Design and Analysis of STATCOM using Asymmetrical Multilevel Inverter for Power Quality Problems

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Abstract-This paper deals with simulation of STATCOM for power quality improvement. The unique structure of proposed multilevel converter circuit based on series/parallel connection of switches significantly reduces the number of switches and increases number of output voltage levels. Photovoltaic source model is simulated and applied as input for multilevel inverter Inverse Sine Pulse Width Modulation (ISPWM) is used to reduce of total harmonic distortion in the proposed multilevel inverter. This multilevel inverter is used as STATCOM in the three phase power system to compensate the sag voltage caused by three phase faults.Thus the simulation of STATCOM is performed in the MATLAB/SIMULINK environment and the results are presented.
Keywords – AMI, ISPWM, THD, STATCOM

I. INTRODUCTION

Power conditioning systems are often designed to supply an AC load from DC source. An inverter should provide constant and ripple free AC voltage to ensure the safety of the equipments .The design of such systems must achieve an output voltage behavior as close as possible to the ideal AC voltage in the sense of fast transient response to load variation and low THD. With the expansion of power electronics towards the medium voltage and high power applications in the past few years, multilevel power conversion is an emerging area. Multilevel voltage source inverter offers several advantages which makes it preferable over the conventional (two level) inverter. These include the possible utilization of higher DC link voltage, improved harmonic performance, reduced power device stress etc. Several multilevel topologies [1-2], namely the diode clamped multilevel inverter, the flying capacitors Multilevel Inverter (MLI) and cascaded multilevel inverter, have evolved and are applied in adjustable speed drives, electric utilities and renewable energy systems. Among the multilevel inverter topologies, cascaded multilevel inverter has more advantages than the other two. Cascaded MLIs use more than one DC voltage source to generate an AC output voltage that resembles a sine wave.

Various modulation methods are available for multilevel inverter [3]. In recent years, asymmetric multilevel inverters have received increasing attention because it is possible to synthesize voltage waveforms with reduced harmonic content, even using a few series- connected cells. This advantage is achieved by using distinct voltage levels in different cells, which can create more levels in the output voltage and minimize its total harmonic distortion (THD) without increasing the number of switching devices and isolated sources [4-7] and without using an output filter. When the number of output levels increases, harmonics of the output voltage and current decreases. The harmonics in the output voltage of power electronic inverters can be reduced using Pulse Width Modulation (PWM) switching techniques. Various control techniques are proposed for the cascaded MLI with single reference /multiple carrier and multiple reference /single carrier [8-13].

This paper presents a novel approaches for controlling the harmonics of output voltage in series/ parallel connected multilevel inverter employing PWM switching strategies. Photovoltaic source is a renewable energy source which is obtained from the radiation of sunlight and applied as input for multilevel inverter Flexible AC transmission system (FACTS) gives solution to the problems and limitations which are introduced in power system with the introduction of power electronics based control for reactive power. A STATCOM is a static synchronous generator operated as a shunt connected static VAR compensator whose capacitive or inductive output current can be controlled independent of the ac system voltage.The proposed multilevel inverter is preferred as a STATCOM and Simulations are performed using MATLAB/SIMULINK.

II. PROPOSED ALGORITHM

For electric power generation, the mathematical modeling of Photovoltaic cell has great importance. For electrical engineers, Photovoltaic cell models are the source to study and analyze the behaviors of photovoltaic cell. A single diode model is preferred to forecast the energy. A diode is associated in shunt parallel with a current source is presented in Fig.1. The current produced in the circuit is

$$I = I_{SC} - I_D \tag{1}$$

Where,

$$I_D = I_{SCref}\left(exp^{\left(\frac{qV_{oc}}{KAT}\right)} - 1\right) \tag{2}$$

The current generated is highly depend on temperature and irradiance. Thus,

$$I_{SC} = \left[I_{SCref} + K_i\left(T_k - T_{ref}\right)\right] * \sigma /100 \tag{3}$$

Where,

I_{SC} - Short circuit current in (A)

K_i - Temperature co-efficient at I_{SCref} (0.0017A/K),

T_k & T_{ref} - exact and reference temperature in K,

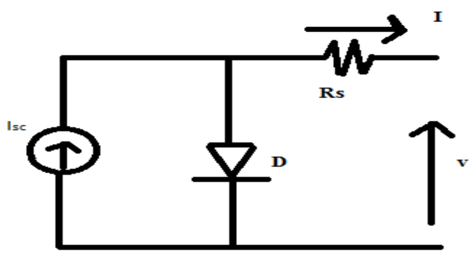


Fig.1. Solar cell model using single diode

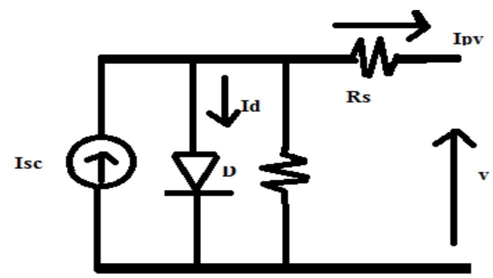


Fig .2.Solar cell using single diode with R_s and R_p

The diode current is varied when the photovoltaic cell is subjected to environmental variations. Therefore a practical model is introduced and is outlined in Fig. 2.

The saturation current (I_o) is decided only by the temperature. The losses in the system is calculated by using the series resistance R_s and shunt resistance R_p .

The I-V characteristic relationship is given by;

$$I_{SC} - I_d - \frac{V_d}{R_P} - I_{pv} = 0 \tag{4}$$

Thus,

$$I_{pv} = I_{SC} - I_d - \frac{V_d}{R_P} \tag{5}$$

The reverse saturation current (I_{rs}) of the circuit is shown as:

$$I_{rs} = I_{SCref}\left(exp^{\left(\frac{qV_{OC}}{N_sKAT}\right)} - 1\right) \tag{6}$$

The saturation current $I_o$varies with the cell temperature which is shown as;

$$I_o = I_{rs}\left[\left(\frac{T}{T_{ref}}\right)^3 e^{\frac{qC_g}{AK*\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)}}\right] \tag{7}$$

Where ,

I_o - Saturation current (A).

The expression for current in the pv cell is given by

$$I_{pv} = N_pI_{SC} - N_sI_o\left\{exp^{\left(q\frac{(V_{pv}+I_{pv}R_s)}{N_S\,AKT}\right)} - 1\right\} \tag{8}$$

Where,

k - Constant , q - Charge , T - Temperature ,A - Ideality factor, R_s – Series resistance ,R_p - Shunt resistance ,N_s - Series connected cells , N_p – Parallel connected cells ,$V_{pv} = V_{oc} = 21.06\ V$

Normally, the low voltages generated by the pv cell are not enough to use as it is. Hence to improve the voltage level, there are multiple pv cells joined in cascade. Based on their requirement of applications the modules are interconnected in series or parallel. The voltages in the circuit are added if they are connected in cascade. Similarly the currents are added if they are connected in parallel. the PV model is simulated and the simulation model is illustrated in fig.3 & fig.4.

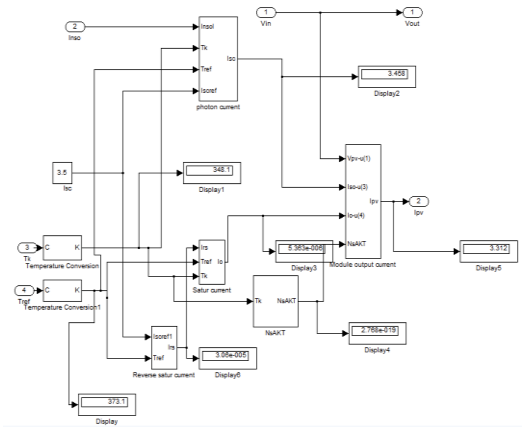


Fig. 3 Calculation of I_{pv}

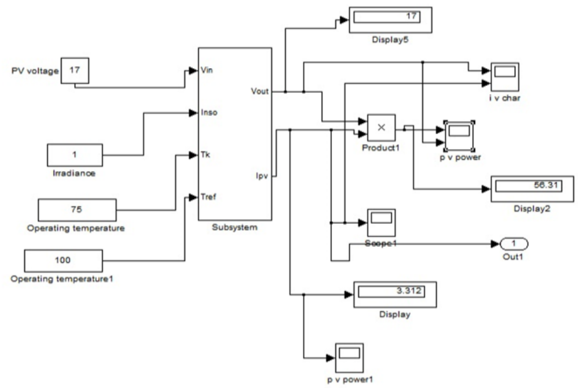
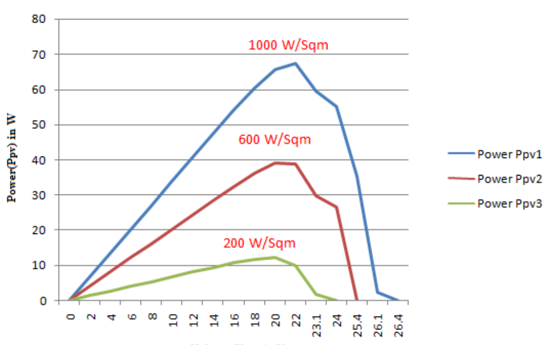


Fig.4 Calculation of output current and voltage

The use of the simplified circuit model for this work makes it suitable for power electronics designers to have an easy and effective model for the simulation of photovoltaic devices with power converters. The value of the parallel resistance Rp is generally high and hence neglected to simplify the model. A procedure based on Simulink model to determine the values to these parameters is proposed. The evaluation of these model parameters at real condition of irradiance and temperature of the target PV modules are then determined according to their initial values. The simulation model is shown Fig. 3.

The P-V and I-V characteristics are shown in Figures 5(a) & (b).



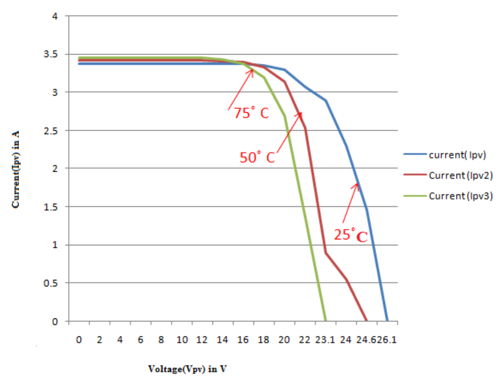


Fig.5(a). Power –Voltage Characteristics
Fig.5(b) Current –Voltage Characteristics

III. PROPOSED ASYMMETRICAL MULTILEVEL INVERTER

The existing cascaded multilevel inverter is modified and a new structure is introduced and is shown in Fig. 6. It has Three H- Bridges and is connected in cascade. The lower bridge is having series/ parallel circuit. A single dc source and 4 switches are utilized in every H-bridge. The quantities of the devices are increased for improved output levels. The switches are combined in various modes and large numbers of steps are acquired.

The inverter levels are specified by

$$n = 12m + 7 \tag{9}$$

Where

n- Levels & m -sources.

Switches preferred will be

$$r = 3m + 9 \tag{10}$$

The inverter output voltage is made more sinusoidal with different source ratio and Fig elaborates the construction of series/ parallel connected inverter circuit. The sequence in which the switches are switched will be configured in Table .1.

By using this principle high numbers of steps are obtained at output series parallel circuit.

Table 1. Conduction sequence for 31 level Inverter

S.NO	Switching states														Output voltage V_0
	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	Sa1	Sb1	
1	0	1	0	1	0	1	0	1	0	1	0	1	0	0	0.0 V_0
2	0	1	0	1	0	1	0	1	1	0	0	1	0	0	0.5 V_0
3	0	1	0	1	1	0	0	1	0	1	0	1	0	0	1.0 V_0
4	0	1	0	1	1	0	0	1	1	0	0	1	0	0	1.5 V_0
5	1	0	0	1	0	1	1	0	0	1	0	1	0	1	2.0V_0
6	1	0	0	1	0	1	0	1	1	0	1	0	0	1	2.5 V_0
7	1	0	0	1	1	0	0	1	0	1	0	1	0	1	3.0 V_0
8	1	0	0	1	1	0	0	1	1	0	0	1	0	1	3.5 V_0
9	1	0	0	1	0	1	0	1	0	1	0	1	0	1	4.0V_0
10	1	0	0	1	0	1	0	1	1	0	0	1	0	1	4.5 V_0
11	1	0	0	1	1	0	0	1	0	1	0	1	1	0	5.0 V_0
12	1	0	0	1	1	0	0	1	1	0	1	0	1	0	5.5V_0
13	1	0	0	1	0	1	0	1	0	1	0	1	1	0	6.0 V_0
14	1	0	0	1	0	1	0	1	1	0	0	1	1	0	6.5 V_0
15	1	0	0	1	1	0	0	1	0	1	0	1	1	0	7.0V_0
16	1	0	0	1	1	0	0	1	1	0	0	1	1	0	7.5 V_0

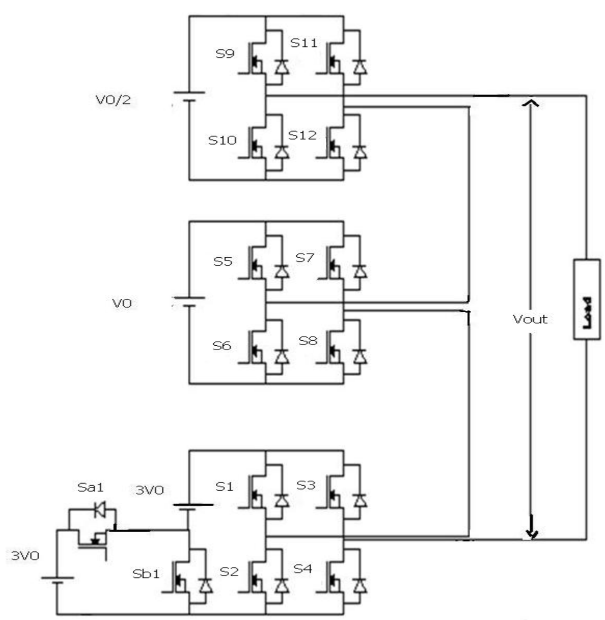


Fig.6. Circuit diagram of Asymmetrical series/parallel inverter

Inverse Sine Pulse Width Modulation (ISPWM)

The inverted sine PWM (ISPWM) method uses the conventional sinusoidal as reference signal and an inverted sine as carrier signal that helps to maximize the output voltage for a given modulation index.

The proposed control strategy replaces the triangular based waveform by inverted sine wave. The inverted sine PWM has a better spectral quality and a higher fundamental voltage compared to the triangular based PWM.

For an 'm' level inverter, (m-1) carrier waves are required. The pulses are generated when the amplitude of the modulating signal is greater than that of the carrier signal.

The ISPWM strategy enhances the fundamental output voltage particularly at lower modulation index ranges. There is also a reduction in the total harmonic distortion (THD) and switching losses. The appreciable improvement in the total harmonic distortion attracts drive applications where low speed operation is required. The performance evaluation of inverted sine pulse width modulated inverter is done using MATLAB and the optimum switching frequency with minimized total harmonic distortion is determined.

Amplitude modulation index

In amplitude modulation index, modulation index depends on the amplitude of carrier signal and the reference signal used. In general the value of modulation index varies between 0 and 1. Amplitude modulation index (m_a) can be defined as

$m_{a=}A_{r/(m-1)}A_c$

where, A_r -Amplitude of reference signal

A_c -Amplitude of carrier signal

Frequency modulation index

In frequency modulation index, the modulation index depends on the frequency of the reference signal and the carrier signal used. The frequency modulation index of the m_f of the multilevel inverter can be defined as

$m_{f=}f_{c/}f_r$

where, f_c- frequency of carrier signal

f_r- frequency of reference signal

Based on ISPWM technique, switching pulses are generated for different switches in the inverter circuit. The 31 level output voltage waveform and THD spectrum is shown in Fig. 7 and Fig. 8.

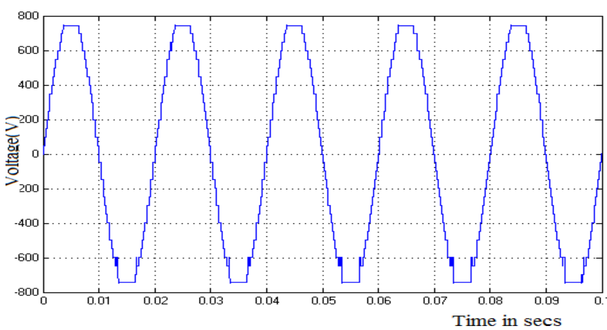


Fig. 7. Output waveform of single phase 31 level inverter

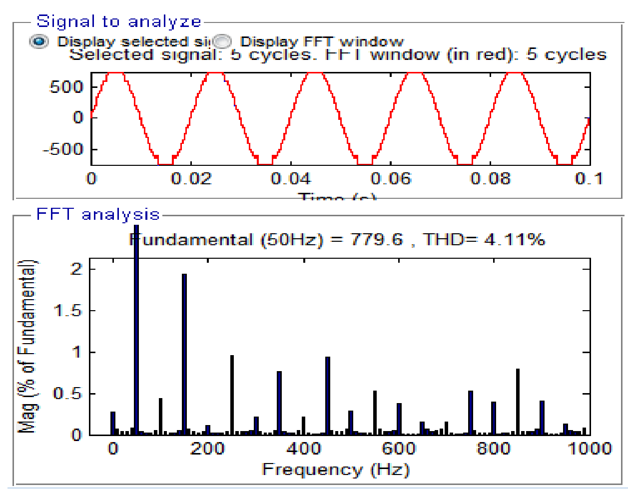


Fig.8. Harmonic spectrum of 31 level inverter

IV. FACTS DEVICE: STATCOM

The problems exists in the power system are rectified or minimized through the electronic based FACTS devices. Flexible Alternating current transmission system is nothing but the integration of electronic components to the power system to enrich the controllability of the system and to improve the capability of the system. This knowledge along with the concept of power electronics upholds the performance of the system. The thermal limit of the transmission line gets improved by this technology. The increased capacity of the line also increases the reliability of the system. Therefore, for huge transfer of power are possible through the optimum utilization of equipment's. Due to this, no need to erect new lines.

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The FACTS controllers are designed to achieve greater controllability in huge power transmission. The oscillations in the grid are completely damped out. To determine the optimum power flow, only one parameter is controlled through the Static VAR controllers. It has been realized that a static VAR compensator, similar to synchronous condenser

STATCOM is a power converter which is nourished from an energy source of suitable rating, and then it is talented for producing or absorbing the real and reactive power independently at its output terminals. A STATCOM is a voltage source inverter that gives rise to three phase ac output voltages and tied to the grid through the reactance. It is generally considered as leakage reactance. The VSI is energetic by a battery, capacitor or Photovoltaic cell.

The reactive power is interchanged either from the system to control device or from device to the system based on the system load and the performance of the system gets improved.

The general schematic diagram is as shown in Fig.9. Regulation of device voltage will control the reactive power of the system.

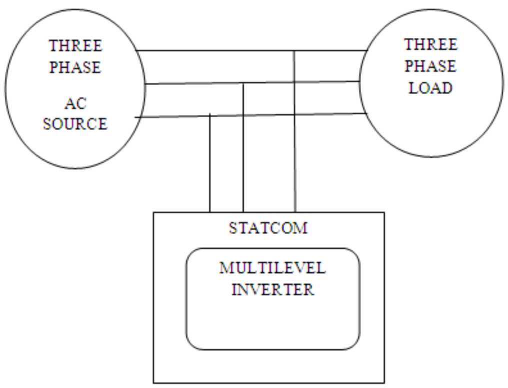

Fig. 9 Structure of Static synchronous compensator (STATCOM)

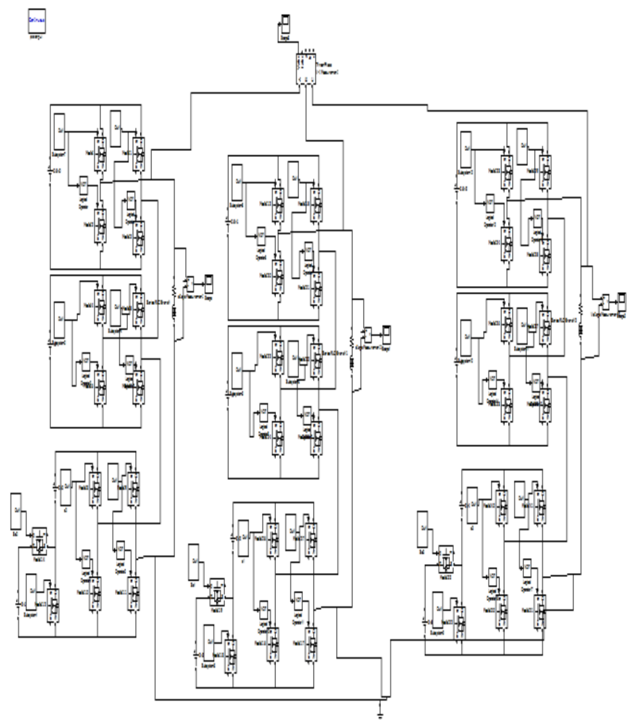

Fig.10. Simulink circuit of 3 phase multilevel inverter

The simulation model of a three phase inverter circuit and its output waveform are shown in Fig.10 &11.

Electrical systems are subject to a wide variety of power quality problems which can interrupt production processes, affect sensitive equipment, and cause downtime, scrap, and capacity losses. Momentary voltage fluctuations can disastrously impact production. Extended outages have an even greater impact. Voltage fluctuations can also impact the stability and reliability of utility transmission and distributions.

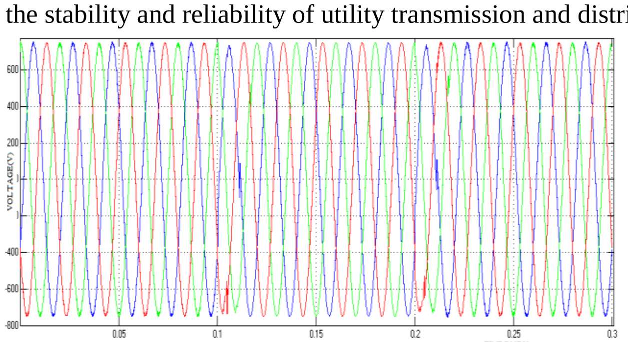

Fig.11. Output voltage of three phase 31 level inverter three phase

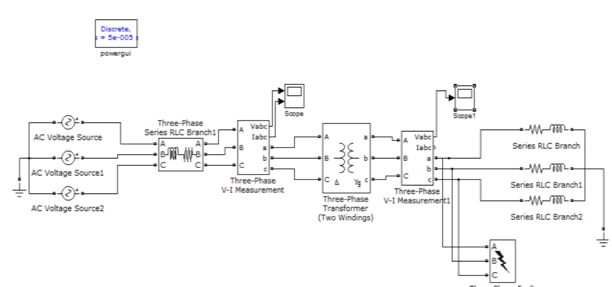

Fig.12. Simulink circuit of power system with fault interruption

Rapidly varying dynamic loads and intermittent renewable generation sources can all impact the grid, requiring systems that will provide the rapid voltage and reactive support needed to maintain grid stability. Some of the major Electrical faults are phase faults include phase to phase faults and phase to ground faults and three phase faults. Three phase faults are called symmetrical fault. This type of faults occurs very rarely but more severe compared to other faults. Fig 12 &13 shows the circuit diagram and load voltage waveform of three phase power system with fault interruption of 0.1 seconds .

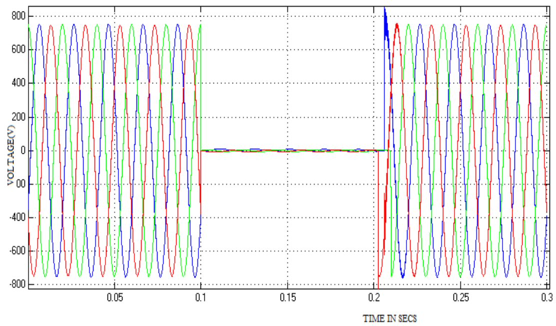

Fig. 13. Load voltage waveform without compensation

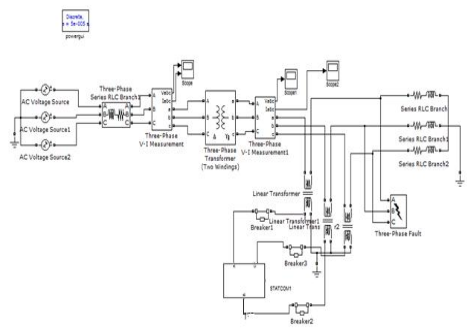

Fig.14. Simulink circuit of power system with STATCOM

The proposed multilevel inverter is used as a STATCOM for compensating reactive power exchange in the circuit. The simulation model of the compensated system and its output load voltage is shown in Fig. 14 & 15.

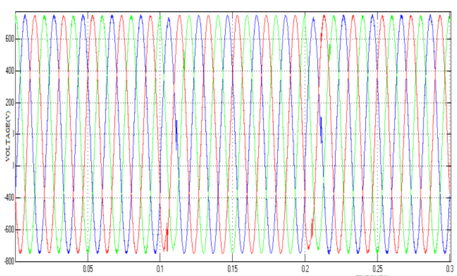

Fig.15 Load voltage waveform with compensation

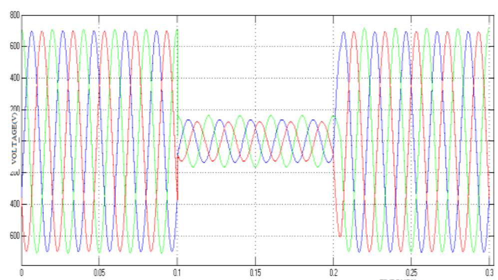

Fig 16 shows load output voltage waveform of three phase power system with voltage sag.

Generally, Sag is a phenomenon observed due to voltage drop, for a given frequency. On the contrary, an interruption, this can be instantaneous, momentary, temporary or sustained depending on its duration and caused by system faults or switching on loads with heavy start-up currents.

Similarly, the effect of swell is opposite to sag. It results an increase in AC voltage. Swells can be caused by high-impedance neutral connections, sudden load reductions and a single-phase fault on a three-phase system. The effects of a swell can be data errors or corruption, lights flickering, degradation of electrical contacts and insulation and damage to sensitive electronics. So these problems are easily compensated by the STATCOM .

Fig.16 & 17 shows the load output voltage waveform of three phase power system with voltage sag and with compensation.

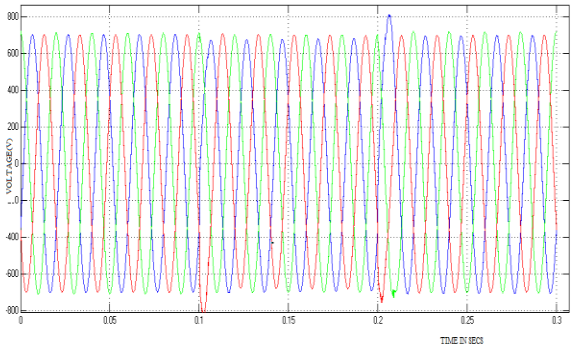

Fig. 17.Load voltage waveform with compensation

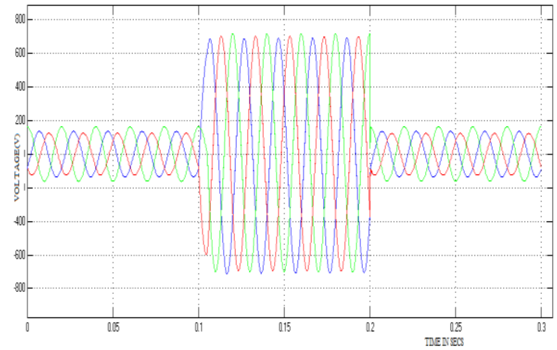

Fig.18.Load voltage waveform with voltage swell

Fig.18 & 19 shows the load output voltage waveform of three phase power system with voltage swell and with compensation.

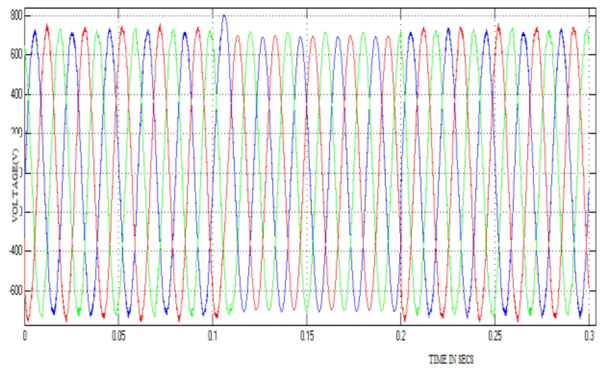

Fig.19.Load voltage waveform with compensation for voltage swell

V.CONCLUSION

This paper has dealt with the new series/parallel connection based asymmetrical multilevel inverter. The main achievement of the proposed PWM control technique is to reduce the total harmonic distortion (THD) and closer to sinusoidal waveform without the usage of an output filter. This inverter reduces the switching losses by reducing number of switches and provides improved output voltage capability. Photovoltaic source model is modelled and act as input to the inverter. The designed 31 level inverter is used as STATCOM in order to compensate voltage during conditions like short circuit , voltage sag and voltage swell and is simulated in MATLAB/SIMULINK package and the results are verified.

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