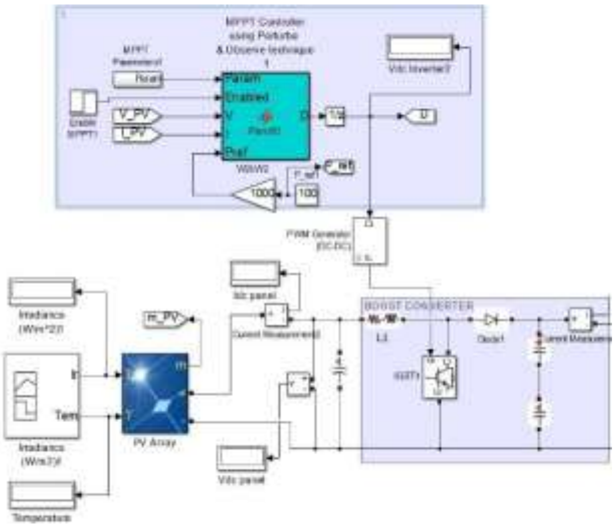

Fig. 2: *Design of MPPT Controller.*

MPPT technique is implemented using a modified P&O algorithm, which has an additional feature of controlling output power from the boost converter, which means we have full control over active power by the VSI into the grid. The inputs to the MPPT P&O blocks are:

Param parameters limits such as duty cycle minimum and maximum limits, delta D, and initial value for duty cycle.

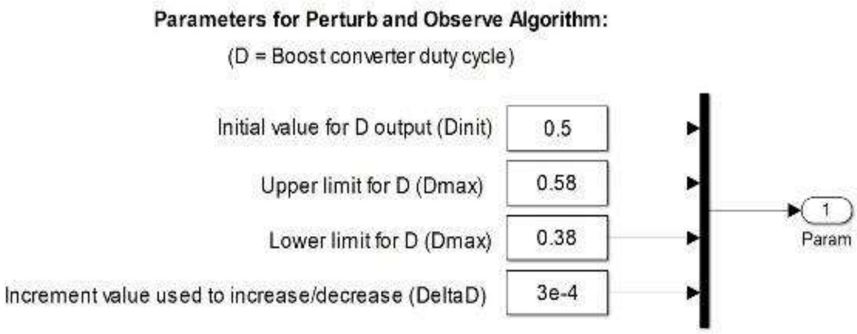

Fig 3: *Design of MPPT Controller.*

- **V_pv** DC voltage across PV array or input voltage of boost converter
- **I_pv** DC current produced by PV array or input current to boost converter
- **Enabled** acts as a switch to enable PV array at 0 seconds

The algorithm inside MPPT controller block is given in the form of flowchart

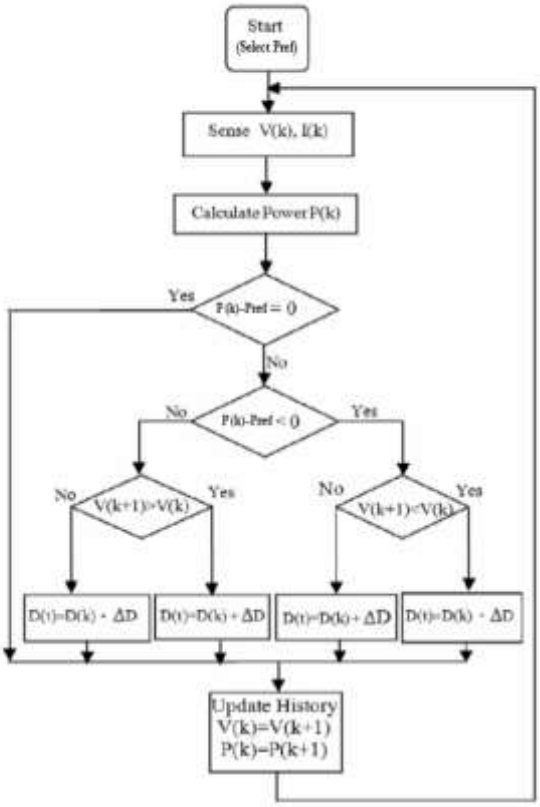

Fig 4: *Modified P&O Flowchart.*

DC-DC Boost Converter

The boost converter, used in this design, not only steps up the voltage but is also in in charge of extracting a controlled active power from the PV-array. So, a MPPT controller block is used to generate the pulses (or duty cycle), to reach reference active power. For switching frequency of 5000Hz, we have designed the boost converter as below:

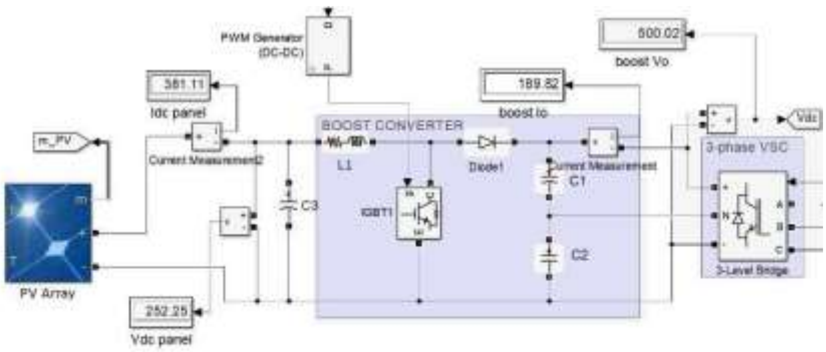

Fig. 5: *Design of Boost Converter.*

As the input voltage and current boost converter is 250V, 380A, and output voltage is maintained at 500V. The calculation for parameters of boost converter of output current (1), duty cycle (2), minimum inductance (3), minimum capacitance (4), are given as below

***Table* 3:** *Formulas for Parameters of Boost Converter*

$I_0 = \frac{V_i \cdot I_i}{V_0}$ ..(1)	$D = 1 - \frac{V_i}{V_o}$ ..(2)
$L = \frac{D \cdot V_i}{\Delta I_L \cdot f_s}$ ..(3)	$C = \frac{D}{R_o \frac{\Delta V_o}{V} f_s} = \frac{D \cdot I_0}{\Delta V_o \cdot f_s}$ ..(4)

Based on the above equations, the minimum ratings are calculated as:
I_o= 189A, D = 0.50, L= 5mH, C=3800µF
But to get better operation of boost converter and smooth graph, we have selected ratings greater than the minimum than minimum requirements as below:
DC input capacitor filter = 100µF
DC output capacitor filter = 6000µF
Resistance of series inductor = 0.005Ω
Inductance of series inductor = 5mH

Voltage Source Inverter
Based on the speed of response required and THD (total harmonic distortion) any of the three models are used.

- Three level bridge (detailed model) for lower THD% but slower response.
- Two level bridge (detailed model) for medium THD% but slower response.
- Average model for faster response but medium THD%.

Loads Connected to Transmission Line
The loads are connected in between the transmission lines, connected from VSI to the three-phase grid. The transmission is divided into 2 parts based on length. One is of length 14km and the other is of 5km. The parameters selected for transmission line are:
Resistance (positive sequence) = 0.1153Ω/km
Inductance (positive sequence) = 1.05mH/km
Capacitance (positive sequence) = 11.33nF/km

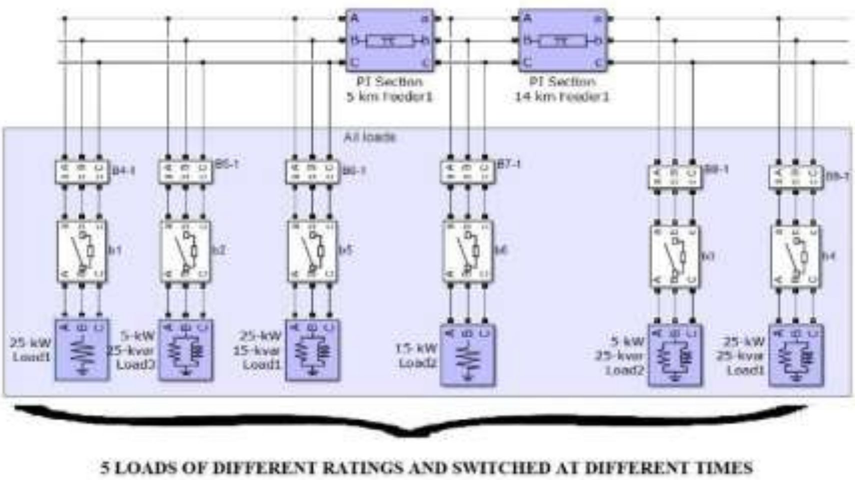

Fig. 6: *Design of Load.*

The switching sequence of the above loads is set as given in the below timing diagram:

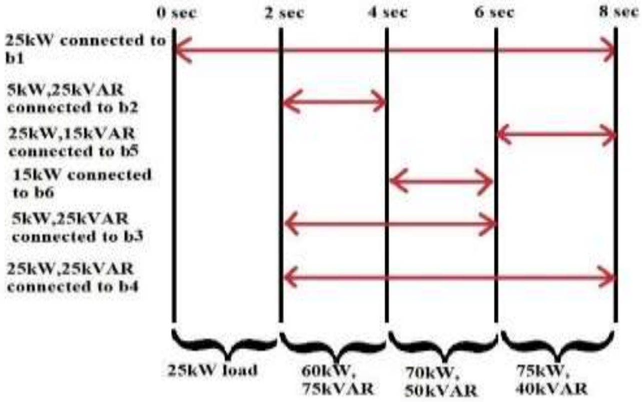

Fig. 7: *Switching Timing of Loads.*

INDEPENDENT CONTROL OF REACTIVE POWER FOR THREE-PHASE GRID CONNECTED VSI

This project deals with decoupled control of reactive power in such a way that change in reactive power does not affect the active power and vice versa.[1] In our proposed project we are adding a new feature, enhancing the abilities of the inverter. This extra feature is the generation and controlling of reactive power. Our project is mainly concerned about the PQ-control mechanism. In this mechanism, we have used the PI controller, as; its inherent feature is that the required values are reached as soon as possible with respect to the reference set.

Reactive Power and DC Voltage Control Mechanism

The mathematical representation of the three-phase PV grid-connected system and its structure diagram has been explained below. From understanding the above block diagram, by writing the KVL equation from the AC point of common coupling bus to the VSI end terminal results in the form equations in the RYB/ABC frame of reference as below:

$$V_{t,abc} = R_t i_{t,abc} + L_t \frac{di_{t,abc}}{dt} + V_{abc}$$

It is very difficult to calculate frequency and phase angle of currents and voltages in the ABC frame of reference. So, we convert the ABC into a DQ frame of reference. Voltages in the DQ frame of reference have a constant magnitude, unlike sinusoidal waveforms, which gives us easy manipulation and calculation. The conversion of a frame of reference from ABC to DQ is known as the Park and Clarke transformation. This transform could be done by applying the below expression:

$$F_{dq0} = K_S F_{abc}$$

Where Ks is defined as below:

$$K_S = \frac{2}{3}\begin{bmatrix} \cos\omega t & \cos(\omega t - 120) & \cos(\omega t + 120) \\ \sin\omega t & \sin(\omega t - 120) & \sin(\omega t + 120) \\ 1/2 & 1/2 & 1/2 \end{bmatrix}$$

Therefore, the equation of the system in the DQ rotating frame of reference is given below:

$$V_{t,dq} = R_t i_{t,dq} + L_t \frac{di_{t,dq}}{dt} + j\omega L_t i_{t,dq} + V_{dq}$$

The above equation, when divided for d-axis and q-axis, can be represented as below:

$V_d{}^* = V_{d,meas} + R_t I_{d,ref} - \omega L_t I_{q,ref}$
$V_q{}^* = V_{q,meas} + R_t I_{q,ref} + \omega L_t I_{d,ref}$

Where $V_{dq}{}^*$ is the output DQ-axis voltages from the inner PI controller loop. To get the reference $V_{dq,ref}$, we apply the following formula,

$V_{dq,ref} = PI \{ I_{dq,ref} - I_{dq,meas} \} + V_d$

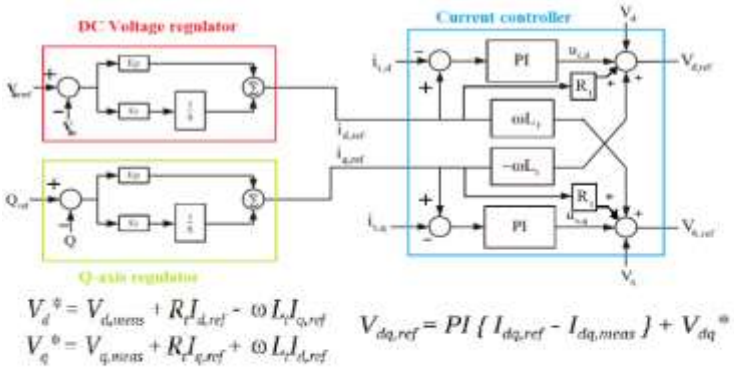

Fig. 8: *Block Diagram of Control Circuit.*

Thus, by using the above equation, $V_{dq,ref}$ is derived, which can be converted into $U_{abc,ref}$ using inverse Park & Clarke transformation.

Design of DC Voltage Regulator AND Reactive Power Controller

The VSI controller with DC-link voltage and reactive power control is designed as below-

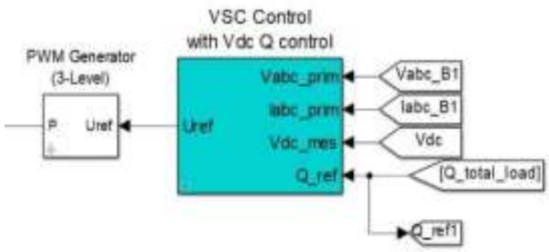

Fig. 9: *VSI Controller Block.*

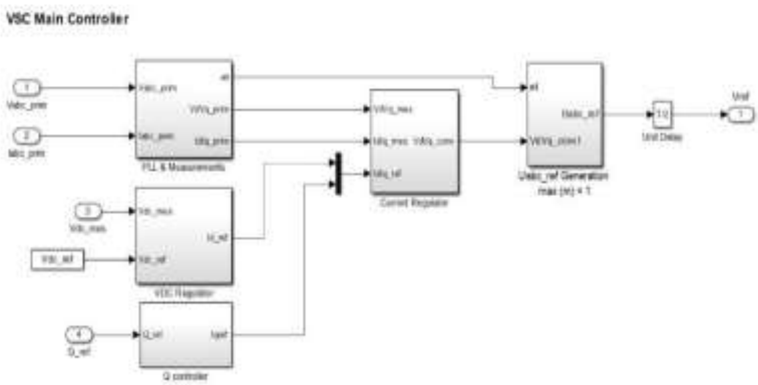

Fig. 10: *Internal Structure of VSI Controlled Block.*

The specifications of the variables used in the design are given below:

- Nominal power(PnomVA) = 100kVA
- Nominal frequency(FnomHz) = 60Hz
- Nominal primary line voltage(Vnom_prim)= 25kV
- Nominal secondary line voltage(Vnom_sec)=260V
- DC bus voltage = 500V
- Ts_control = 1X10^{-4} seconds

Inside the VSI controller the major blocks, as mentioned the block diagram, are:

PLL & ABC-DQ0 conversion

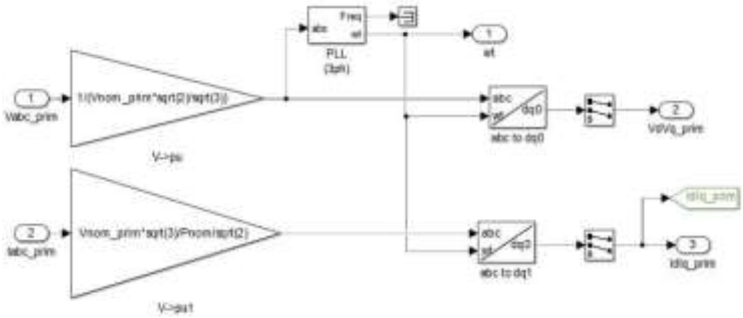

Fig. 11: *PLL & ABC-DQ0 Conversion.*

In this block, as represented above, the three-phase currents and voltages at AC point of coupling in-between step-up transformer and the grid are converted into per-unit values. Here, Three-phase per unit voltages are converted into dq0 components of voltages.

V_{DC} regulator

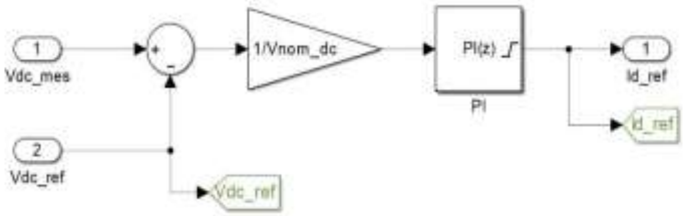

Fig. 12: *DC Voltage Regulator.*

First, the difference is calculated between PCC DC link voltage measured and reference, and per unit of error in voltage is found. Here, Vnom_dc = 500V. PI controller is then applied to the error to get $I_{d,ref}$ current. The selected k_p and k_i are as follows:
Kp_VDCreg = 7, Ki_VDCreg = 800

Reactive power controller

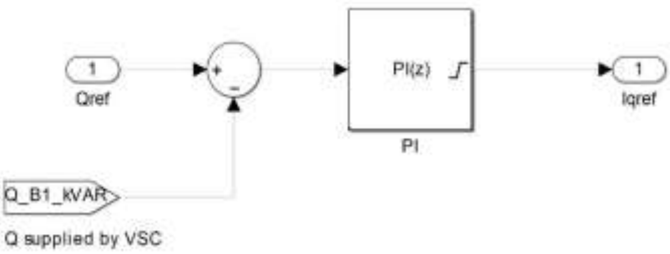

Fig. 13. *Reactive Power Controller.*

Q controller is simply designed by applying a PI controller on the error between the reference reactive power (which can be set in between the range of -100kVAR (lag) to +100kVAR (lead)).

As the loads are generally inductive loads, thus, we need to keep the VSI to generate reactive power, and we set total load reactive power as a reference to this controller. The selected k_p and k_i are selected based on trial and error process, given as follows:
Kp_VDCreg = -(1/100), Ki_VDCreg = 1/1000000000000

Current regulator

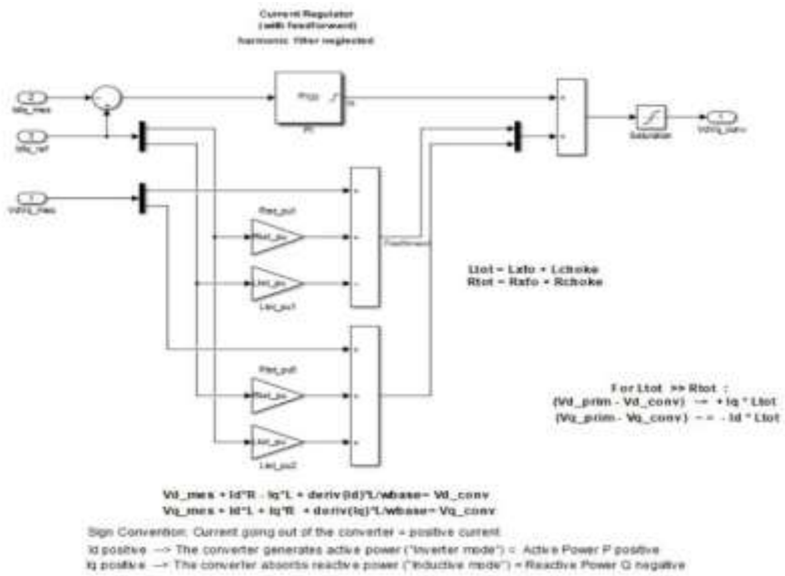

Fig. 14: *Current Regulator.*

The current controller is the main component, to convert reference voltages, with respect to which the VSI must work. As discussed in the block diagram and controller equation derivation, the design is made. Parameters are selected as K_p = 0.3, K_I= 20. Total transformer leakage impedance (in pu) is (Rxfo = 0.002, Lxfo = 0.06), and Choke impedance is (Rc = 2mΩ, Lc=250µH).

DQ0-ABC conversion & rectification of errors in phase angles

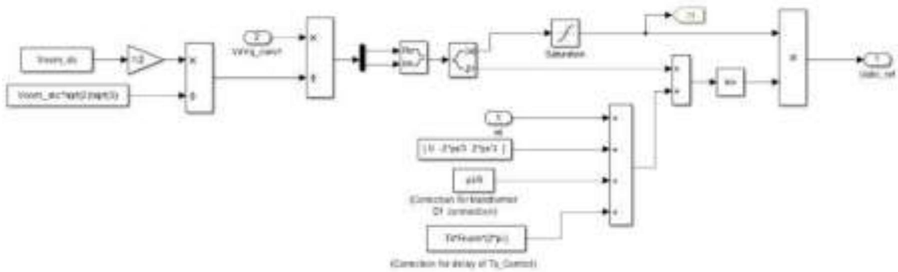

Fig. 15: *DQ0-ABC Conversion along with Error Correction.*

V_{dq} calculated in the current controller is converted into per-unit values. Phase angle delays to the delta type transformers and controller delays are added to the phase angle of the three-phase voltages at 0^o,-120^o, +120^o, to remove the error. $U_{abc,ref}$ is the final three-phase reference voltages. $U_{abc,ref}$ is now fed to the (2 or 3 level)PWM generator.

SIMULATION, RESULTS, AND ANALYSIS[2,5,6]

We have 5 objectives of the proposed project that are needed to be satisfied by the proposed design, which are:

Objective 1 Independent Active Power Control of VSI for the Given Load Switching Sequence

We have used a 2-level detailed model of VSI, and set Q_{ref} equal to the reactive power of load, to verify whether the active power produced by the VSI remains constant even for sudden changes in loads or not.

Case 1 If P_{ref} = 100kW to the boost converter

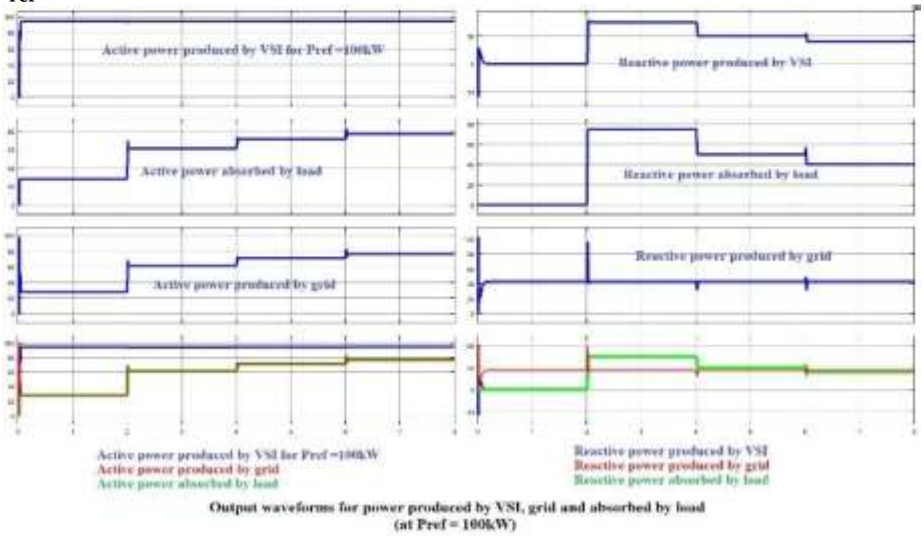

Fig. 16: *Output Waveforms for Power Produced by VSI, Grid and Absorbed by the Load (P_{ref} = 100kW).*

As we can see from the scope, even with the load changes, (changes in active power, and reactive power) inverter active power remains almost constant at 94.5kW.

Case 2 If P_{ref} = 75kW to the boost converter

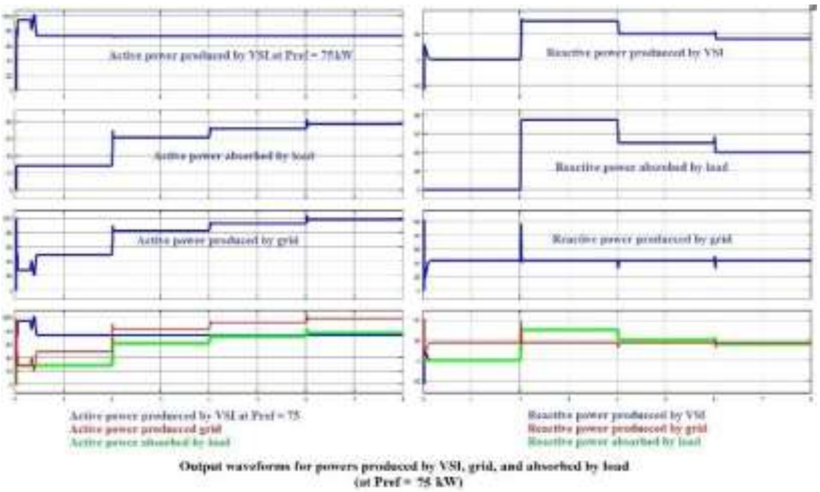

Fig. 17: *Output Waveforms for Power Produced by VSI, Grid and Absorbed by the Load (P_{ref} = 75kW)*

As we can see from the scope, even with the load changes, (changes in active power, and reactive power) inverter active power remains constant at 73kW.

From the above observations, we can say that we can independently control active power, without affecting reactive power. Thus, our design satisfies the objective independent active power control of VSI for the given load switching sequence.

Objective 2 Independent Reactive Power Control of VSI for the Given Load Switching Sequence

For the same 2-level detailed model of VSI, we set P_{ref} = 100kW.

Case 1 If Q_{ref} = 90kVAR to the VSI

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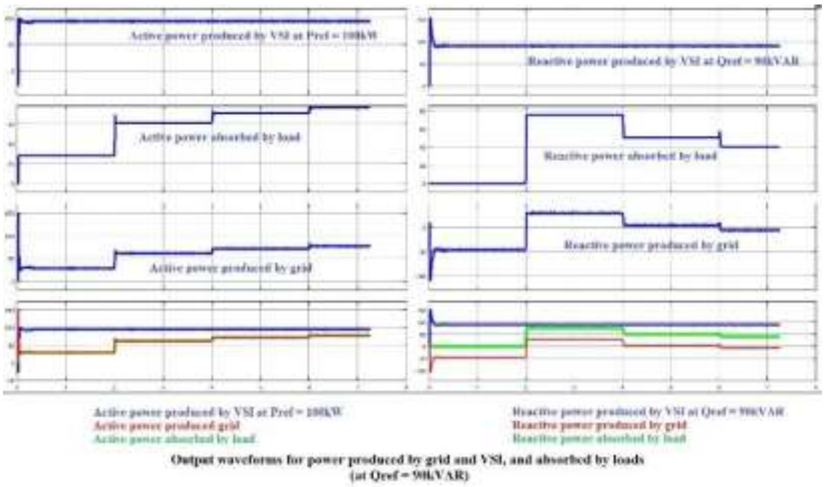

Fig. 18: *Output Waveforms for Power Produced by VSI, Grid and Absorbed by the Load (Q_{ref} = 90kVAR).*

We can see that the reactive power produced by the VSI is constant and maintained at almost 90kVAR.

Case 2 If Q_{ref} = 70kVAR to the VSI

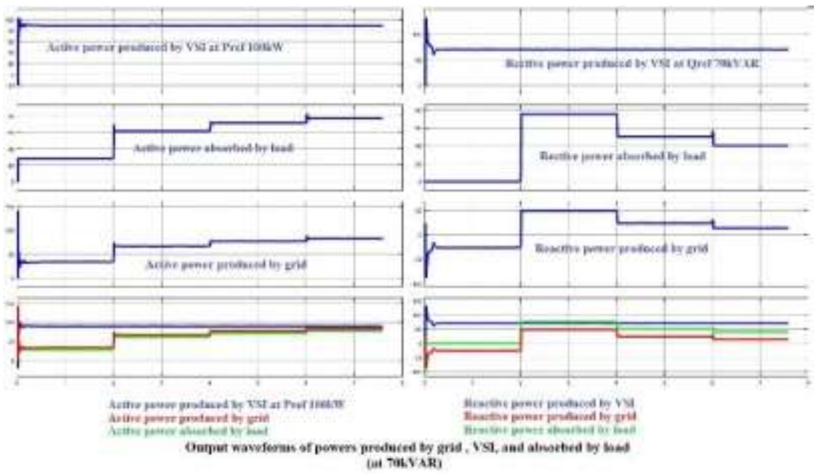

Fig. 19: *Output Waveforms for Power Produced by VSI, Grid and Absorbed by the Load (Q_{ref} = 70kVAR)*

We can see that the reactive power produced by the VSI is constant and maintained at almost 70kVAR.

From the above observations, we can say that we can independently control reactive power, without affecting active power produced by the VSI. Thus, our design satisfies the objective of independent active power control of VSI for the given load switching sequence.

Objective 3 Maintaining Constant Reactive Power Supplied by the Grid Even Though Load Fluctuates

For the same 2-level detailed model of VSI, we have set P_{ref} = 100kW and set Q_{ref} equal to the reactive power required by the load, to verify whether the reactive power supplied by the grid is constant or not.

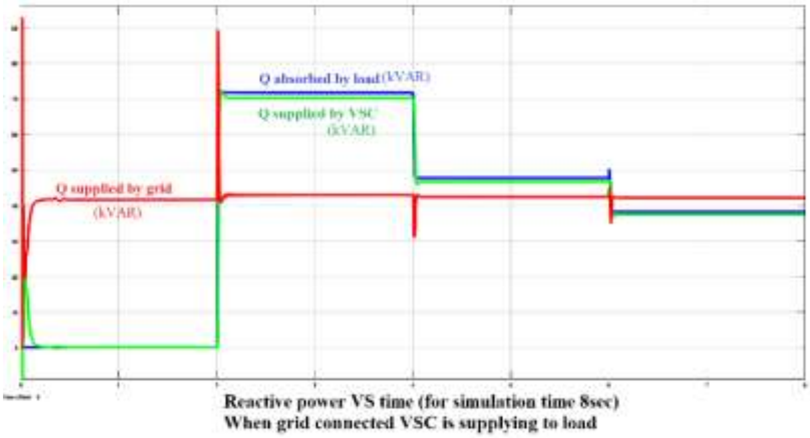

Fig. 20: *Output Waveforms for Power Produced by VSI, Grid and Absorbed by the Load (Q_{ref} = Q_{load}).*

From the above waveform, it can be proved that the VSI can handle all the loads effectively and instantaneously, thus, reactive power produced by the grid system is constant for the whole simulation time of 8 seconds.

Objective 4 Maintaining Voltage Stability Even Though Load Changes

In this case, we have used the average model of the boost converter and VSI, so as to get a smoother and faster response. We have reduced the simulation time from 8 seconds to 1 second, and the timing sequence is changed accordingly. Let P_{ref} = 100kW for boost converter, we design two circuits:

Case 1 When only grid is supplying the load, the design for the same loads and timing sequence

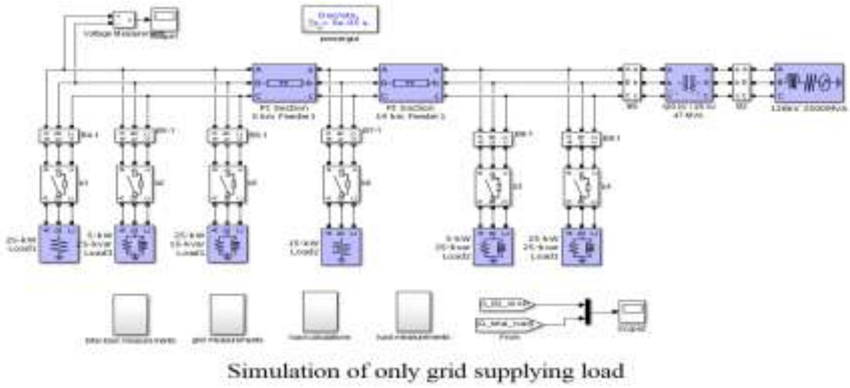

Fig. 21: *Simulation Design of Grid Connected Load.*

When the only the grid is supplying the load, reactive powers of grid and load are given as:

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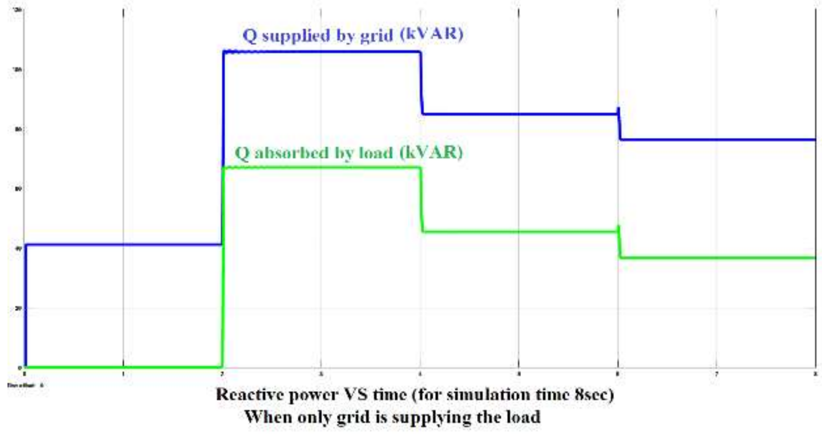

Fig. 22: *Output Waveforms for Power Produced by Grid to the Load (VSI not Connected).*

As, we can see the reactive power by grid changes with the load fluctuations, and if we check the voltage variation with reactive power fluctuations, we can see that:

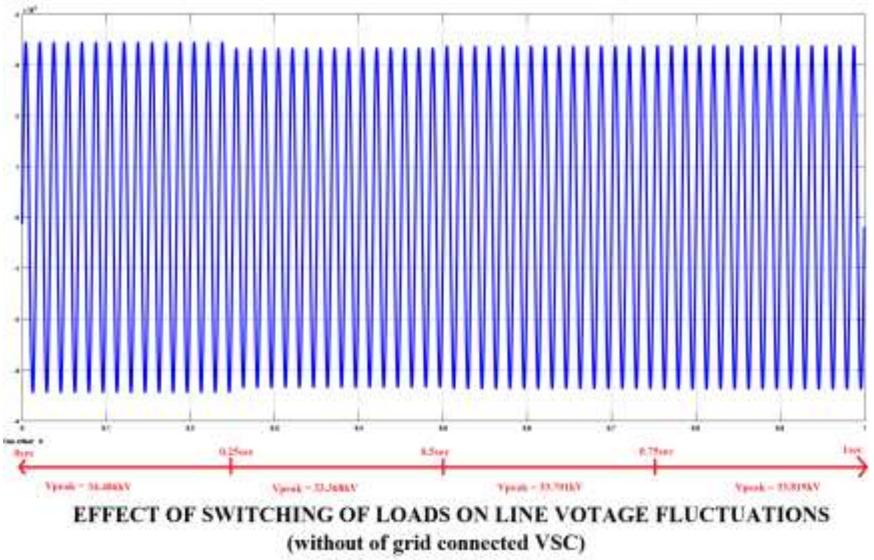

Fig. 23: *Effect of Load Fluctuations on Line Voltage (without VSI)*

As seen from the voltage waveform, we can say that due to load reactive power fluctuations, the amplitude of the load terminal voltage fluctuates. As the reactive power required by the load increases, the peak/amplitude of voltage decreases (at 0.2 seconds). Similarly, as the load reactive decreases the peak/ amplitude of voltage increases (at 0.5 and 0.75 seconds).

Case 2 When both grid and VSI (where Q_{ref} = Q_{load}) are supplying the load, the design for the same loads and timing sequence

As, compared with the scope of case 1, the reactive power supplied by the grid system in average remains constant 43kVAR, as the VSI is supplying the load.

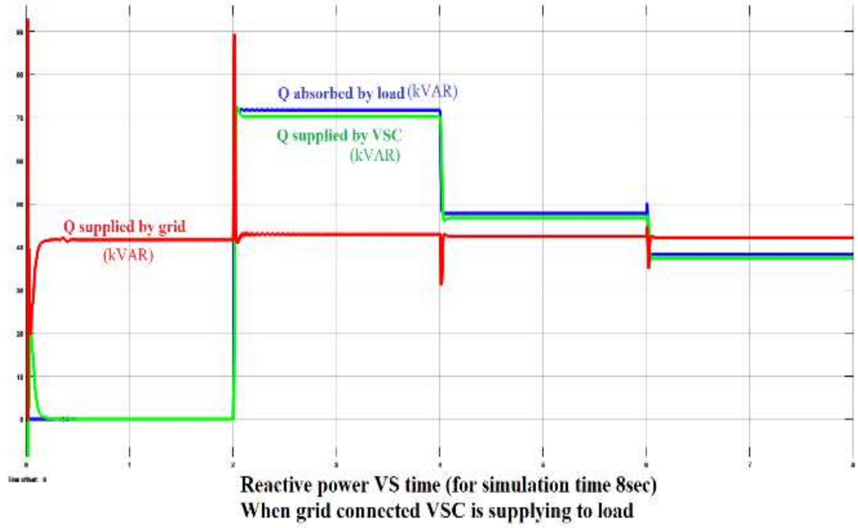

Fig. 24: *Output Waveforms for Power Produced by VSI, Grid and Absorbed by the Load ($Q_{ref} = Q_{load}$).*

If we check the effect on terminal voltage:

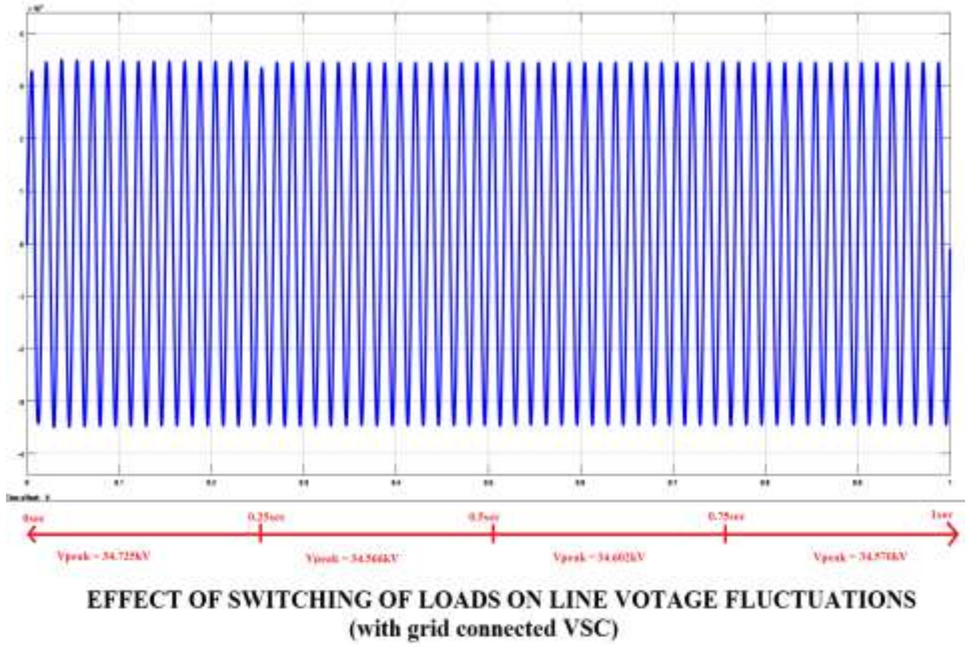

Fig. 25: *Effect of Load Fluctuations on Line Voltage (with VSI).*

If we compare this voltage waveform, with the waveform of case 1, the amplitude of voltage remains nearly constant for the whole simulation time. Thus the simulation satisfies this objective.

Objective 5 Reducing THD% of the Output Voltage of VSI Within I.E.E.E Standards

Case 1 The Three-phase voltages of output of the 2-level VSI

By using the LC filter with 2-level PWM, most of the harmonics can be removed. The voltage wave shape is made more sinusoidal, hence higher-order frequency is eliminated, as shown below:

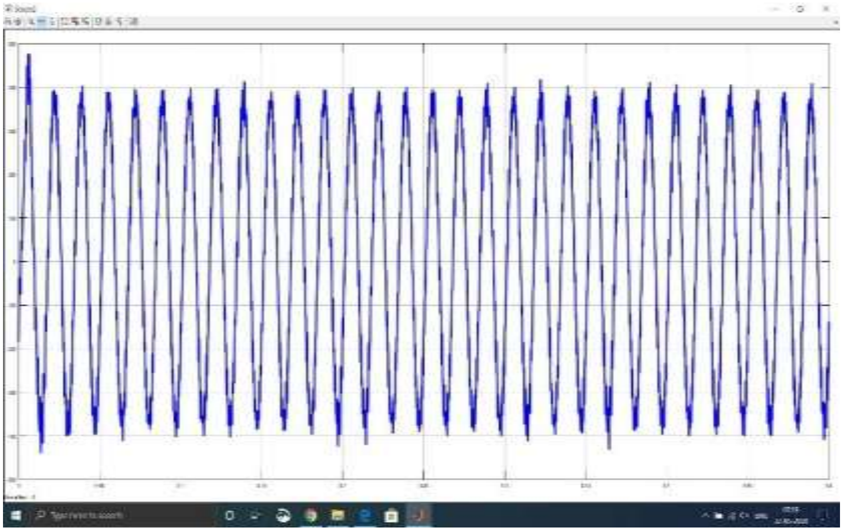

Fig. 26: Voltage Waveform of 2-Level Inverter with Filter.

As seen in the simulation, the FFT analysis is done on the output voltages after applying filters as seen below. The total harmonic distortion observed is now reduced to 8.92%, which is less. Harmonics can be further much reduced by using higher-level PWM technique. The following analysis was made for a 3-level IGBT bridge and using 3-level PWM generator.

Case 2 The Three-phase voltages of output of the 3-level VSI

By using the LC filter with 3-level PWM, most of the harmonics can be removed, as shown below:

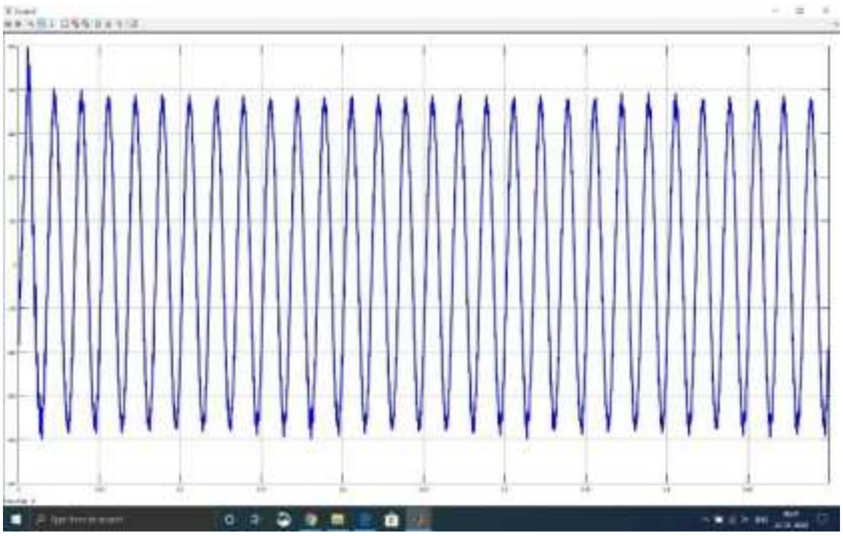

Fig. 27: Voltage Waveform of 3-Level Inverter with Filter

As seen in the simulation, the FFT analysis is done on the output voltages after applying filters as seen below. The total harmonic distortion observed is now reduced to 4.54%, which is even less.

According to government norms, 5% is the maximum limit for total harmonic distortion. As PV systems are producing THD <5%, this design is used to build the prototype.

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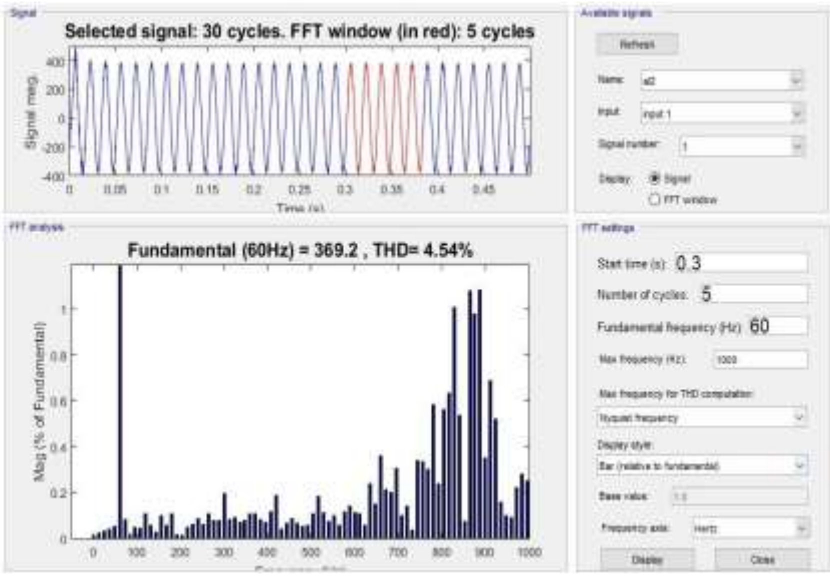

Fig. 28: *THD% of Output Voltage of 3-Level Inverter with Filter.*

CONCLUSIONS

Grid-connected PV systems are being installed more and more, and the total installed capacity in our country is increasing exponentially. VSI has become one of the major equipment devices in the field of power electronics as they can be used for their emerging new features. In our project, we have designed a circuit proving for one such feature, which is the generation of reactive power independently, keeping the active power generation constant. Simulation results of our proposed topology are shown and proof for its robust performance has been successfully shown by satisfying the objectives.

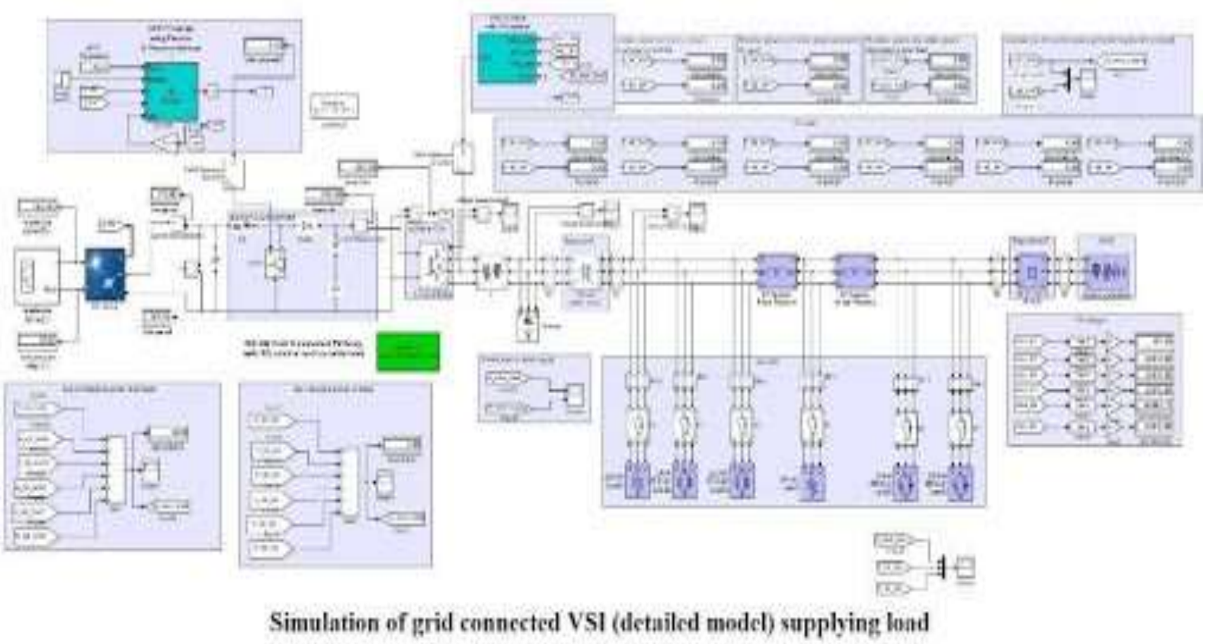

Fig. 29: *Complete Simulation Model of Proposed Work.*

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