Sinusoidal PWM Signal Generation Technique for Three Phase Voltage Source Inverter with Analog Circuit & Simulation of PWM Inverter for Standalone Load & Micro-grid System

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Abstract- Inverter is the most important device to utilize the renewable energy sources efficiently. The Sinusoidal Pulse Width Modulation (SPWM) technique is one of the most popular PWM techniques for harmonic reduction of inverters since there are used three sine waves displaced in 120^0 phase difference as reference signals for three phase inverter. Nowadays the SPWM switching signal is generated with the help of different FPGAs, microcontrollers and microprocessors. But for these kind of devices it is necessary the programming or coding. This paper represents the SPWM technique for harmonic reduction & shows how to generate SPWM switching signal using different simple Operational-Amplifier (Op-Amp) circuits/analog circuits for three phase pulse width modulated (PWM) voltage source inverter (VSI). All the Op-Amp circuits are simulated and their outputs are shown step by step. This analog circuit (Op-Amp) controlled voltage source inverter is simulated for both standalone load & high voltage sensitive loads/systems like micro-grid system and large industrial machines respectively with transformer & without transformer. The simulation results are shown before and after harmonic reduction using an appropriate passive filter. Furthermore, the paper represents two typical inverter based micro grid system structures where one is with common DC bus & another one is with common AC bus.

Keywords- Op-Amp, MOSFET, Inverter, VSI, SPWM, Load, Micro-grid, Harmonics, Filter

1. Introduction

In the last years, new energy sources have been proposed and developed due to the dependency and constant increase of costs of fossil fuels. On other hand, fossil fuels have a huge negative impact on the environment. In this context, the new energy sources are essentially renewable energies [1]. It is estimated that the electrical energy generation from renewable energy sources will increase from 19%, in 2010, to 32%, in 2030, leading to a consequent reduction of CO_2 emission [2]. In rural areas particularly in the developing world, where most of the population up to 80% is located, more than 1 billion people lack the essential energy services to satisfy the most basic needs and to improve their social and economic status [3]. The growing energy demand around the world led us to utilize these renewable energy resources. In recent years, the efforts to spread the use of renewable energy resources instead of pollutant fossil fuels and other forms have increased [4]. To utilize these renewable energy resources an inverter is essential which converts DC power to AC power as most of the renewable energy is found in DC form. In hybrid power system and micro-grid system the use of inverter is significant. In industrial applications, such as single phase and Three Phase Induction Motor & other rotating machines, variable frequency &variable voltage supply is needed. To vary the supply frequency and supply voltage, voltage source inverter (VSI) is used. The voltage source inverters (VSIs), where the independently controlled AC output is a voltage waveform, behave as voltage sources required by many industrial applications [5]. While the single-phase VSIs cover low-range power applications, three-phase VSIs cover medium to high-power applications.

Three-phase bridge inverters are widely used in motor drives and general-purpose AC supplies [5]. For the following energy sources and loads inverters are necessary:

- Photovoltaic System (PV).
- Variable speed wind power system.
- Hybrid power system.
- UPS/IPS system.
- Micro grid & Distributed generation (DG) system.
- Electric & Hybrid vehicles.
- FACTS.
- Variable frequency drives (VFD). Etc.

Modern power electronics have contributed a great deal to the development of new powerful applications and industrial solutions; but at the same time, these advances have increased the harmonic contamination present in line currents, which ends up distorting the voltage waveforms [6]. For high efficiency DC-AC conversion and peak power tracking it must have low harmonic distortion along with low electromagnetic interference and high power factor [7]. An inverter is evaluated after design by using the inverter performance and testing standards which are IEEE 929-2000 and UL 1741 in US EN 61727 in EU and IEC 60364-7-712. The total harmonic distortion (THD) generated by the inverter is regulated by international standard IEC-61000-3-2 [8]. The total harmonic distortion (THD) of the voltage must be kept at minimum and according to recommended limit by IEEE Standard 519-1992 has to be kept at less than 5% for harmonic spectra up to 49^{th} harmonic [9]. For the partial loads THD is generally much higher. There are several switching techniques to control the VSI and for harmonic reduction. Pulse Width Modulation (PWM) technique is the best one among them. Till now, many types of modulating modes have been brought forward in motion control and power conversion, such as sinusoidal PWM, space vector PWM, current tracking PWM, harmonic elimination PWM and so on [10-12]. These methods have some advantages and disadvantages, but the most widely techniques used are the sinusoidal PWM and the space vector PWM. Pulse Width Modulation (PWM) has become the facto in industrial standard. This technique is the heart of the inverter system control signal [13].

In this paper firstly Voltage Source Inverter (VSI) and its components is discussed. Later the Sinusoidal Pulse Width Modulation (SPWM) techniques for harmonic reduction of three phase inverter are described. Then the techniques of generating SPWM switching signal using analog circuit (Operational-Amplifiers) are described for three phase SPWM voltage source inverter (VSI). All the components of analog switching circuit are simulated and their simulation outputs are shown. The switching circuit is checked by simulating it for different types of loads. The simulation outputs of the inverter are shown for both low voltage & high voltage system before and after filtering step by step. Moreover, two structures of inverter based micro grid system are shown where one is common DC bus with a single central inverter and another one is common AC bus with individual inverters. To end with an appropriate passive filter for micro-grid system is presented in the paper.

2. Components of Inverter

There are five main groups of power semiconductors. They are: power diode, thyristor, power bipolar junction transistor (BJT), insulated gate bipolar transistor (IGBT), and static induction transistor (SIT). Figure 1 gives a picture of each.

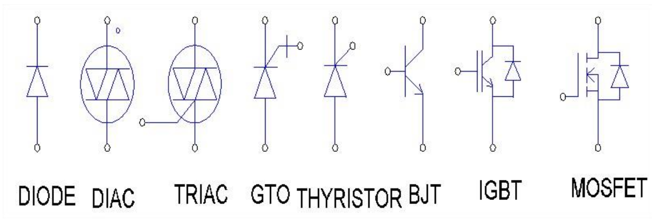

Fig. 1. Different power semiconductor switches

To assemble an inverter the MOSFET and IGBT are heavily used power semiconductor devices. Power MOSFET can operate at somewhat higher frequencies (a few to several tens of kHz), but is limited to power ratings, usually 1000V, 50A. Insulated-gate bipolar transistor (IGBT) is voltage controlled power transistor that is used while voltage requirement increases and it also offers better speed than a BJT but is not quite as fast as a power MOSFET [14]. In higher switching frequencies MOSFET is superior to IGBT but higher switching operation of IGBT is feasible by employing soft switching power conversion [15]. Therefore, according to our requirements MOSFET is chosen to design the inverter. Moreover power diode is used as freewheeling diode. A three phase PWM inverter is shown in Figure. 2.

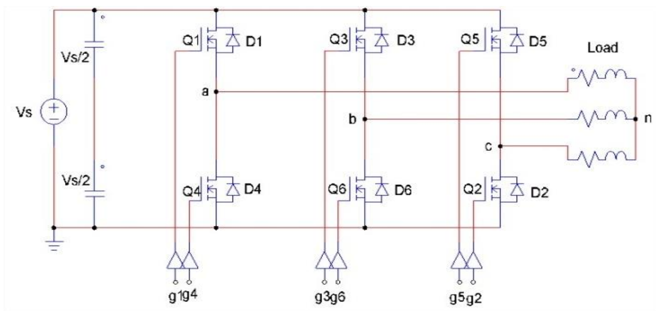

Fig. 2. Three-phase voltage source inverter (VSI)

3. Sinusoidal Pulse Width Modulation Technique

The voltage source inverter that use PWM switching techniques have a DC input voltage ($V_{DC} = V_S$) that is usually constant in magnitude. The inverter job is to take this DC input and to give AC output, where the magnitude and frequency can be controlled. There are several techniques of Pulse Width Modulation (PWM).The efficiency parameters of an inverter such as switching losses and harmonic reduction are principally depended on the modulation strategies used to control the inverter [16-18]. In this design the Sinusoidal Pulse Width Modulation (SPWM) technique has been used for controlling the inverter as it can be directly controlled the inverter output voltage and output frequency according to the sine functions [19]. Sinusoidal pulse width modulation (SPWM) is widely used in power electronics to digitize the power so that a sequence of voltage pulses can be generated by the on and off of the power switches. The PWM inverter has been the main choice in power electronic for decades, because of its circuit simplicity and rugged control scheme. Sinusoidal Pulse Width Modulation switching technique is commonly used in industrial applications or solar electric vehicle applications [20].

SPWM techniques are characterized by constant amplitude pulses with different duty cycles for each period. The width of these pulses are modulated to obtain inverter output voltage control and to reduce its harmonic content [21]. Sinusoidal pulse width modulation is the mostly used method in motor control and inverter application [20]. In SPWM technique three sine waves and a high frequency triangular carrier wave are used to generate PWM signal [5]. Generally, three sinusoidal waves are used for three phase inverter. The sinusoidal waves are called reference signal and they have 120^0 phase difference with each other. The frequency of these sinusoidal waves is chosen based on the required inverter output frequency (50/60 Hz). The carrier triangular wave is usually a high frequency (in several KHz) wave. The switching signal is generated by comparing the sinusoidal waves with the triangular wave. The comparator gives out a pulse when sine voltage is greater than the triangular voltage and this pulse is used to trigger the respective inverter switches [22-23]. In order to avoid undefined switching states and undefined AC output line voltages in the VSI, the switches of any leg in the inverter cannot be switched off simultaneously. The phase outputs are mutually phase shifted by 120^0 angles [5]. The ratio between the triangular wave & sine wave must be an integer N, the number of voltage pulses per half-cycle, such that, 2N= f_c/fs. Conventional SPWM signal generation technique for three phase voltage source inverter is shown in Figure 3.

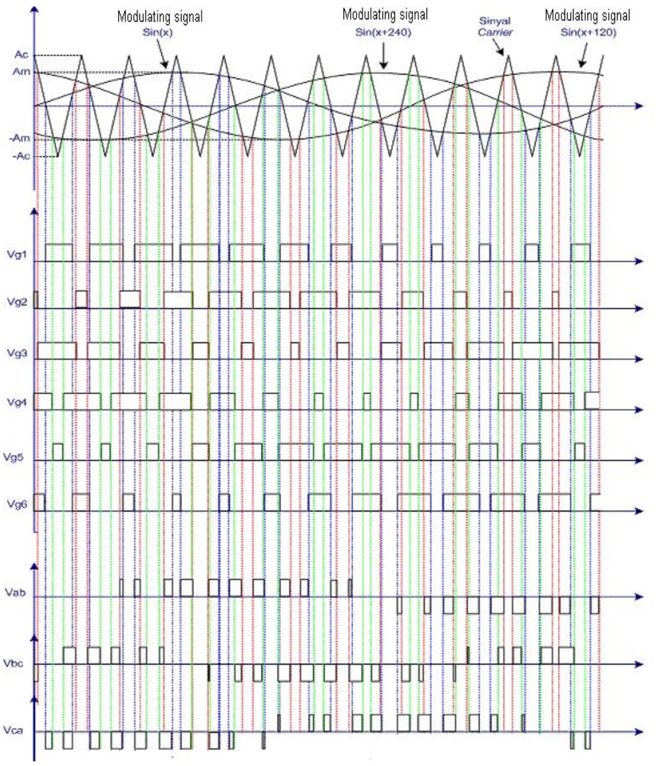

Fig. 3. Conventional SPWM generation technique for three phase voltage source inverter [13]

Amplitude Modulation, $M_a = \frac{A_s}{A_c}$ (2)

Frequency Modulation, $M_f = \frac{f_s}{f_c}$ (3)

Percentage of individual harmonics is calculated by the eqn.

$$\% \frac{rms(n)}{V_{DC}} = 100\left(\frac{4}{n\pi\sqrt{2}}\sum_{p=1}^{M_f}(-1)^{i+1} cosn\alpha_i\right) \quad (4)$$

Where, n= n^{th} harmonics.
Percentage of total RMS of the output, when M_f is even,

$$\%\text{Vn} = 100 \times \sqrt{\frac{2}{\pi}\sum_{p=1}^{\frac{Mf}{2}}(\alpha_{2p} - \alpha_{2p-1})} \quad (5)$$

When M_f is odd,

$$\%\text{Vn} = 100 \times \sqrt{\left[\frac{2}{\pi}\sum_{p=1}^{\frac{Mf-1}{2}}(\alpha_{2p} - \alpha_{2p-1}) + \frac{\pi}{2} - \alpha_{M_f}\right]} \quad (6)$$

Total harmonics distortion (THD) is given by,

$$THD = \frac{V_h}{V_1} \quad (7)$$

Where, $V_h = \sqrt{\sum_{n=2,3,..}^{\infty} {V_n}^2}$ or, $V_h = \sqrt{{V_{out}}^2 - {V_1}^2}$

And, V_1 = Fundamental component.

4. Components of SPWM Signal Generating Analog Circuit

In this segment of the paper different components of the analog switching control circuit have been shown. A block diagram of SPWM generating control circuit for three phase voltage source inverter has been given in figure 4.

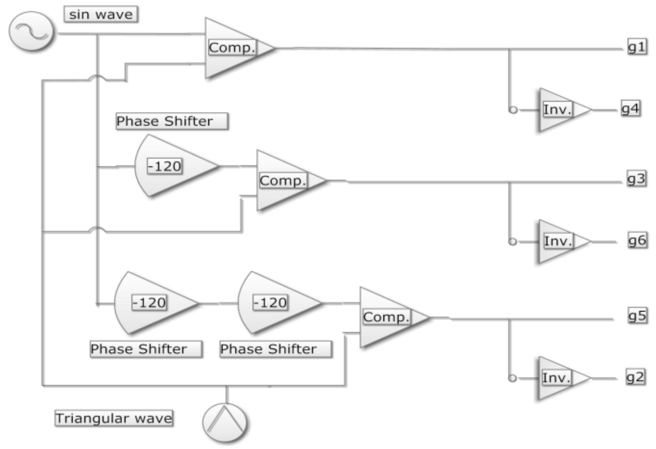

Fig. 4. Block diagram of SPWM generating control circuit for three phase PWM voltage source inverter

The most important component of the analog control circuit for inverter is sine wave oscillator. It is possible to generate the sine wave using Wien Bridge Oscillator [24]. In

Wien Bridge Oscillator a normal Op-Amp is used. Moreover to generate the sine function another analog circuit can be used which is called Precision Sine Wave Generator where the AD639 is used [25]. But due to easiness of simulation in the software it has been used the Wien Bridge Oscillator. The output frequency of the oscillator is 50Hz. Wien Bridge sine wave Oscillator and its sine wave (50 Hz) output is shown in figure 5 and figure 6 respectively.

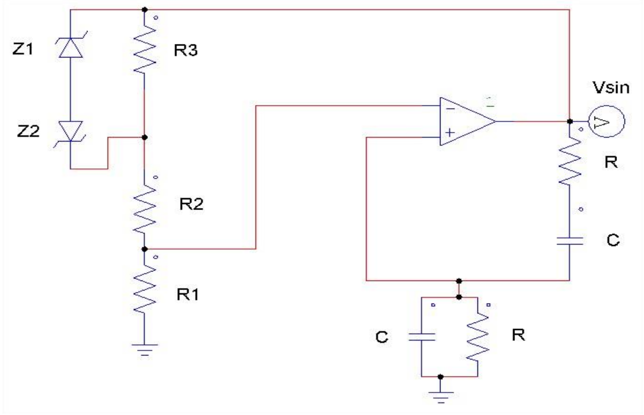

Fig. 5. Wien Bridge sine wave Oscillator

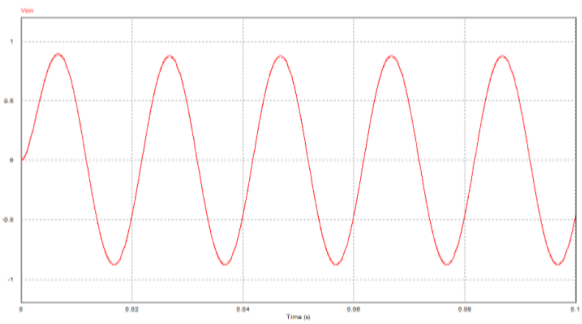

Fig. 6. Output sine wave (50 Hz) of the Wien Bridge Oscillator

A single phase shifter is used at the output of Wien Bridge Oscillator to create -120^0 phase difference and two phase shifters to create -240^0 phase difference [25]. A phase shifter circuit (-120^0) and its output is shown in figure 7 and figure 8 respectively.

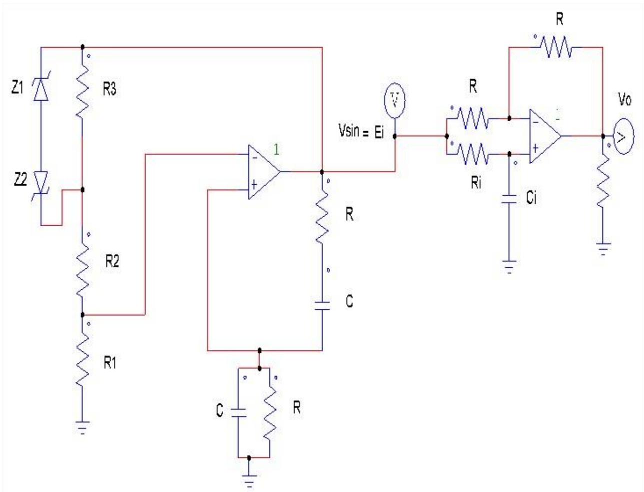

Fig. 7. Phase shifter circuit (120^0) with sine wave input

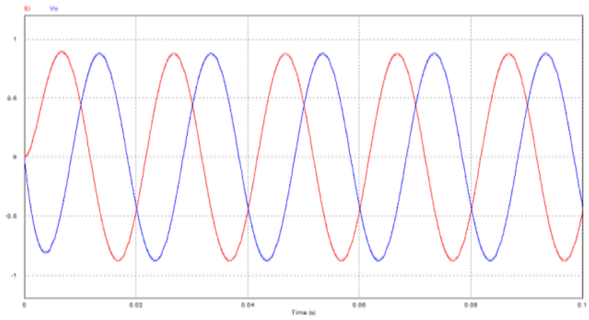

Fig. 8. (-120^0) phase shift of Wien Bridge Oscillator output sine wave

Output voltage of the phase shifter, $V_o = E_i \angle -\theta$

And the phase angle, $\theta = 2\arctan 2\pi f R_i C_i$

$$\text{Or, } R_i = \frac{\tan\left(\frac{\theta}{2}\right)}{2\pi f C_i} \tag{8}$$

When, $\theta = -120^0$ then, $C_i = 1\mu\text{F}$ and, $R_i = 5.51\ \text{K}\Omega$.

Another important component of analog control circuit is triangular carrier wave generator. To generate the high frequency triangular carrier signal the Bipolar Triangular Wave Generator is used [25]. Here a 741 integrator circuit and 301 comparator circuits are wired to make the triangular generator [25]. Frequency of the triangular waveform is ten (10) KHz. The amplitude of carrier triangular wave is controlled by the amplitude of V_{sat} and the frequency is controlled by the R_i potentiometer.

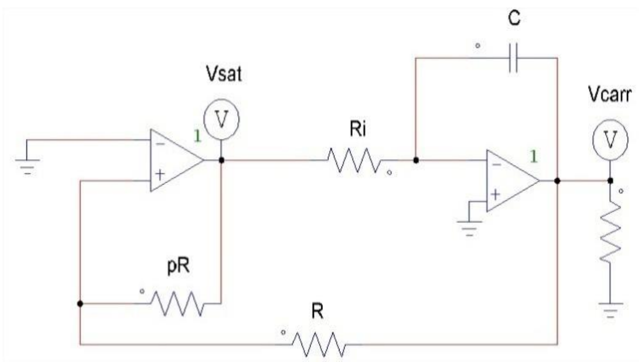

Fig. 9. Triangular carrier signal generator

The upper limit and lower limit magnitude of the triangular wave respectively are,

$$V_{UT} = -\frac{-Vsat}{p} = \frac{Vsat}{p} \tag{9}$$

$$V_{LT} = -\frac{+Vsat}{p} = -\frac{Vsat}{p} \tag{10}$$

Where, $p = \frac{pR}{R}$

Frequency of the triangular wave is found by the following equation,

$$f = \frac{p}{4R_i C} \tag{11}$$

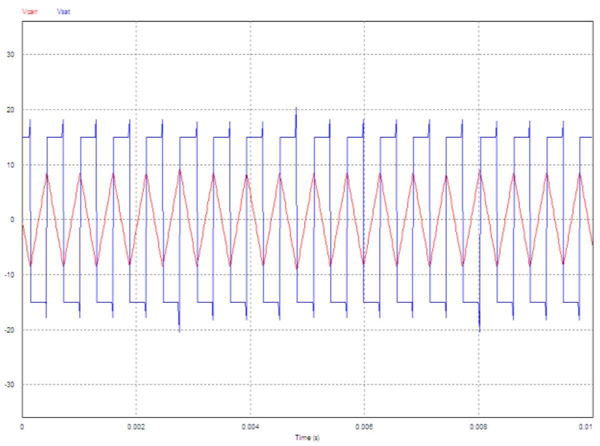

Fig. 10. Triangular carrier signal (10 KHz)

Three individual 301 comparator circuits [25] are used to compare the reference sine waves with the triangular carrier waves. Below in figure 11 a comparator circuit is given and in figure 12 its output is given.

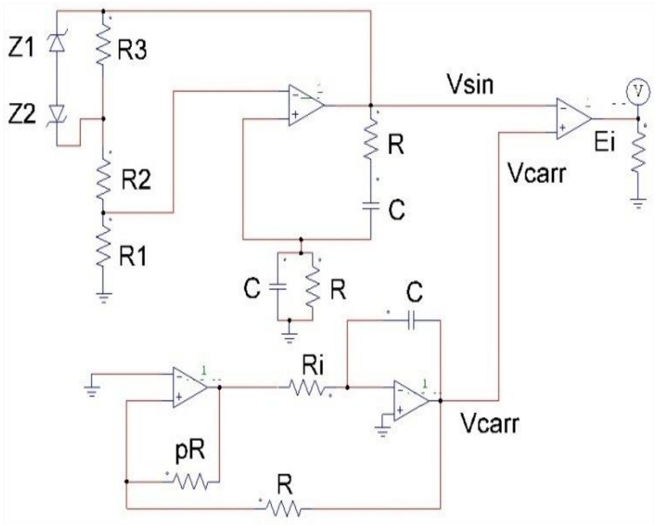

Fig. 11. Op-Amp Comparator circuit with inputs from sine wave and triangular wave generator

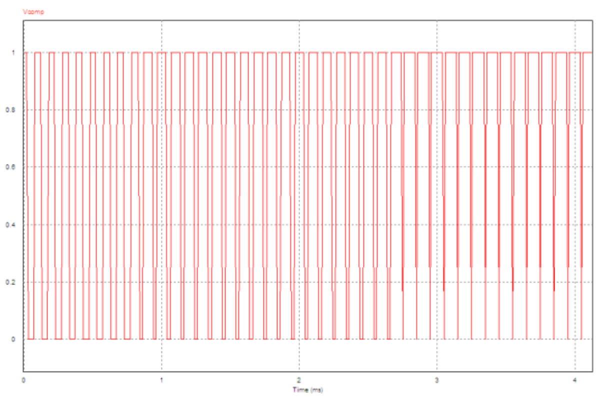

Fig. 12. Output of comparator when inputs are sine wave and triangular wave

Three inverting amplifier is used [25] at the output of comparator circuit to invert the switching signals. In figure 13 inverting amplifier is shown and its output is given in figure 14.

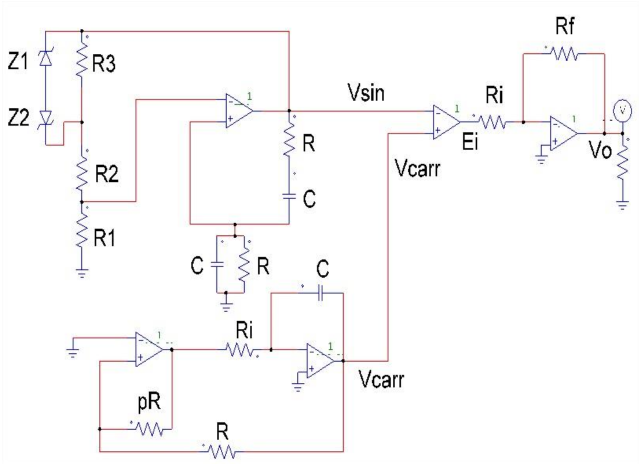

Fig. 13. An inverting amplifier with input from comparator output

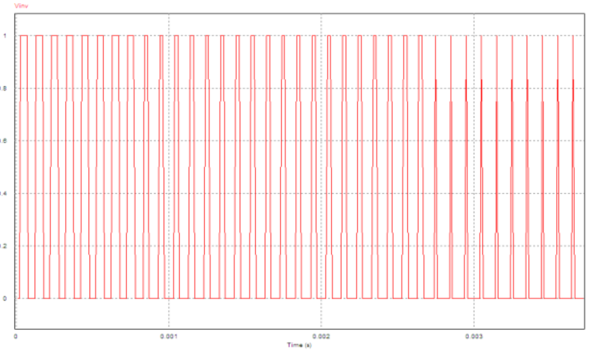

Fig. 14. Output of Inverting circuit when the input is from comparator

The output voltage of the inverting amplifier,

$$V_o = -\frac{R_f}{R_i} E_i \qquad (12)$$

Whereas the magnitude of inverting signal must be equal to the output switching signals of comparators,

$$R_i = R_f \ \text{So,} \ \frac{R_f}{R_i} = 1$$

$$\text{So, } V_o = -E_i$$

Now to drive the MOSFET gates opt-couplers are used as gate driver device. Moreover opt-couplers keep the gates isolated from the switching circuit.

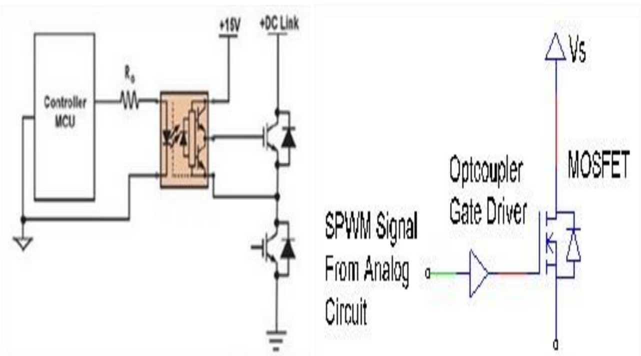

Fig. 15. Opt-coupler MOSFET gate driver

5. Generation of SPWM Switching Signal Using Analog Control Circuit

All the components of analog control circuit are wired as shown in the figure 16. Initially three sinusoidal reference signals are generated using a Wien Bridge Sinusoidal Oscillator circuit. In the next stage, phase difference (120^0) between the sinusoidal waves is generated using the phase shifter circuits and the triangular carrier wave is generated using Triangular Wave Generator. Then using three individual comparator circuits SPWM switching signals g1, g3 & g5 and using three inverting circuits g2, g4, g6 are generated and these SPWM switching signals are applied to the gates of MOSFET of three phase voltage source inverter.

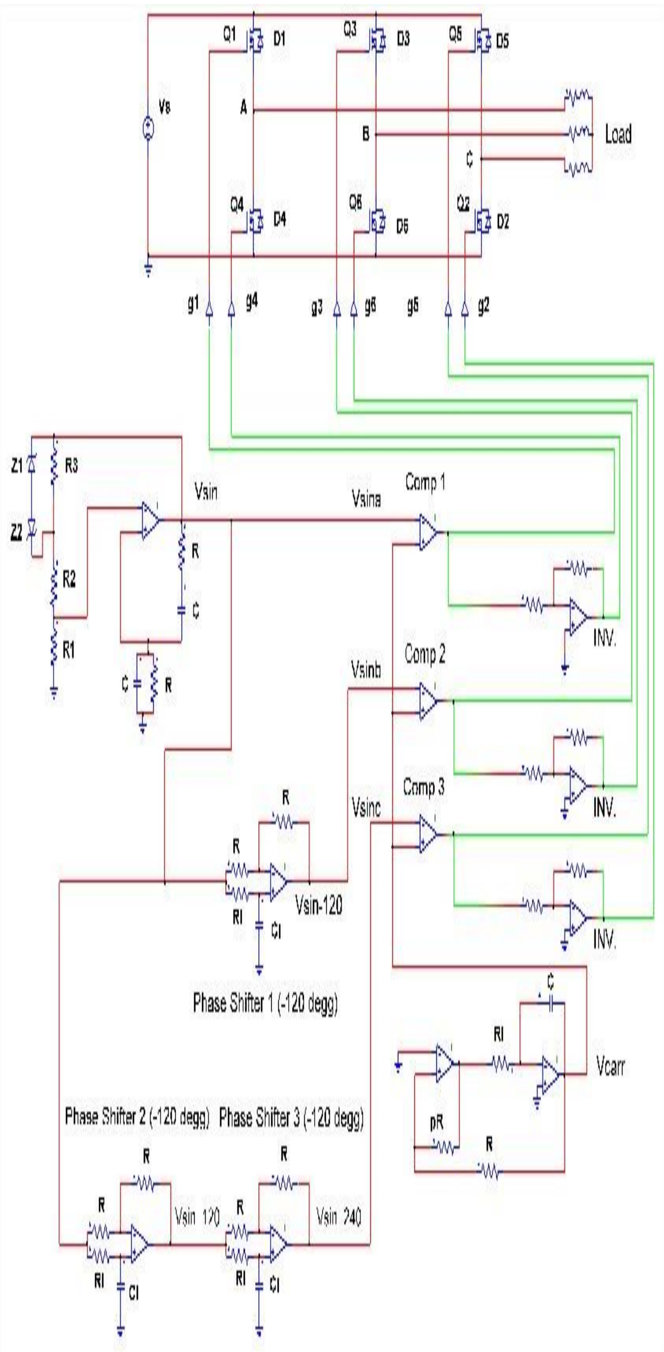

Fig. 16. Circuit diagram of analog circuit controlled SPWM three phase VSI without transformer for Standalone load

The reference sinusoidal signals with amplitude A_s are,

$$Vref.sin_a = A_s V sin(\omega t) \quad (13)$$

$$Vref.sin_b = A_s sin(\omega t - 120^0) \quad (14)$$

$$Vref.sin_c = A_s sin(\omega t - 240^0) = A_s sin(\omega t + 120^0) \quad (15)$$

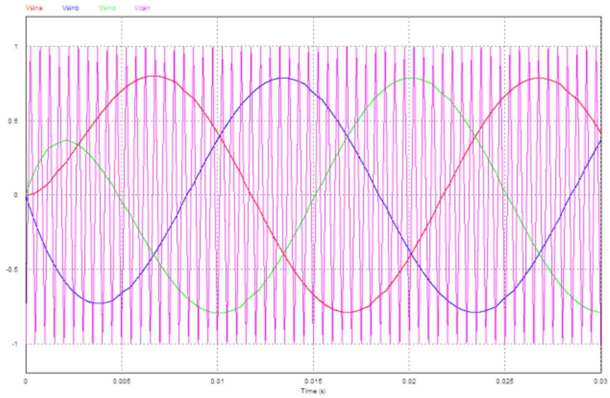

Fig. 17. Reference sine waves and carrier triangular signal

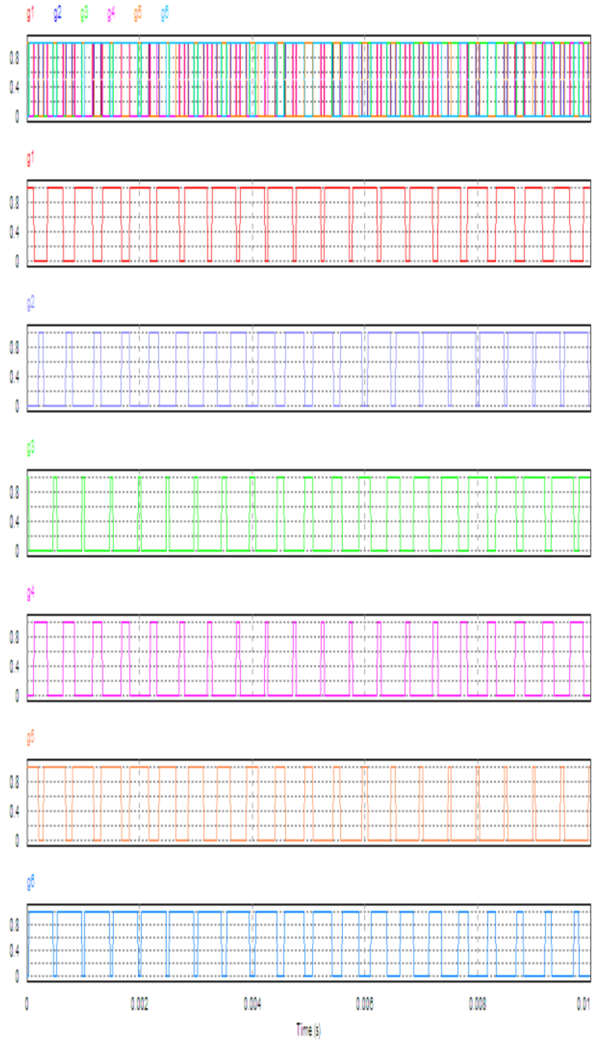

Fig. 18. Individual switching signals (g1, g2, g3, g4, g5, g6) for three phase voltage source inverter

6. Simulation of Three Phase Inverter for Standalone Load without Transformer Before Filtering

The line to neutral voltages of the three phase inverter can be defined by following equations,

$$Van = Vsin(\omega t) \tag{16}$$

$$Vbn = Vsin(\omega t - 120^0) \tag{17}$$

$$Vcn = Vsin(\omega t - 240^0) = Vsin(\omega t + 120^0) \tag{18}$$

And the line voltages are found from,

$$Vab = Van - Vbn \tag{19}$$

$$Vbc = Vbn - Vcn \tag{20}$$

$$Vca = Vcn - Van \tag{21}$$

Table 1. Switching patterns in a three-phase inverter and line to neutral voltages and line to line voltages as co-efficient of DC bus voltage Vs.

Switching pattern			*Line to neutral voltage*			*Line to line voltage*		
g1	*g2*	*g3*	*Van*	*Vbn*	*Vcn*	*Vab*	*Vbc*	*Vca*
0	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
1	*0*	*0*	*2/3*	*-1/3*	*-1/3*	*1*	*0*	*-1*
1	*1*	*0*	*1/3*	*1/3*	*1/3*	*0*	*1*	*-1*
0	*1*	*0*	*-1/3*	*2/3*	*2/3*	*-1*	*1*	*0*
0	*1*	*1*	*-2/3*	*1/3*	*1/3*	*-1*	*0*	*1*
0	*0*	*1*	*-1/3*	*-1/3*	*-1/3*	*0*	*-1*	*1*
1	*0*	*1*	*1/3*	*-2/3*	*-2/3*	*1*	*-1*	*0*
1	*1*	*1*	*0*	*0*	*0*	*0*	*0*	*0*

For 450V input DC voltage the simulation results such as, output line to neutral voltages, line to line voltages, currents & harmonics spectrums of all voltages and currents of the inverter have been given below from figure 19 to figure 25.

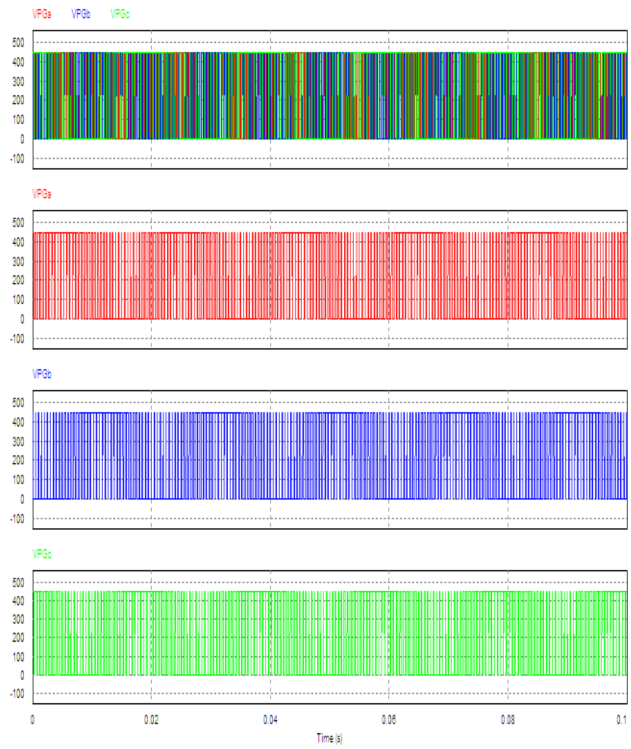

Fig. 19. Three phase Sinusoidal Pulse width modulated voltage source inverter open circuit output voltage

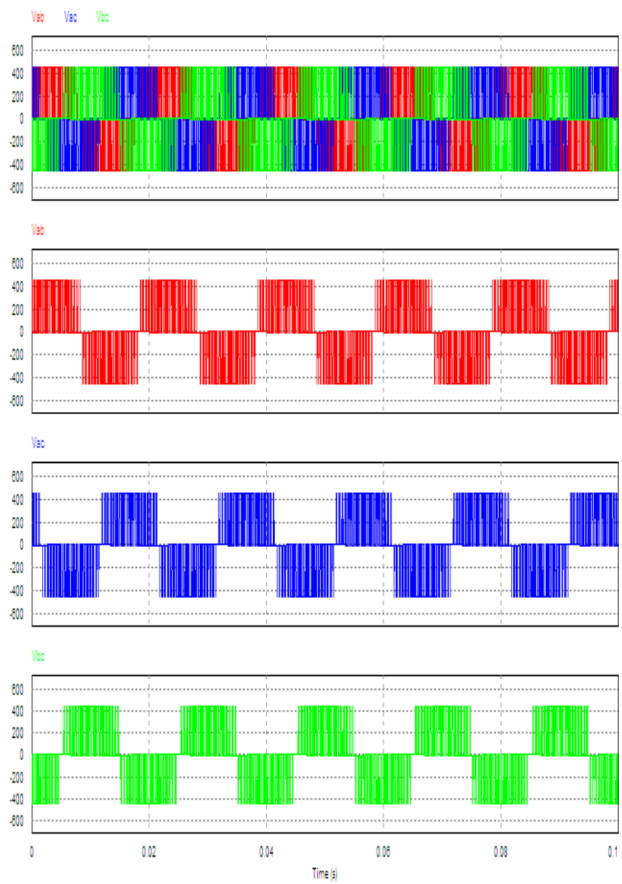

Fig. 20. Three phase line to line voltage (450 V) of the inverter

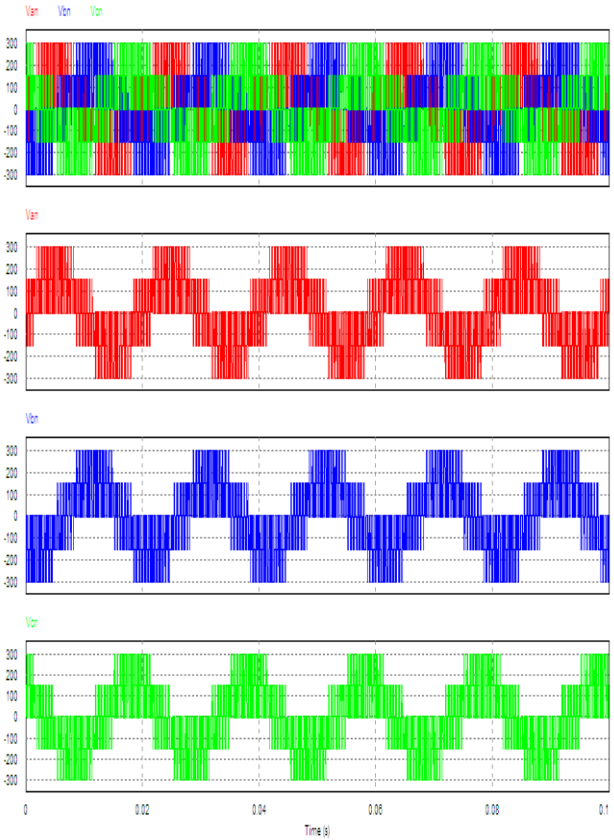

Fig. 21. Three phase load line to neutral voltage (300V)

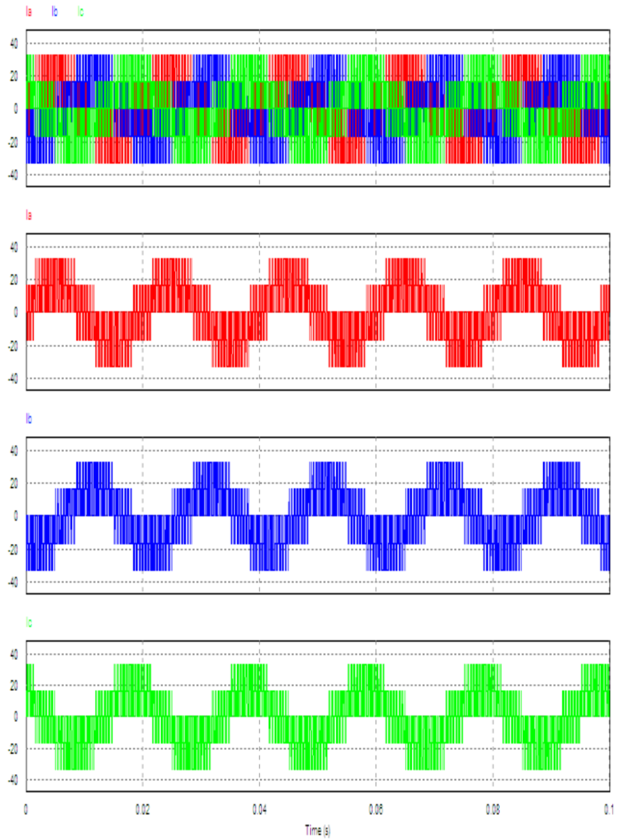

Fig. 22. Three phase current of inverter for resistive load

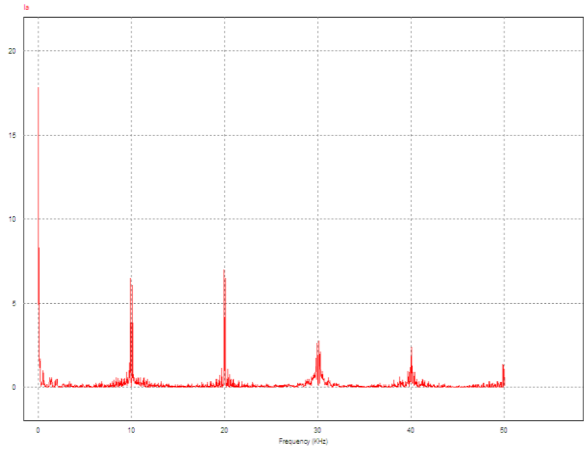

Fig. 23. FFT analysis of phase current for resistive load

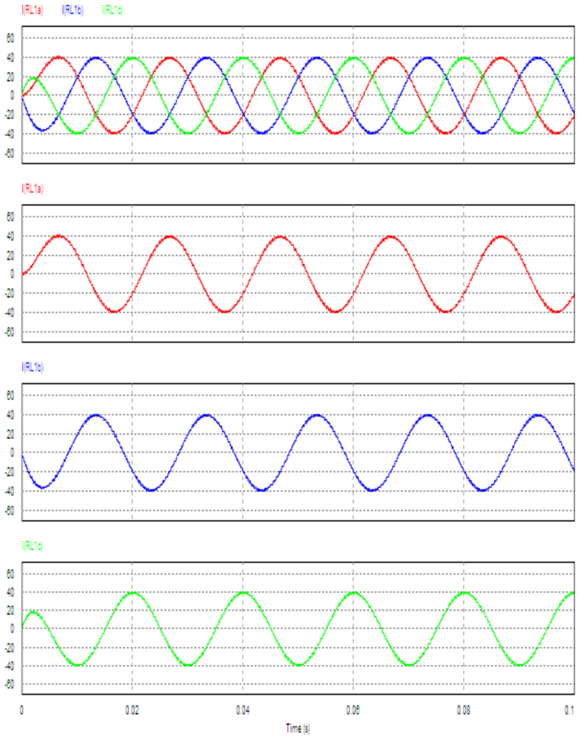

Fig. 24. Three phase output current for RL load

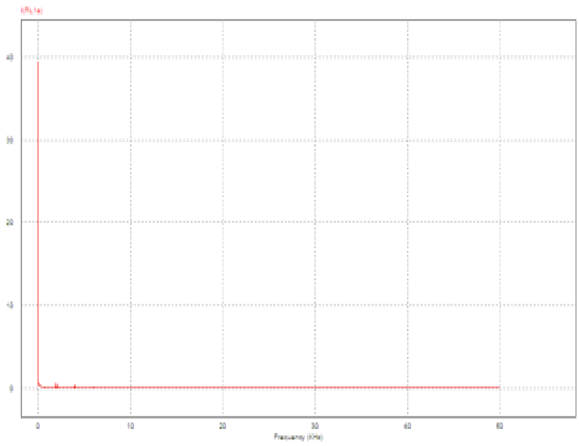

Fig. 25. FFT analysis of output current for RL load

7. Simulation of Inverter With Passive Filter & Transformer

Solar energy system cannot provide a continuous source of energy due to the low availability during no-sun period such as during winter and rainy season. The wind system cannot satisfy constant load due to different magnitudes of wind speed from one hour to another. So there are big problems in the separately use of these renewable energy sources [26]. For ensuring stable and continuous power, a hybrid renewable energy system including more than one type of energy component, is often used [27]. A hybrid renewable energy system making most efficient use of the different renewable resources is used to ensure stable and reliable power generation [28]. Moreover, the small autonomous regions of power systems, called micro grids, can offer increased reliability and efficiency and can help to integrate the renewable energy and other forms of distributed generations (DG) [29]. Many forms of DG such as fuel-cells, PV and micro-turbines are interfaced to the network through power electronic converters [30]. These interface devices make the sources more flexible in their operation and control compared to the conventional electrical machines. However, due to their negligible physical inertia, they also make the system potentially susceptible to oscillation resulting from network disturbances [31]. Usually, in order to inject energy to the grid, current source inverter (CSI) is used, while in island or autonomous operation voltage source inverter (VSI) is used [32]. To achieve flexible micro grids, which are able to operate in both grid-connected and island mode, VSIs are required [33]. Two diagrams of typical inverter based micro grid systems are shown in figure 34 and 35.

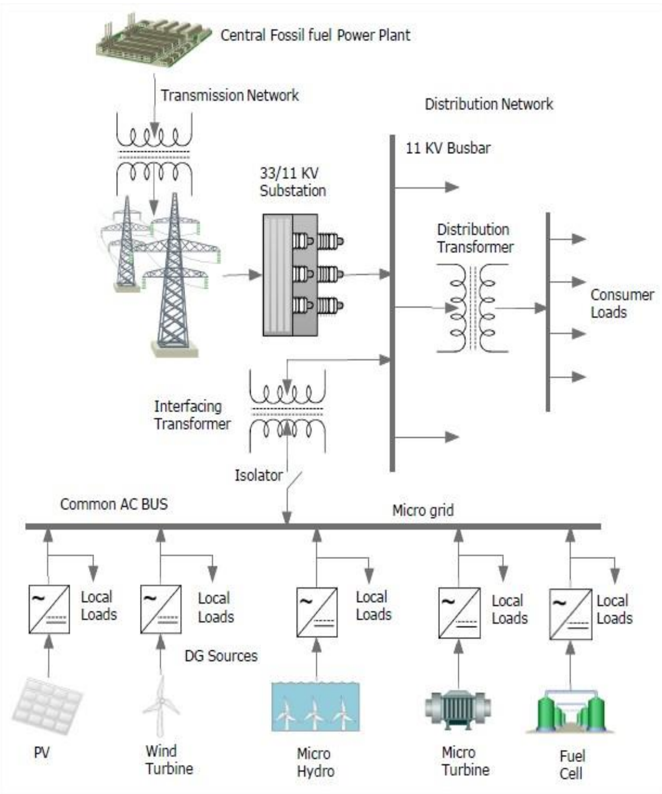

Fig. 26. A typical inverter based micro grid system with common AC bus

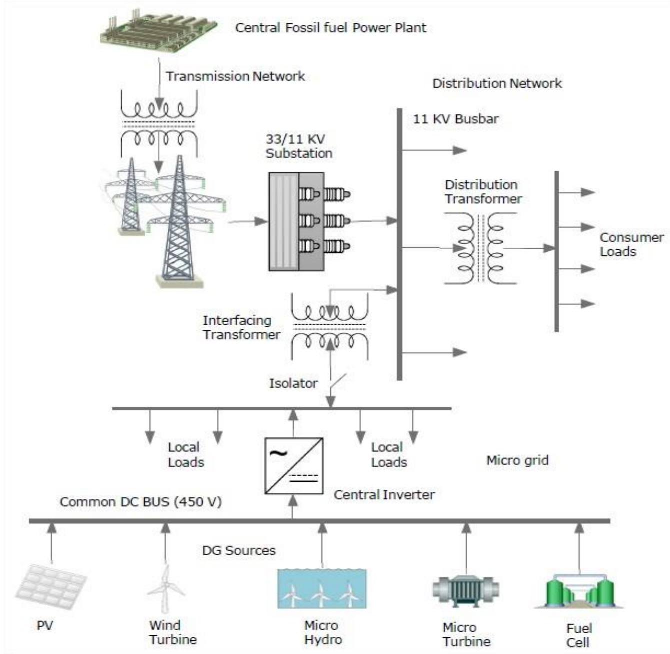

Fig. 27. A typical inverter based micro grid system with common DC bus

The outputs of an inverter contain large amount of harmonics content. The VSI generates an AC output voltage waveform composed of discrete values (high dv/dt); therefore, the load should be inductive at the harmonic frequencies in order to produce a smooth current waveform [5]. The need for inverters in distributed generation systems and micro-grids has clarified the significance of achieving low distortion, high quality power export via inverters. Both switching frequency effects and grid voltage distortion can lead to poor power quality. A well designed filter can attenuate switching frequency components but impacts on control bandwidth and the impedance presented to grid distortion [34]. To the standalone load system where the loads are low voltage, the inverter is used without transformer but in case of utility grid or high voltage sensitive loads (several KV) it should be used step up transformer with the inverter. As a result, due to the noise/harmonic components the loss in the transformer will be increased and then it will be badly affected. Moreover, the core loss in the machine is also increased by the presence of harmonics in the supply voltage and current [35].

Harmonic attenuation can be achieved by several methods such as by resonating of the loads, by an LC filter, by pulse width modulation, by sine wave synthesis, by selected harmonic reduction and by polyphase inverters [36]. Apart from these in PWM technique, if the carrier frequency is increased, the harmonics components are reduced. A high-carrier ratio improves waveform quality by raising the order of the principle harmonics. At low fundamental frequencies, very large carrier ratios are feasible and resulting in near-sinusoidal output current waveforms account for one of the main attributes of the sine wave PWM inverter [35]. However, there are different types of filtering circuits. RC & LC filters are the most used passive filters. They are divided into 1^{st} order, 2^{nd} order & 3^{rd} order filters according to the combination of the passive components. L or C is the first order filter, LC is the 2nd order filter and LCL is the 3rd order filter.

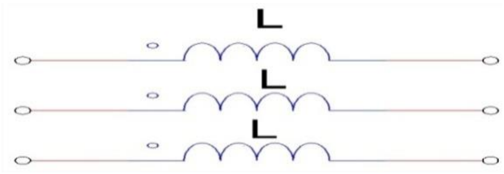

Fig. 28. 1st order filter for 3 phase system

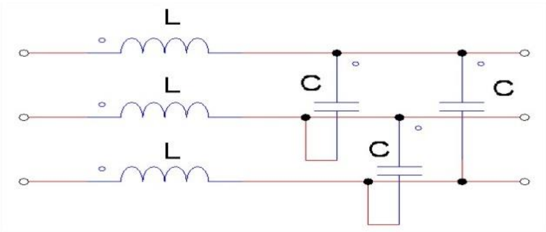

Fig. 29. 2nd order LC filter for 3 phase system

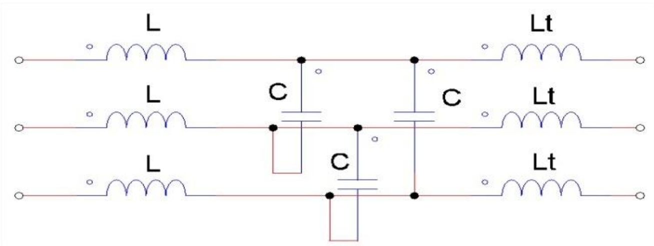

Fig. 30. 3rd order LCL filter for 3 phase system

With low inductance on the inverter side, it is difficult to comply with IEEE519 standards without an LCL filter. An LCL filter can achieve reduced levels of harmonic distortion with lower switching frequencies and with less overall stored energy [34]. In this system L_t is the inductance of the transformer through which the inverter is connected to the grid. After LC filter a transformer is used and the LCL filter is formed. It eliminates all high order harmonics from the output waveform of the inverter so that the output is 50Hz, low distortion, pure sinusoidal voltage wave. The cut-off frequency of the low pass filter is selected such that, total THD is less than 5%. The calculation is done by the following equation,

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{L+L_t}{LL_tC}} \quad (22)$$

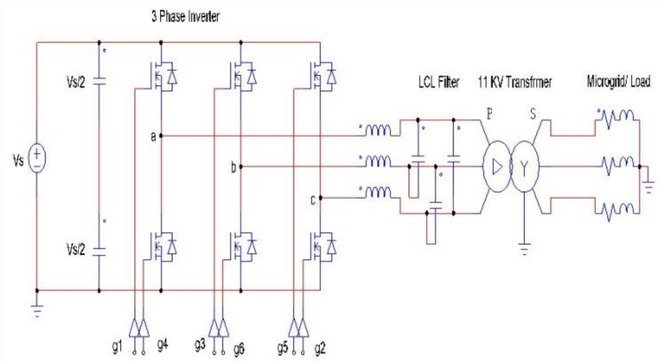

Fig. 31. Circuit diagram of three-phase inverter with transformer

The simulation results of the transformer inputs after filtering and transformer outputs have been given below,

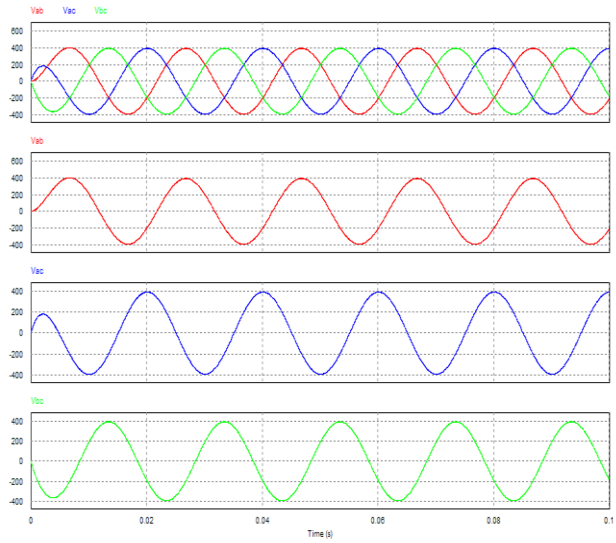

Fig. 32. Three phase line to line voltage after filtering

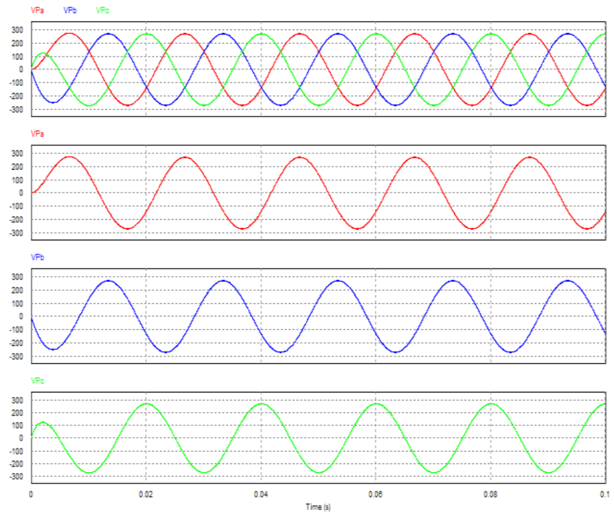

Fig. 33. Three phase line to neutral voltage after filtering

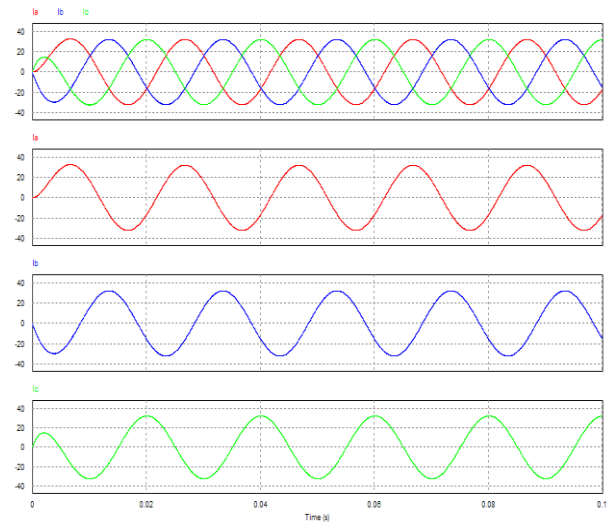

Fig. 34. Three phase output current after filtering

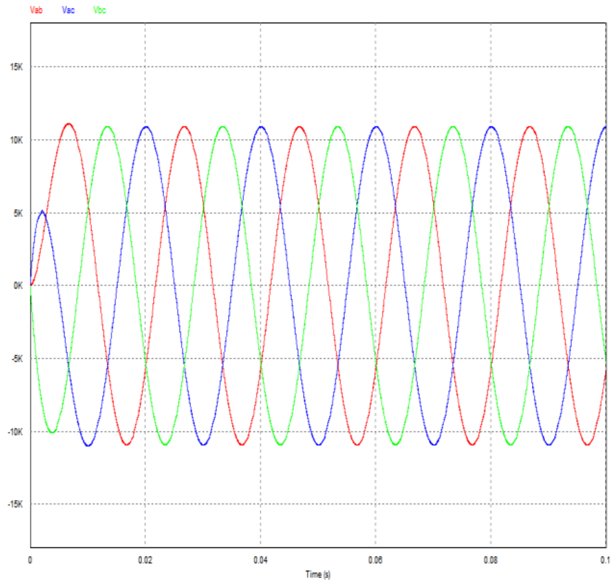

Fig. 35. Output line to line voltage (11KV) of transformer

8. Discussion

The DC input voltage of three phase inverter is 450V. The MOSFET switches assumed as ideal device. The output voltage of single phase inverter is 450V. At the same time, according to the simulation output wave shapes of three phase inverter, all the output voltages match with the table1. The line to neutral peak voltage is 300V AC and line to line peak voltage is 450V AC before filtering. The THD of the output voltage is9.1279672e-001 or, 91.279672 %.And after filtering the output line to neutral voltage is almost 270V AC and line to line voltage is almost 405V AC, which are less due to some voltage drop to the inductor of the LC filter and reduction of harmonic components. The THD is 14.943469e-003 or, 1.4943469% after filtering using the LCL 3rd order passive filter. The fundamental frequency is 50Hz. Thus the output is pure sinusoidal. The output voltage and frequency can be varied/adjusted by varying the modulation index and reference sine wave frequency. Moreover, the output line to line voltage of the transformer is 11KV AC, 50 Hz. The transformer is three-phase D-Y tap changing transformer.

9. Conclusion

From all the simulation results it is seen that the designed Op-Amp/Analog circuit controlled PWM inverter works accurately. It fulfills all the requirements for a voltage source inverter. The THD is less than 5% after filtering. The inverter outputs can be varied by varying the resistance of potentiometer. The inverter responses better for standalone inductive loads like induction motor.

If the power is not enough to supply to the grid then it will supply the power to the local standalone loads. If the carrier frequency is increased much enough then the filtering system will be much better and the loss will be less. But better response can be achieved by using the feedback system, means the closed loop control system. The future work can be done on the feedback loop system.

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