# ENHANCING POWER QUALITY ON SOLAR GRID CONNECTED SYSTEM USING MULTI-LEVEL INVERTER AND DYNAMIC VOLTAGE RESTORER

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***Abstract:*** *This paper presents the effectiveness of a Dynamic Voltage Restorer (DVR), for improving voltage quality in Photovoltaic (PV) fed grid connected system. at three phase fault conditions. The innovation here is that the DVR acts as voltage controller with the main aim of protecting the load voltage during short circuit fault condition in photovoltaic fed grid connected system. The DVR is a power electronic based device that provides three-phase controllable voltage source, whose voltage vector (magnitude and angle) adds with the load voltage during fault condition, to restore the load voltage. The DVR can restore the load voltage within few milliseconds. In this paper, three phase fault (like L-G, LL-G and LLL-G) is introduced in the grid connected system and DVR is simulated to compensate the load voltage during fault period. Validation of proposed control method and DVR model is done through simulations by using MATLAB/SIMULINK. The obtained results shows the performance and the advantages of dynamic voltage restorer used in grid connected power system.*

***Key words:*** *Photovoltaic, multi- level inverter, three phase fault, power quality, Total Harmonic Distortion (THD)*

## 1. Introduction

Nowadays, the need for clean power generation is being increased more and more worldwide [1]. Environmental issues like global warming caused by greenhouse gas emissions, air pollution, acid precipitation, ozone depletion, and possible radioactive substance emissions have been generated by conventional energy sources. To overcome these problems, one of the possible solutions is renewable energy supplies [2]. Among these, the solar photovoltaic (PV) source is called as one of the leading and popular potential sources of electricity generation for the 21st century [3]. This is due to several reasons like it utilizes an abundant energy source (the sun), has no emissions, can be easily integrated in buildings, and the cost of the in-stalled kilowatt peak is decreasing and more affordable [4]. The worldwide-installed PV power capacity shows a nearly exponential increase, which is mostly dominated by grid-connected applications [5].

Power quality is considered as a very important issue due to its impact on electricity suppliers, equipment manufactures and electric utilities. Power quality is defined as the variation of voltage, current and frequency in a power system [6]. It refers to a wide variety of electromagnetic phenomena that characterize the voltage and current at a given time and at a given location in the power system. An important issue among all power quality problems is the three phase fault.

Generally, faults occur in a power system due to various reasons like insulation failure, flashover, physical damage or human error. These faults may be either three phase in nature involving all three phases in a symmetrical manner, or may be asymmetrical where usually only one or two phases may be involved [7]. Various types of unsymmetrical faults that occur in power system are: Single line to ground (LG) fault, Line-to-Line Fault (L-L) and Double line –to-ground fault (LL-G).

In this work, efforts are taken to introduce the multilevel inverter for grid connected system to enhance the power quality. And also the effects of three phase fault LLL-G) on the grid connected system are presented. Dynamic voltage restorer has been introduced to compensate the voltage in the system during the occurrence of fault. The simulation is done using MATLAB/SIMULINK and the results are in line with the theoretical values.

## 2. Circuit Description

The grid connected photovoltaic system with multi-level inverter is shown in the Fig. 1. In this system, when fault is introduced, DVR detects and injects required compensated voltage with the use of series injection transformer.

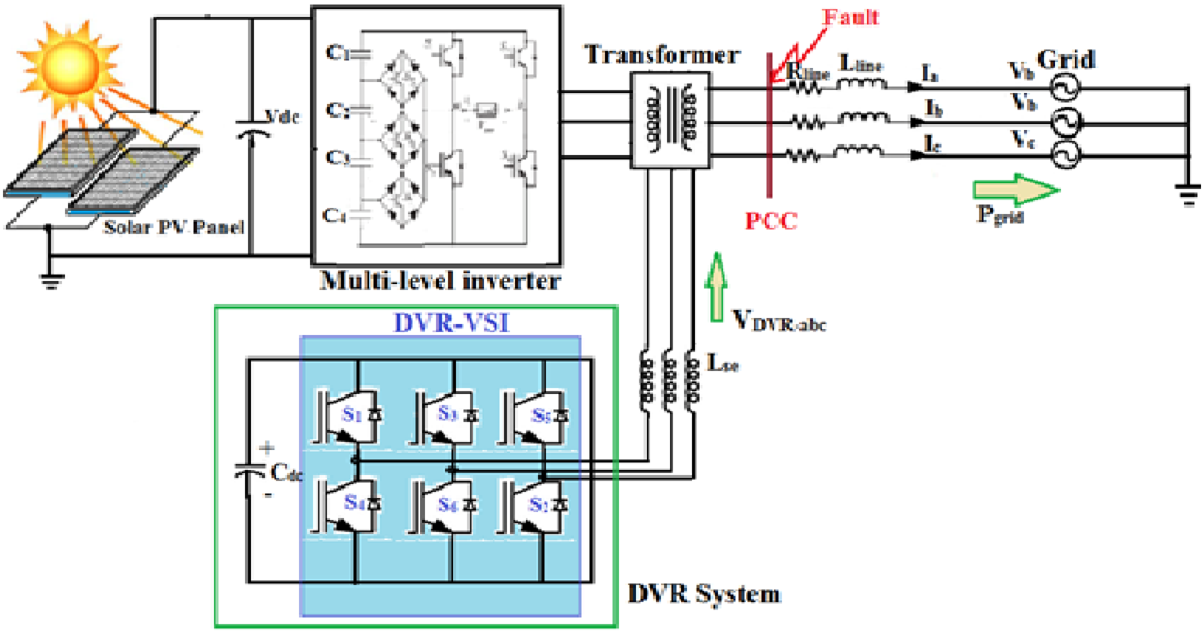



Fig.1. Grid connected PV system with multi-level inverter and DVR

A grid connected power system is a very complex system. It is more important to remove any system faults or abnormalities so that the rest of the power distribution network is not interrupted or damaged [8]. When a sudden fault or an abnormality occurs somewhere in a power distribution network, the voltage is suffered throughout the power system. Among various power quality issues, the majority of abnormalities are caused by voltage sag or a voltage swell [9].

In symmetric three phase fault, all the three phases of voltage waveforms collapse and the current magnitude becomes very high during fault period. Among different types of fault, LLLG fault is most severe. This type of fault on the grid side will hardly affect the power system.

Dynamic voltage restorer is a static var device that is used in a variety of transmission and distribution systems [10]. It is a series compensation device, which protects sensitive electric load from power quality problems such as voltage sags, swells, unbalance and distortion through power electronic controllers. These controllers uses Voltage Source Inverters (VSI). Generally, DVRs have been applied to protect critical loads in utilities, semiconductor and food processing [11]. The various units of DVR are explained as follows.

The first major unit is energy storage unit. The purpose of the energy storage unit is to supply the required energy to the VSI which will be converted to alternating quantity and fed to the injection transformer. Batteries are most commonly used and the capacity of the battery determines the duration that to be compensated by the DVR [12]. The next important unit is injection transformer. The DVR transfer the voltage to the distribution network which is required for the compensation from DC side of the inverter through the injection transformer. In this work, three single phase transformers are connected instead of a single three phase injection transformer [13]. Each transformer is connected in series with each phase of the distribution feeder to couple the VSI (at low voltage level) to the higher distribution level

[14]. The transformer also helps in isolating the line from the DVR system.

Structure of multi-level inverter has been developed to overcome shortcomings in solid-state switching device ratings so that they can be applied to high-voltage electrical systems. The multilevel voltage source inverters allow the switching devices to attain high voltages with low harmonics without using any transformer [15].

The main function of the multi-level inverter is to synthesize a desired AC voltage from several levels of DC voltages. Multi-level inverters have several advantages over conventional inverters like reducing switching losses, producing output voltage with very less harmonics and reduced dv/dt stress across the switching devices [16].

In this work, three single phase transformers are connected instead of a single three phase injection transformer. Each transformer is connected in series with each phase of the distribution feeder to couple with the three phase grid.

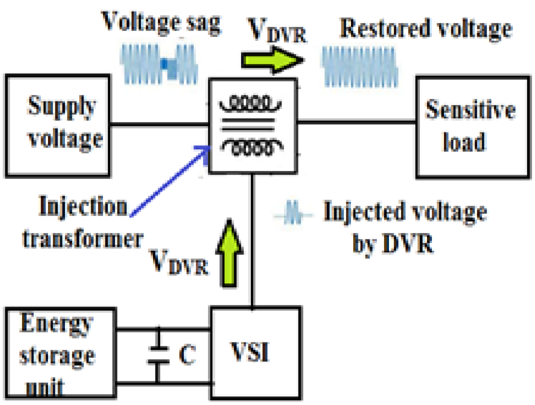



Fig.2. Equivalent circuit of DVR

As per the equivalent circuit of the DVR as shown in the Fig.2 , when the source voltage is reduced or increased, DVR injects the required amount of voltage through the series injection transformer so that the desired load voltage magnitude $V_L$ can be maintained at the nominal value [17].

The voltage injected by DVR can be expressed as,

$$V_{inj} = V_L + V_S \tag{1}$$

Where $V_L$ is the magnitude of desired load voltage and $V_S$ is the source voltage during sags and swells condition. The load current $I_L$ is calculated by,

$$I_L = \frac{P_L + jQ_L}{V_L} \tag{2}$$

In this proposed method, DVR is connected in between the supply and the load. The main function of the DVR is to compensate the load side voltage when sudden change in voltage occurs.

## 3. Multi -level inverter for grid connected system

In this model, three phase grid is fed by multi-level inverter. Generally multi-level inverter is used to achieve high power from medium voltage source. The main feature is the lower harmonic distortion content due to the multiple voltage levels at the output. Therefore it can eliminate the use of filter circuits. The multilevel inverter can operate at both fundamental switching frequency and higher switching frequency.

The simulation circuit of multi-level inverter (thirteen level inverter) is shown in Fig. 3. With the use of sine Pulse Width Modulation (PWM) scheme, Total Harmonic Distortion (THD) value can be reduced without any additional control technique. This type of inverter can eliminate the choice of large filter inductor and capacitance. To reduce the THD value, the thirteen level MLI is simulated with sine PWM technique. It uses nine switches to produce the required levels at the output voltage.

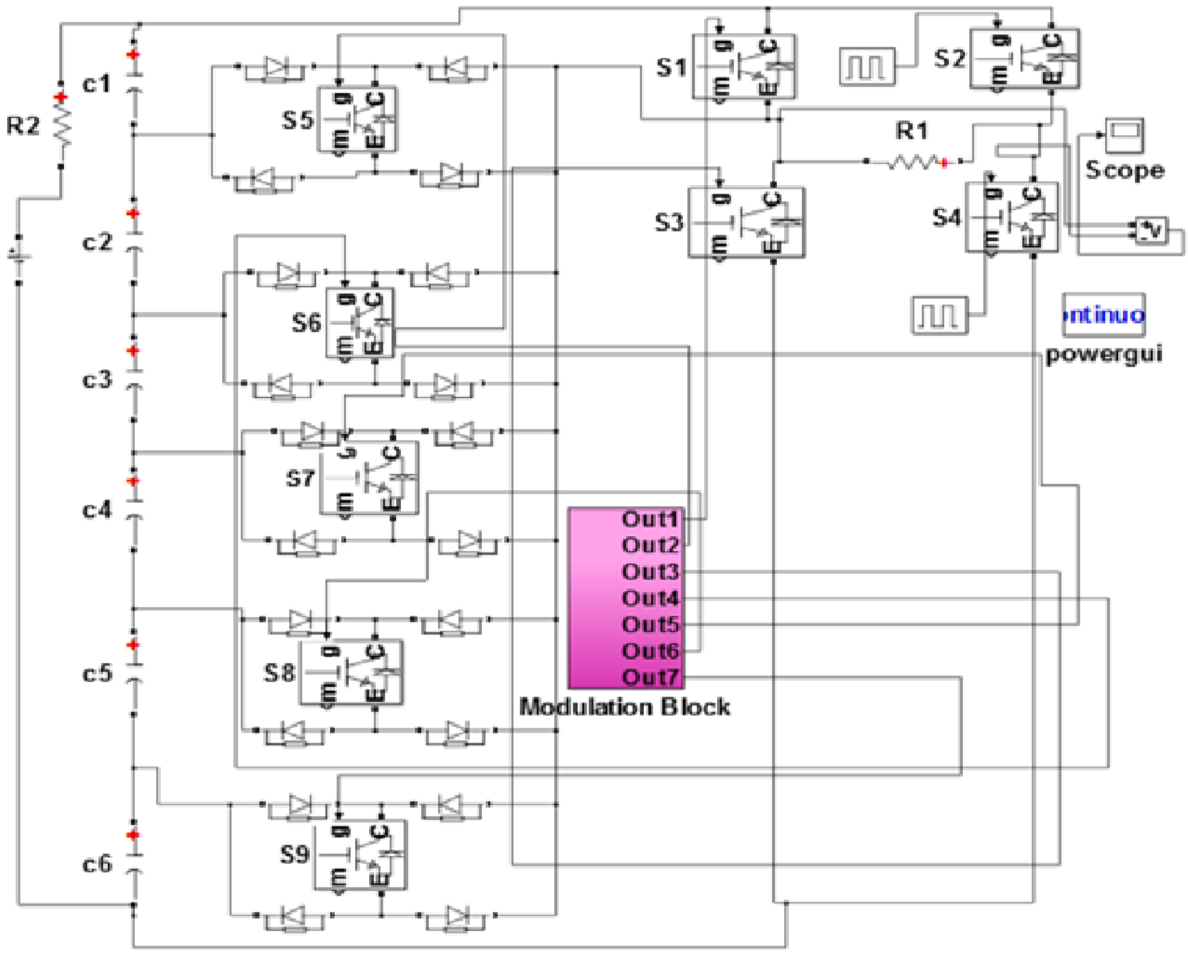
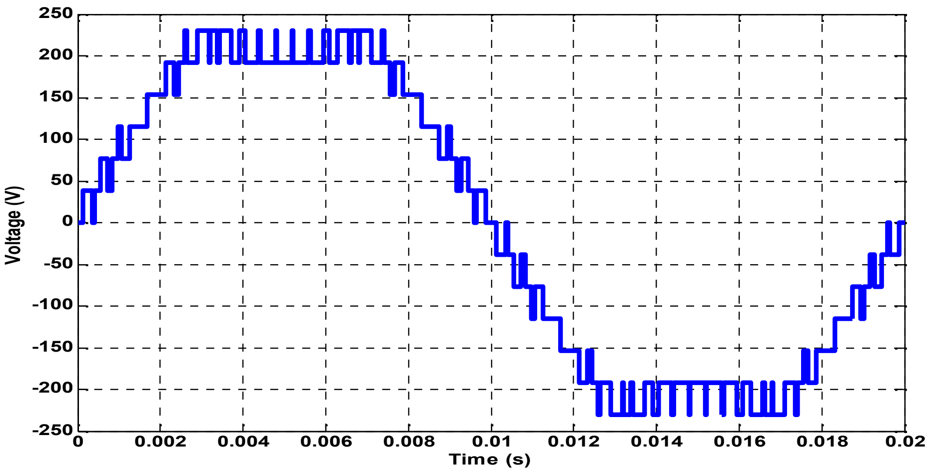
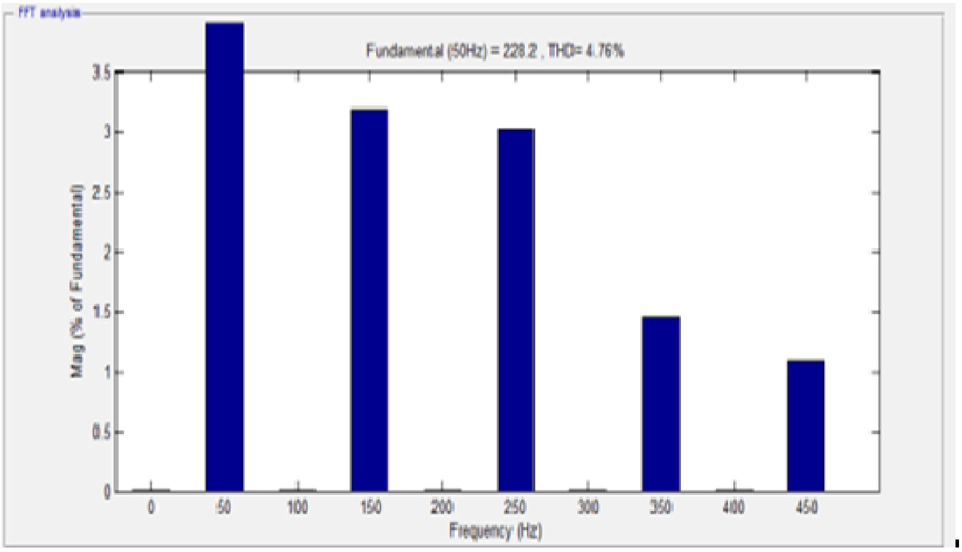



Fig.3.Thirteen level inverter with modulation scheme.




**(a)**




(b)

Fig.4. Performance of thirteen level inverter (a) Output voltage of inverter (b) Harmonic spectrum of output voltage

The output voltage of thirteen level inverter is shown in the Fig.4.a. From the Fig.4.b, it is observed that the percentage of THD is 4.78 which are relatively very low when compared with other levels of inverter.

## 4. Multi carrier modulation strategy

In this work a sine PWM modulation technique is introduced to generate the PWM switching signals. For thirteen level inverter, single reference signal ($V_{ref}$) is compared with a high frequency carrier signals ($V_{carrier}$). The number of carrier signals is more to produce the PWM signal. The reference signals had the same frequency and amplitude are in phase with an offset value that is equivalent to the amplitude of the carrier signal. The control circuit used to generate the driving pulses is shown in Fig.5.

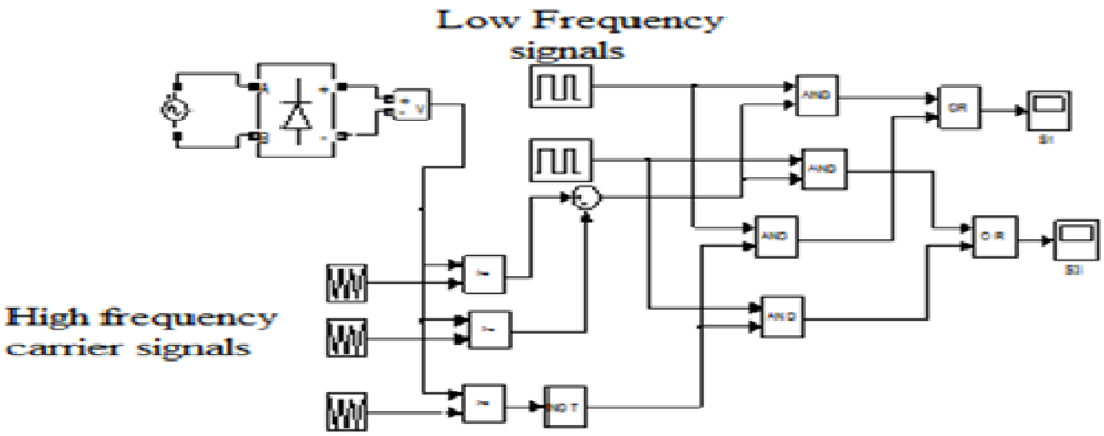



Fig.5. Circuit for generating PWM signal

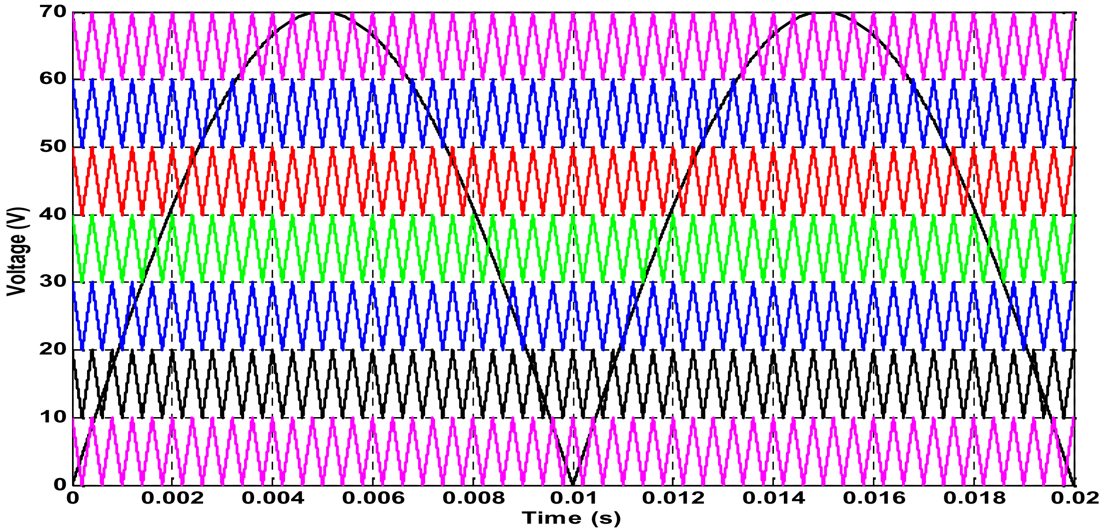



Fig.6. Generated PWM signal

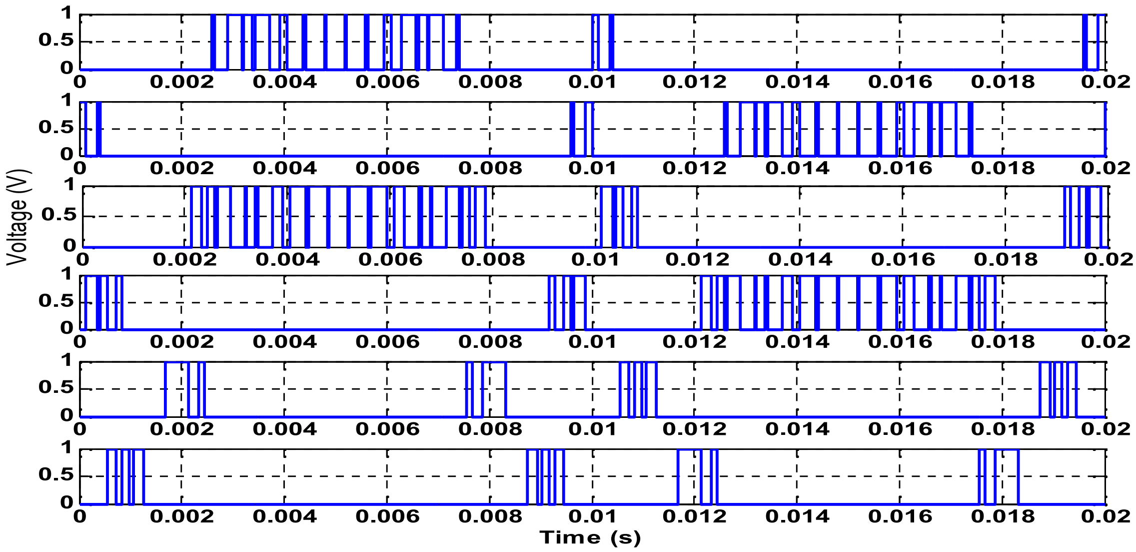



Fig.7. Control signals of multi-level inverter

In this multi-level inverter configuration, one leg of the inverter is operated at a high switching rate that is equivalent to the frequency of the carrier signal, while the other leg is operated at the rate of the fundamental frequency (i.e. 50 Hz). Switches $S_5$, and $S_9$ are operated at the rate of high frequency (10 kHz) carrier signal. Initially, the thirteen level inverter is simulated with sine PWM modulation technique and it is presented in Fig.6.To produce the PWM signal, seven carrier signals and single reference signal are compared as shown in Fig.7. Here the frequency of carrier signal is considered as 10 kHz.

Table 1. THD value of various levels of inverter

| Level of inverter | % of THD without modulation | % of THD with modulation |
|---|---|---|
| 7 | 21.86 | 13.72 |
| 9 | 18.32 | 10.21 |
| 11 | 16.24 | 9.42 |
| 13 | 15.10 | 4.76 |

Table 1. shows the THD value of various levels of inverter with and without modulation technique. It has been observed that, as levels of multi-level inverter is increased; its corresponding THD value can be reduced.

## 5. Three Phase Fault Analysis

### 5.1. Fault analysis without DVR

To analyze an effect of three phase fault in grid connected PV system, three phase thirteen level inverter is connected to grid via transformer using MATLAB/SIMULINK.

The grid connected PV system without DVR under LLLG fault condition is shown in Fig.8. The three phase fault is generated on the grid side. The fault duration is set for 0.1 second only. It starts from 0.15 and ends at 0.25 second. During the fault period, the grid side voltage and current waveforms and inverter side voltage and current waveforms are taken and observed. To validate the performance of grid connected systems, FFT analysis is also done and THD values are observed. In this work, the three phase multi-level inverter is simulated and the output is connected with three phase grid with the use of coupling transformer.

The Fig.9. shows the voltage and current waveforms at grid side during LLLG fault. It is observed that system maintains the zero value of reactive power at grid side during no fault period and during fault period it shoots up to 220 VAR. This value of reactive power is very high when compared with other three types of faults like LL fault, LG fault, and LLG fault. During this LLLG fault period, the active power decreases up to 30 W. The voltage and current waveforms of grid as well as inverter is presented in Fig.10.

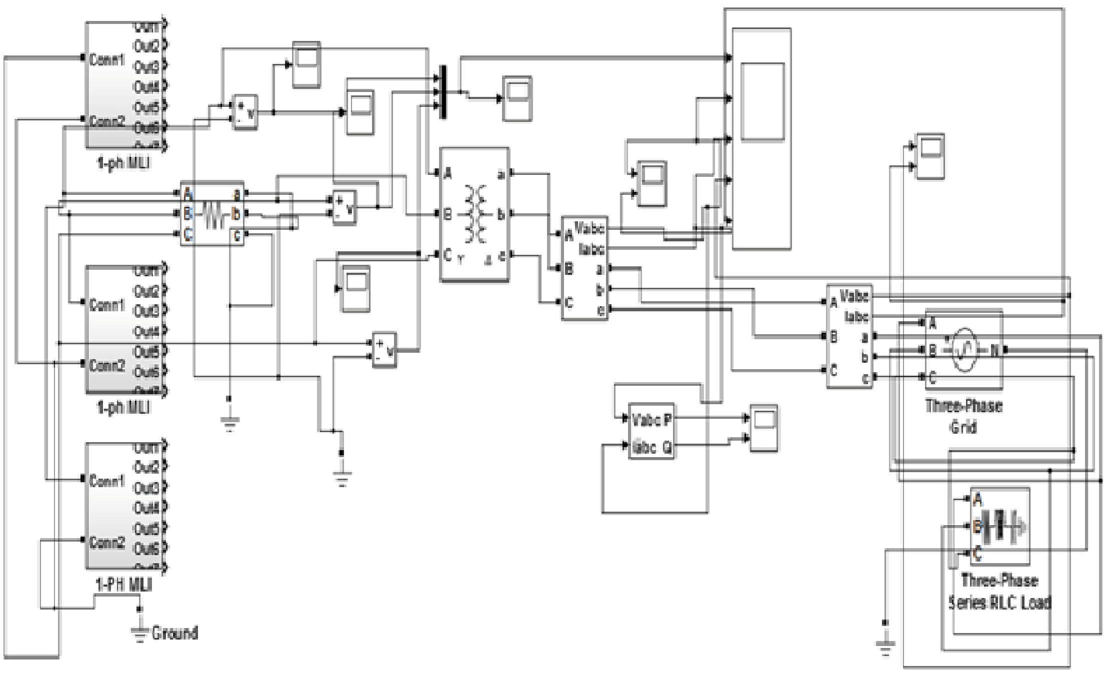



Fig.8. Multi-level inverter connected with grid

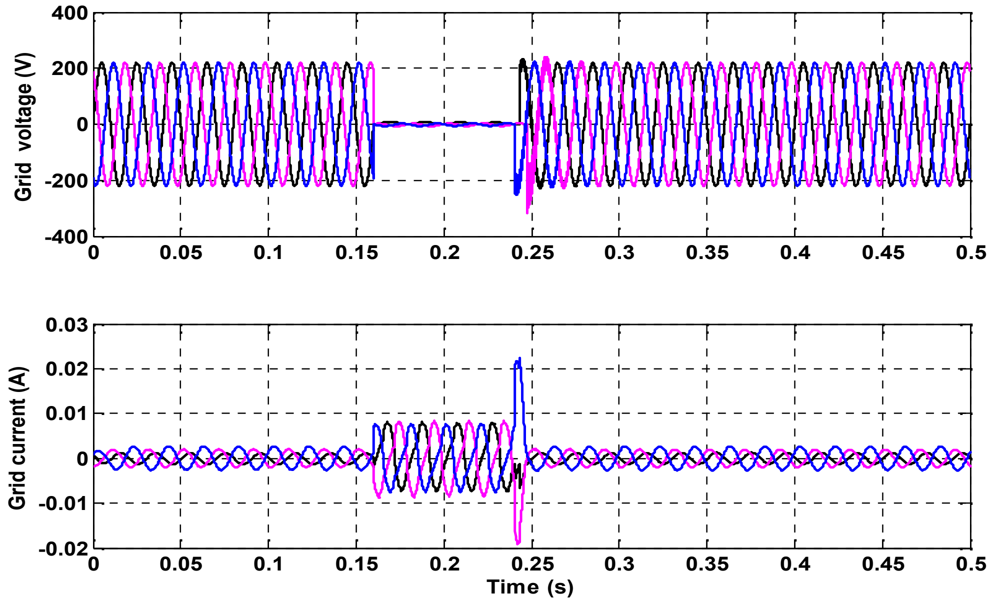



Fig.9. Grid voltage and current waveforms under LLLG fault

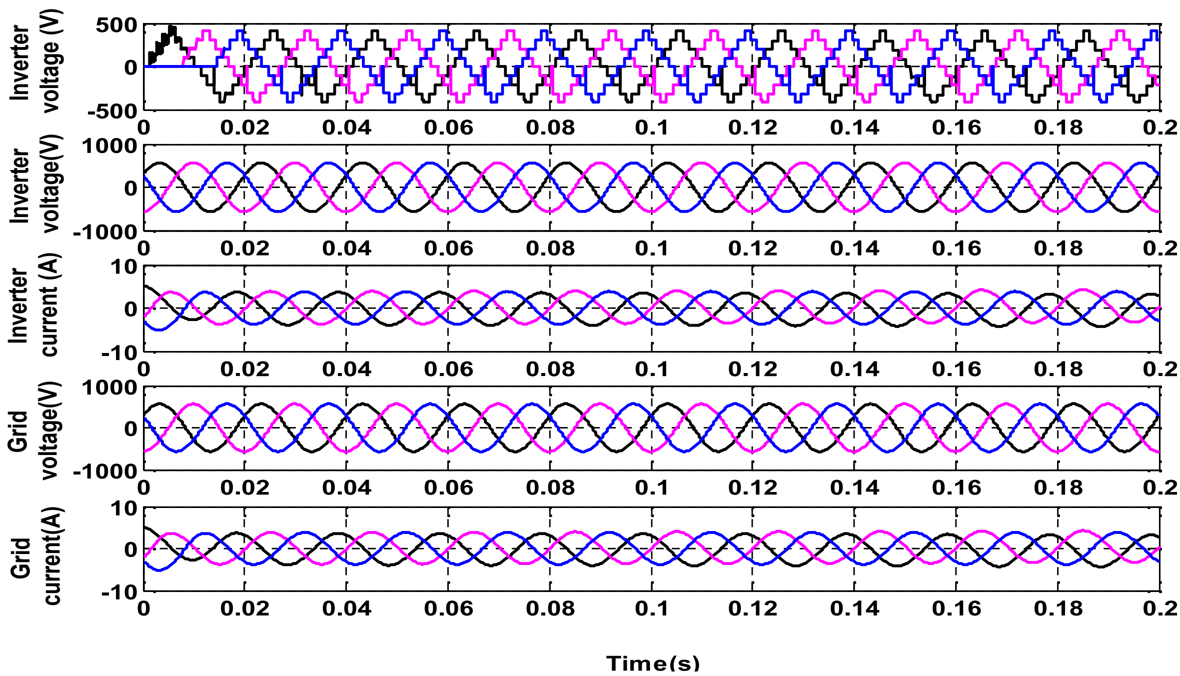



Fig.10.Output waveforms of grid connected system under no fault condition

At inverter side, the system maintains the zero values of reactive power during no fault period and during fault period it is changed to 200VAR. This value of reactive power is very high when compared with other three types of faults.

### 5.2. Fault analysis with DVR.

In this proposed method, DVR is connected in between the supply and the load as shown in the Fig.11. The main function of the DVR is to compensate the load side voltage when fault is occurred in the system. In this model, three phase grid is fed by multi- level inverter. As sudden fault is detected in the system, the actual supply voltage is compared with the reference voltage level; the error signals are generated to trigger the inverter switches. Fault is introduced at the grid side and simulation results are obtained.

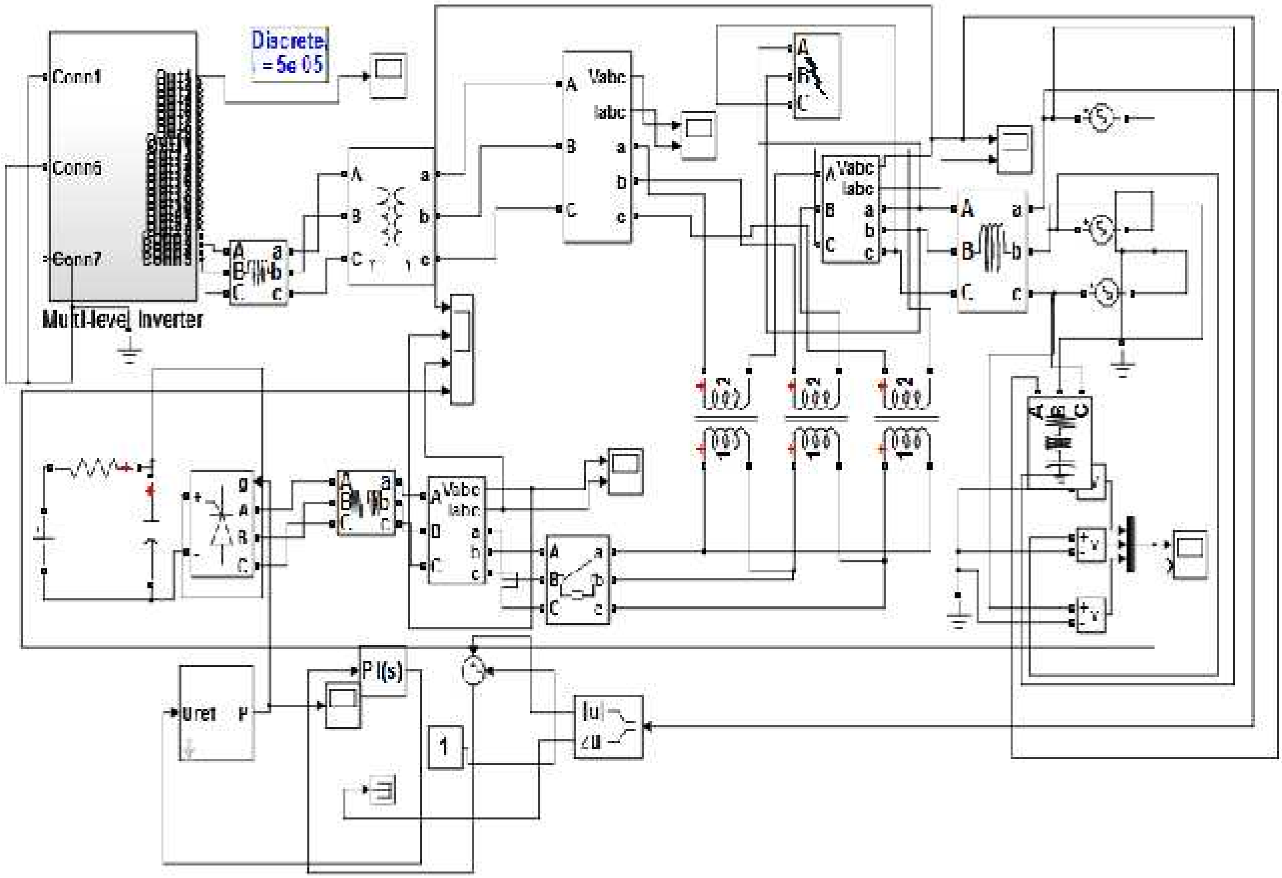



Fig.11. DVR test model under three phase fault condition

In this section, the various results obtained by simulation are analysed and discussed. The system has been examined under three phase to ground fault condition. The three phase fault (LLL-G) is considered as major fault on the power system. In this grid connected system, a symmetrical fault (i.e) three phase to ground on the grid side is considered for the fault analysis.

The DVR test model is verified under three phase fault condition. In this case 100% three-phase voltage sag occurring at the utility grid in the duration of 0.15 second to 0.25 second as shown in Fig 12.a. The Fig 12.b and Fig 12.c shows the voltage injected by the DVR and the corresponding load voltage with compensation.

From the simulation results, the load voltage is maintained at the nominal value with the use of the DVR. As fault is introduced in the system, DVR reacts quickly to inject the appropriate voltage component to correct the load voltage.

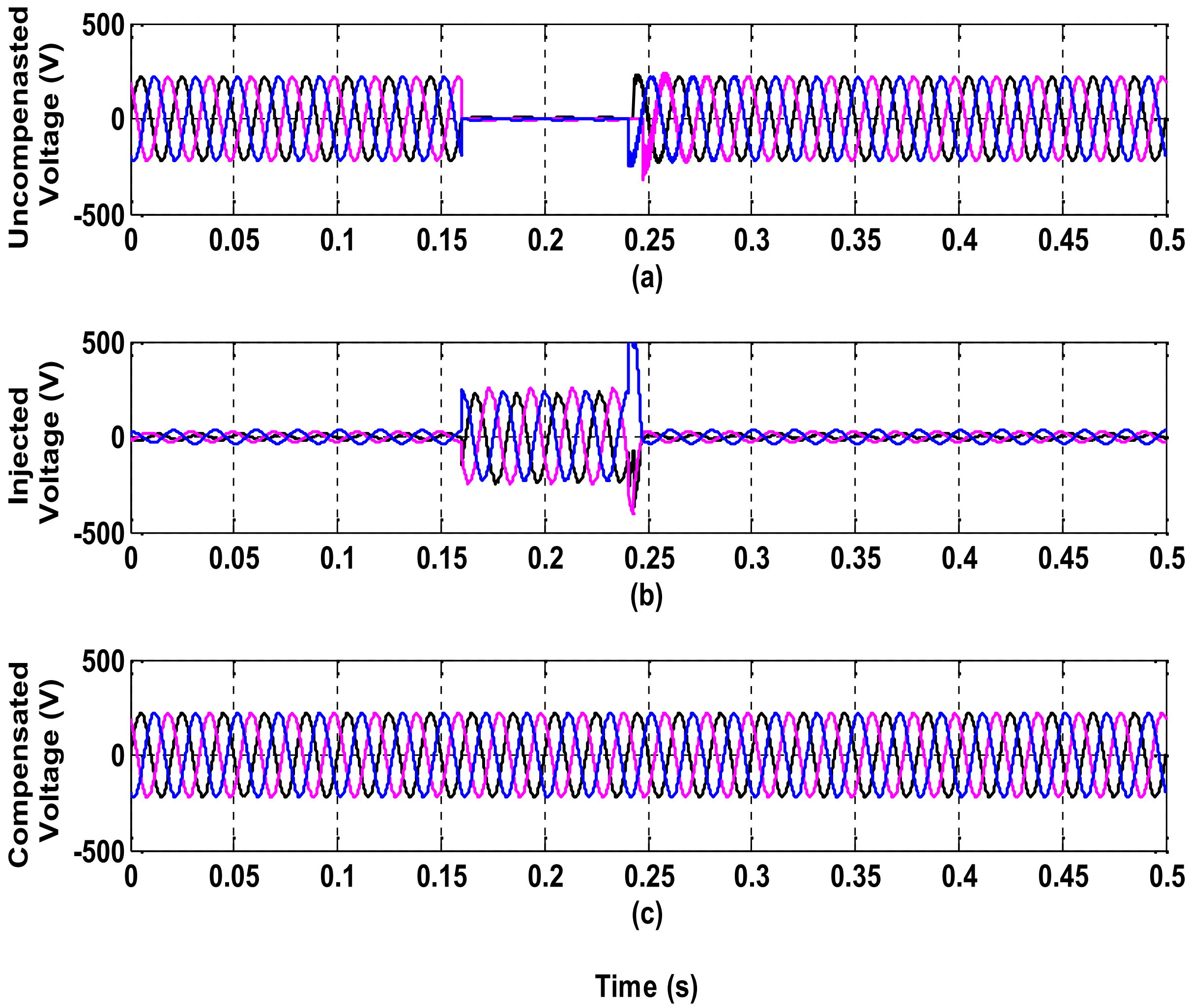



Fig.12. Performance of grid connected system with DVR under LLLG fault (a) uncompensated voltage (b) Injected voltage by DVR (c) Compensated voltage

## 6. Experimental Results and Discussion

The complete hardware setup of multi-level inverter is shown in Fig.13. It consists of PV panel, digital multi meter and multi-level inverter. This prototype model is used to test the output voltage of PV panel. The test readings are taken under open circuit condition is listed in Table 2. The power supply circuit provides the necessary 5V for microcontroller and 12V for driver IC IR2110. In addition with this, 5V supply is also given to trigger the opto coupler of driver IC IR2110.External crystal of 4MHz is used to speed up the operation of PIC microcontroller. A suitable coding is written using MPLAB and the same is burnt on PIC microcontroller chip. At each time instant, the data of the actual sun irradiance obtained from the experiment is recorded. In this model, the sun is assumed to travel from 0 degree (sunrise) to 180 degree (sunset).The test readings are taken from 10.30.A.M to 4.00.P.M. From the Table 2, it is observed that, at noon time high output power have been obtained due to high irradiance from sunlight.

The hardware is implemented using PIC16F84A microcontroller. It generates the gate pulses for respective switches. The experimental result of multi-level inverter is shown in Fig.14. Inverter produces the output voltage when switches are triggered with proper switching interval. The switching pulses are generated by microcontroller.

Fig.13. Setup of the 1211-SUNSTAR solar panel and multi-level inverter

Table 2. Test Readings of solar panel

| Time | Voltage (V) | Current (A) | Power (W) |
|---|---|---|---|
| 10.30AM | 20.5 | 0.344 | 7.052 |
| 11.00AM | 20.2 | 0.343 | 6.928 |
| 11.30AM | 20.0 | 0.391 | 7.820 |
| 12.00PM | 20.1 | 0.420 | 8.442 |
| 12.30PM | 20.2 | 0.421 | 8.504 |
| 1.00 PM | 20.1 | 0.401 | 8.060 |
| 1.30PM | 20.1 | 0.400 | 8.040 |
| 2.00PM | 20.0 | 0.395 | 7.900 |
| 2.30PM | 20.1 | 0.350 | 7.035 |
| 3.00PM | 20.0 | 0.301 | 6.020 |
| 4.00PM | 19.9 | 0.200 | 3.980 |

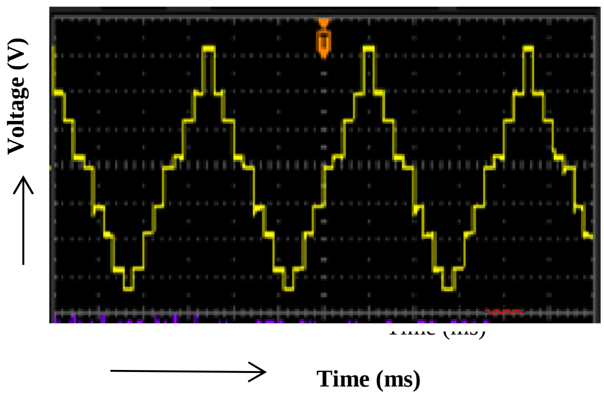



Fig.14. Output voltage of Multi-level inverter

In order to verify the theoretical concept and above simulation results experimentally, a hardware prototype of the complete single phase DVR system was constructed and is shown in Fig.15. It consists of a switch, an inverter circuit, injection transformer, controller circuit, and their power supply circuit. To record the data, Digital Storage Oscilloscope (DS-1022C) is used. The simulations results are validated by real-time testing of the DVR circuit. Here, voltage sag is generated by connecting heavy loads to the DVR circuit. The power supply circuit provides the necessary 5V for microcontroller and 12V for driver IC IR2110. The 5V supply is also given to trigger the opto coupler of driver IC IR2110. Coding for generations of pulses is derived from the modes of operation. A suitable dead band is given in order to prevent short circuiting of switches. The generated pulses are amplified using IR2110 driver IC. The high and low side driver output is correspondingly given to upper and lower switches of power circuit.

In this circuit model, load experiences voltage sag of 10% magnitude for 0.5ms duration as shown in Fig. 16. From this waveform, it can be observed that, after 0.5ms the load voltage reduces and this continues during the entire circuit operation. This sag voltage will be compensated by injecting the required amount of voltage through the injection transformer

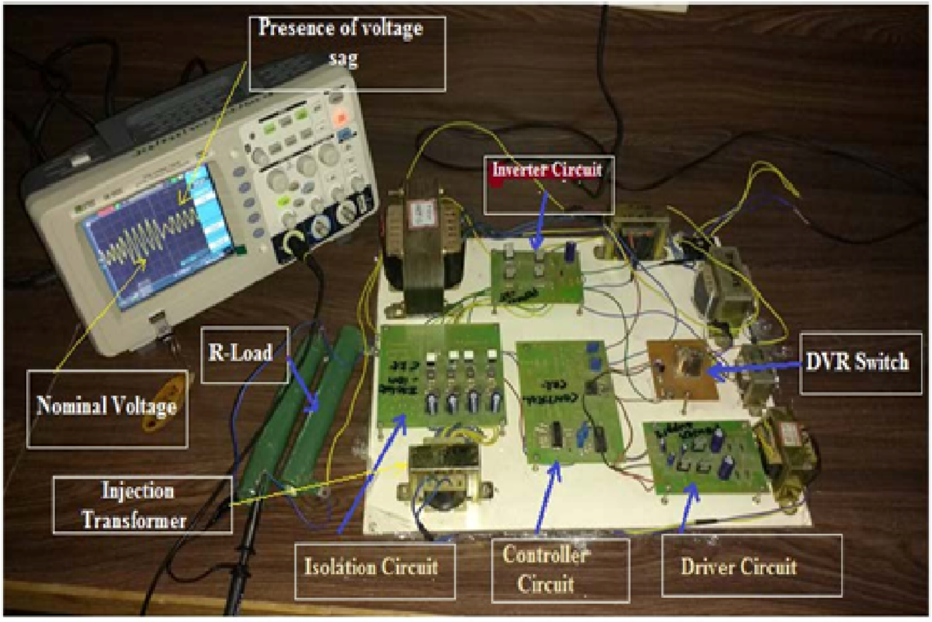



Fig.15. Experimental setup of DVR model

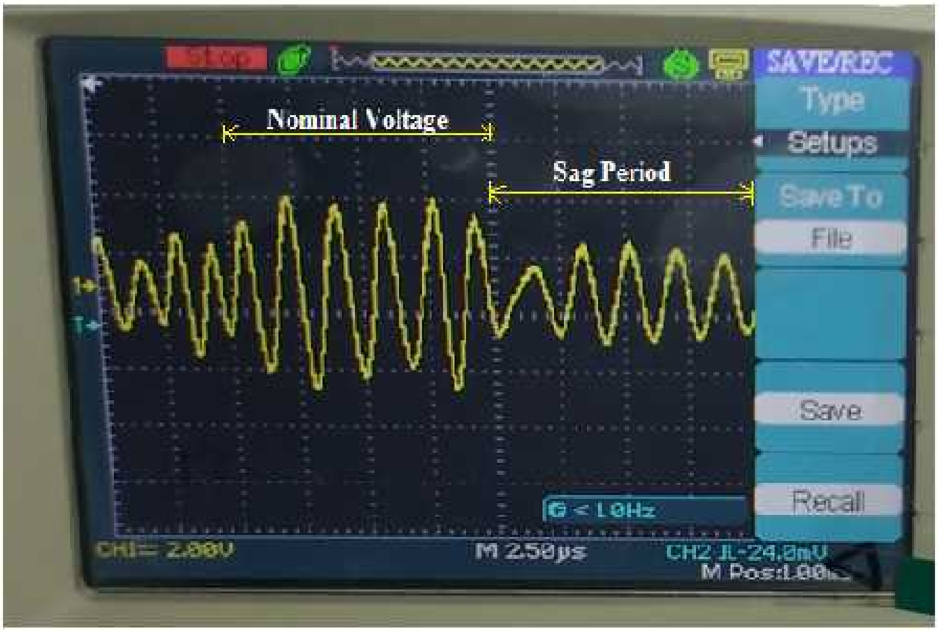



Fig.16. Voltage sag waveform

Whenever DVR detects voltage sag or swell, it must inject the required amount of voltage properly to the load. When DVR is activated, magnitude of load voltage remains constant due to the injected voltage, which increases during the voltage sag event to compensate for the voltage sag. The compensated voltage by DVR action is shown in the Fig. 17. From the waveform, it is found that, after 0.5ms, load maintains the same amount of voltage. Therefore, from DVR experimental waveforms, it can be concluded that the designed DVR system hardware setup is able to respond instantaneously to compensate voltage sags. The above simulation results are compared with the hardware results and it shown in the Table 4.

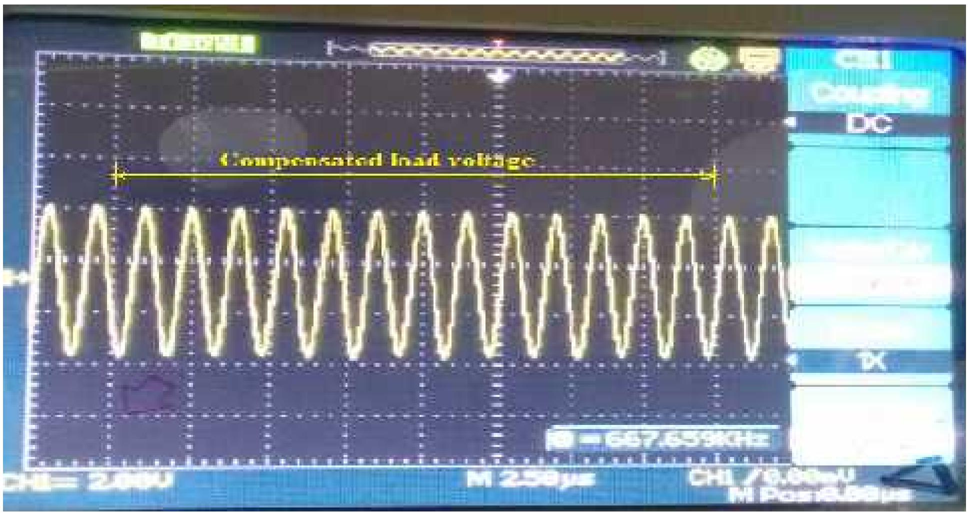



Fig.17. Compensated load voltage by DVR action

Table 4. Comparison of simulation results and hardware results

| S.No | Simulation Results | | Experimen-tal results |
|---|---|---|---|
| 1 | Period of Voltage sag occurence | 0.15sec to 0.25sec | 0.5ms to 1msec |
| 2 | Percentage of voltage reduction in load voltage | 90% | 30% |
| 3 | Compensation by DVR | 95% | 85% |

## 7. Conclusion

In this paper, the concept of integrating multi-level inverter to the DVR system to improve its voltage restoration capabilities is proposed. With this integration method, the DVR will be able to independently compensate voltage sags to compensate for faults on the grid. The simulation of multi-carrier modulation strategy used in MLI is explained in detail. The control strategy adopted in DVR is also discussed. The proposed control strategy is very simple to implement and it is based on injecting voltages in-phase with the system voltage through the injection transformer. The simulation of the PV fed grid connected system with DVR and without DVR is analysed very well. From the analysis part, it is shown that, DVR is able to compensate the voltage sag in all the phases occurred due to severe grid faults. A hardware experimental result of multi-level inverter is also presented. And also, experimental setup of the single phase DVR system is presented and its ability to provide temporary voltage sag compensation is tested. The proposed configuration could be very useful for large scale distributed power generation system where voltage regulation and fault compensation are required.

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