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A NEW TECHNIQUE TO MINIMIZE THE RIPPLE CURRENT OF THE PWM INVERTER

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ABSTRACT

This paper presents an efficient technique to minimize the output ripple current of the conventional pulse width modulated (PWM) inverters. The output ripple current waveforms of the conventional PWM inverters due to different load conditions are simulated and analyzed. The effect of change in modulation index of the conventional PWM inverters to maintain constant output rms voltage due to load variation and the harmonic components using Fast Fourier Transform (FFT) are also simulated and analyzed. In the proposed inverter the transformer windings are split into three different rated windings and the controller is such designed that, during load variation the comparator compares the load with reference values and decides which coil(s) should be connected to the battery through the switching devices using digital technology. The output voltage and current waveforms of the proposed PWM inverter are simulated and compared with the same of the conventional inverter. The output ripple current and the harmonic components of the proposed inverter are satisfactorily less than that of the conventional PWM inverter for the same carrier frequency and for the same load. The article explores the efficient technique to produce sufficient high quality of sinusoidal output wave shape by lowering the ripple current and harmonic components with the ordinary switching devices available in the market with a moderate carrier frequency for all load conditions. The MATLAB software has been used in overall simulation work.

INTRODUCTION

Inverters are widely used in industrial applications such as induction heating, standby power supplies and uninterruptible supplies. The PWM techniques and strategies have been the subject of intensive research since 1970's were to fabricate a sinusoidal ac output voltage. Sinusoidal PWM (SPWM) is effective in reducing lower order harmonics while varying the output voltage and gone through many revisions and it has a history of three decades. For low and medium power applications, square wave or quasi square wave voltages may be acceptable and for high power applications, low distorted sinusoidal waveforms are required. The most efficient method of controlling the gain and output voltage is to incorporate pulse width modulation control within the inverters (Said *et al.*, 2008; Gunwant, 2009; Bor-Ren, 2005; Narong, 2005; Michael, 1998). A basic circuit diagram representation of a single-phase inverter is shown in Figure 1. The inverter consists of four switching devices (represented as MOSFET) connected in the form of a bridge and known as diode MOSFET bridge. Another basic circuit diagram is shown in Figure 2. It consists of two switching devices (represented as MOSFET) and known as a single arm bridge. According to Figure 1, in case of the input of G1 and G4 are low level and the input of G2 and G3 are high level, G2 and G3 are become ON condition and G1 and G4 become OFF condition.

Therefore, the electric current flows through the direction from A to B of the secondary coil of the transformer. In case of the input of G1 and G4 are high level and the input of G2 and G3 are low level, G2 and G3 are become OFF condition and G1 and G4 become ON condition. Therefore, the electric current flows through the direction from B to A of the secondary coil of the transformer. According to Figure 2 in case of the input of G1 is low level and the input of G2 is high level, G2 become ON condition and G1 become OFF condition. Therefore, the electric current flows through the direction from P to A of the secondary coil of the transformer. In case of the input of G1 is high level and the input of G2 is low level, G1 become ON condition and G2 become OFF

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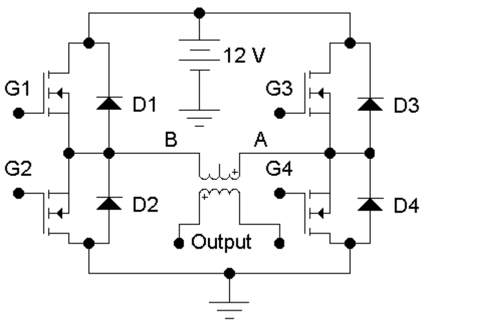

Figure 1. A double arm bridge inverter

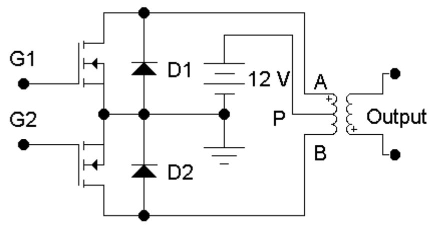

Figure 2. A single arm bridge inverter

condition. Therefore, the electric current flows through the direction from P to B of the secondary coil of the transformer. Therefore, the electric current which flows through the transformer becomes contrary to the both cases of the above two. The output voltage of the inverter depends on the transformer winding. For a particular inverter, the winding is fixed. Therefore in modern inverters PWM technique is used to maintain fixed output voltage due to change in load. In PWM signal generator a sinusoidal reference signal V_{ref} is compared with the triangular waveform V_{tri} as shown in the Figure 3. When the value of the sinusoidal signal is greater than the triangular signal the value of PWM signal generator is high level and vice versa. The amplitude modulation index "M", which controls the rms value of the output voltage, is defined as,

$$M = V_{ref} / V_{tri} \qquad (1)$$

According to Figure 1, the applied pulse at gate G1 and G4 is shown in Figure 3 and the applied pulse at G2 and G3 is shown in Figure 4. According to Figure 2 the applied pulse at gate G1 is shown in Figure 3 and the applied pulse at G2 is shown in Figure 4. In other word the inverted signal applied for G1 is applied to G2 for single arm bridge inverter and the inverted signal applied for G1 and G4 is applied to G2 and G3 for double arm bridge inverter.

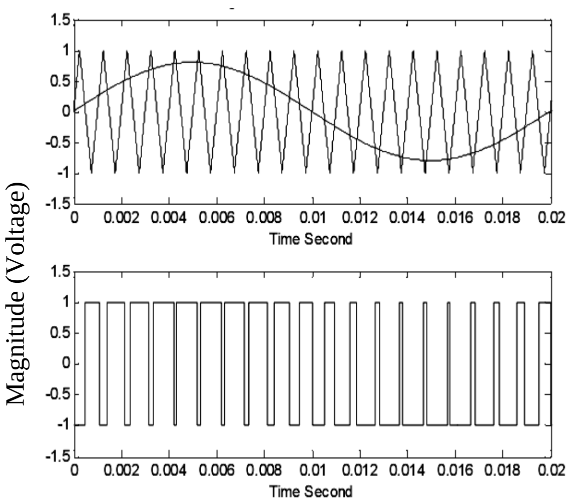

Figure 3. PWM signal generation technique for terminal G1 and G4

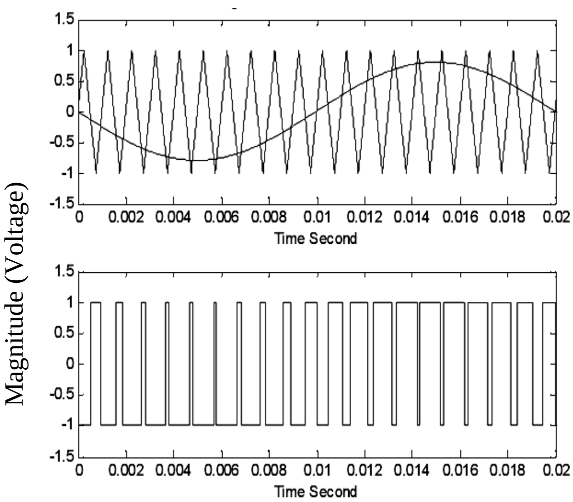

Figure 4. PWM signal generation technique for terminal G2 and G3

The quality of output waveshape increases with increase in the value of carrier frequency and vice-versa. But there is a limitation of increase in the value of carrier frequency. The PWM signal generated with a higher carrier frequency has lower pulse width as shown in the Figure 5 with some arrows. The pulse width decreases with the increase in carrier frequency.

As the switching devices like transistor, MOSFET etc. are not ideal so the value of reverse recovery time is not equal to zero. The difference of the pulse width indicated by the arrow must be greater than the reverse recovery time of the switching devices. In this technique very fast switching devices are required. Also the comparator devices should be very fast. The costs of the fast switching devices are more.

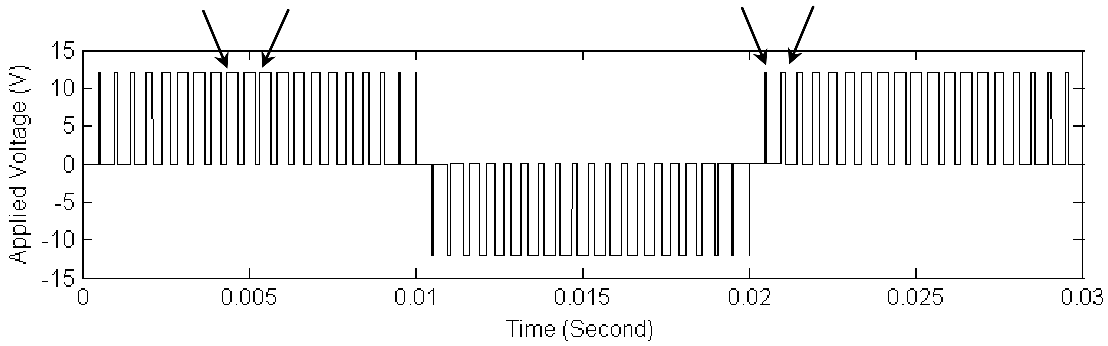

Figure 5. Voltage input to the primary side of the transformer by switching devices in PWM technique

CONVENTIONAL PWM INVERTER

With increase in load, the terminal voltage tends to decrease in any practical transformer. The modulation index, M should be changed for voltage regulation, that is, the value of M is greater for large loads than the value of M for small loads in conventional PWM inverter. Figure 6 and 7 shows the harmonic profile with the variation of modulation index M for multiple PWM and sinusoidal PWM (SPWM) according to Equation 2 and 3 respectively. The distortion factor increases significantly with decreasing in M (Joachim, 1992). The fundamental amplitude of the output waveforms for the multiple PWM and SPWM is also smaller with decreasing in M. Thus the PWM techniques, however, exhibit poor performance with lower loads with regard to maximum load. For some of the higher order harmonics the amplitude changes a little but it does not affect much (S. Jeevananthan *et al.*, 2004; P. Enjeti *et al.*, 1988).

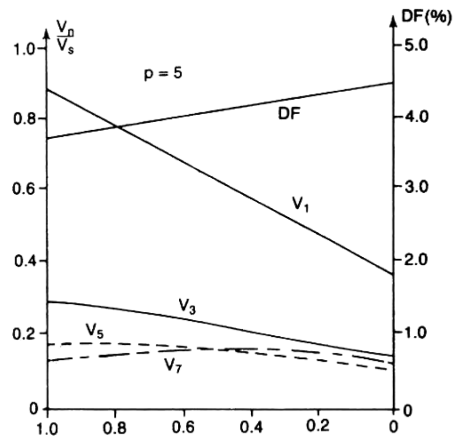

Figure 6. Harmonic profile of multiple pulse width modulation

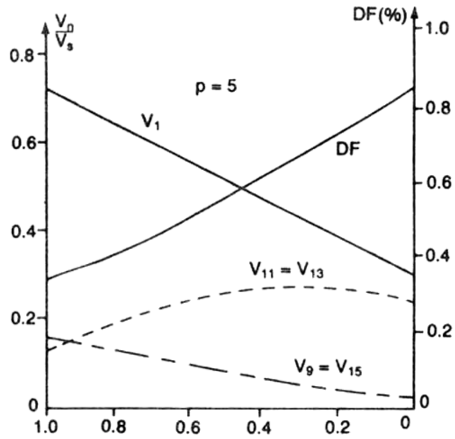

Figure 7. Harmonic profile of sinusoidal pulse width modulation (SPWM).

$$V_o = \left[\frac{2p}{2\pi} \int_{(\pi/p-\delta)/2}^{(\pi/p+\delta)/2} V_s^2 d(\omega t) \right]^{1/2} ; \; B_n = \sum_{m=1}^{p} \frac{2V_s}{n\pi} \sin\frac{n\delta}{2} \left[\sin n \left(\alpha_m + \frac{\delta}{2} \right) - \sin n \left(\pi + \alpha_m + \frac{\delta}{2} \right) \right] \quad (2)$$

$$V_o = V_s \left(\sum_{m=1}^{p} \frac{\delta_m}{\pi} \right)^{1/2} ; \; B_n = \sum_{m=1}^{p} \frac{2V_s}{n\pi} \sin\frac{n\delta_m}{2} \left[\sin n \left(\alpha_m + \frac{\delta_m}{2} \right) - \sin n \left(\pi + \alpha_m + \frac{\delta_m}{2} \right) \right] \quad (3)$$

Here V_o is the output rms voltage, B_n is the fourier coefficient and p represents the number of pulses per half cycle in both multiple PWM and SPWM inverters, For multiple PWM technique δ

is the pulse width and α is the angle where the pulse is started. For SPWM technique δ_m is the pulse width of m^{th} pulse and α_m is the angle where m^{th} pulse is started.

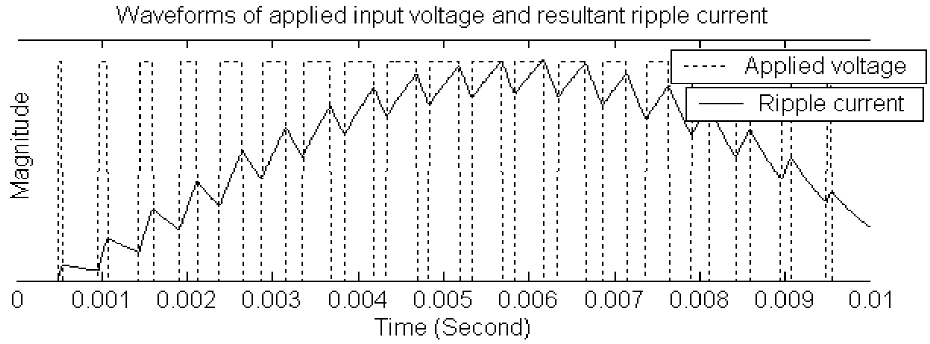

Figure 8. The output ripple current for 50 percent of full load

In the conventional PWM inverter the modulation index, M depends on load. Therefore when load decreases the output voltage tends to increase so the M should be decreased. The distortion factor DF increases with decrease in M. So the distortion factor increases with decrease in load in conventional inverters for a constant carrier frequency which is fixed for almost any particular PWM inverter, can be treated as one of the major disadvantages. The output ripple current depends on the load for any particular transformer as the equivalent series resistance and inductance can be considered fixed. The magnitude of the ripple current decreases with increase in load and vice-versa. The simulation result of the conventional PWM inverter of 700 VA rating for 50 percent of full load is shown in Figure 8 and the same for 25 percent of full load is shown in Figure 9.

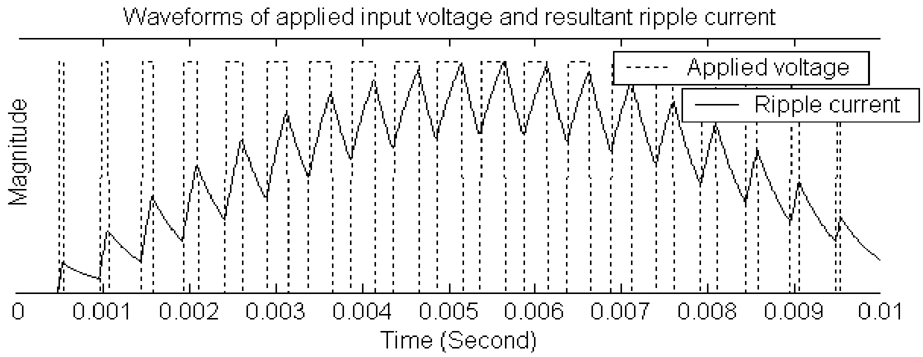

Figure 9. The output ripple current for 25 percent of full load

The resistive value of the 50 percent of full load is half than that of the 25 percent of full load. Both the loads are connected to the output of this inverter individually. Due to the variation of resistance the ripple current is changed and it is clear that for the 25 percent of full load the value of the ripple current is greater than that of the 50 percent of full load. So the ripple current increases with decrease in the load and in other word with decrease in M. For 50 percent of full load which is 350 watt load the modulation index is 0.71 and for 25 percent of full load the modulation index is 0.57. In the both cases the carrier frequency is 1000 Hz and the positive half sine wave is shown. It does not matter what is the VA rating of the inverter rather it matters what is the percentage of load is connected to the output terminal; so a purely resistive load of 50 watt connected to a 100 VA rated inverter results the same in voltage and current waveshapes for the purely resistive load of 300 watt connected to a 600 VA inverter. The voltage applied across the primary coil of the transformer at 1 KHz of carrier frequency at 0.71 modulation index is shown in Figure 5. The waveshape of the ripple current depends on the load. The most simplified equivalent circuit of a transformer consists a resistance and an inductance in series if magnetization current is neglected as considered in the most cases because the value of the magnetization current is very small (S. Jeevananthan *et al*., 2007; Muhammad H. Rashid, 2003; Irving L. Kosow, 1999). The most simplified equivalent circuit of transformer is shown in Figure 10. The magnitude and slope of the current waveshape shown in Figure 8 and 9 depends on the transformer's equivalent series resistance and reactance represented as R and X respectively as shown in Figure 10.

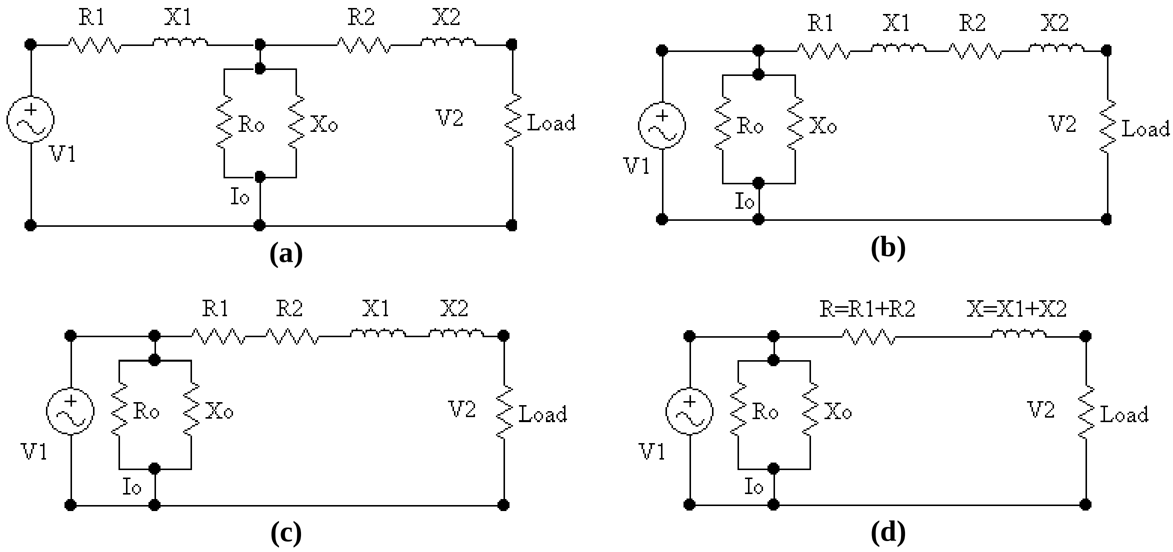

Figure 10. The equivalent circuit of the transformer

In most practical cases switching devices are cascaded in parallel to obtain more power rating. A single switching device either BJT or MOSFET cannot handle full power operation. The conventional parallel operation is shown in Figure 11. For simulation work, let the maximum power handling capacity of the conventional inverter is 700 VA. MOSFET bridges are used in most applications now a days as it has low switching loss. In this inverter seven single arm MOSFET bridges are connected totally assuming that the rating of a single arm MOSFET bridge is 100 watt. So the inverter is capable to handle total 700 watt of power at unity power factor. All the G1 are a common point and all the G2 are another common point. Its operation is exactly same as a single arm bridge inverter. The dc voltage source is applied from the 12 volt lead acid battery which is widely used in most of the inverter commercially.

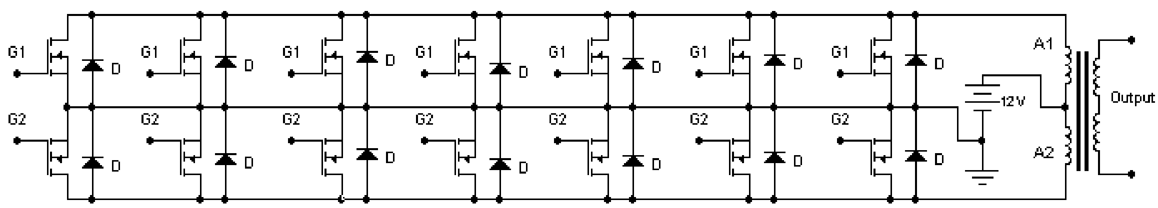

Figure 11. The conventional parallel operation of the switching devices.

THE PROPOSED INVERTER

The basic circuit diagram containing switching devices is shown in Figure 12 for single arm bridge operation. Its VA rating is also 700 VA as the conventional inverter. Seven single arm MOSFET bridges are used also but the transformer windings are subdivided into three windings. If the current rating of coil A is I, than the current rating of coil B is 2I and the current rating of the coil C is 4I. So if coil A is capable to transfer P VA of power than coil B is capable to transfer 2P VA of power and coil C is capable to transfer 4P VA of power. So in this case, the transformer coil A, B and C are capable to transfer 100 VA, 200 VA and 400 VA of power respectively so the transformer is capable to handle total 700 VA of power. There are total six input gates of MOSFETs; G1, G2, G3, G4, G5 and G6. The control scheme is such that when G1 and G2 are in operation and G3, G4, G5 and G6 are off, the inverter is than capable to handle 400 VA as this section is connected to the coil C that is capable to deliver 400 VA to its secondary. And when G3 and G4 are in operation and G1, G2, G5 and G6 are off, the inverter is than capable to handle 200 VA as this section is connected to the coil B that is capable to deliver 200 VA to its secondary. And when G5 and G6 are in operation and G1, G2, G3 and G4 are off, the inverter is than capable to handle 100 VA as this section is connected to the coil A that is capable to deliver 100 VA to its secondary.

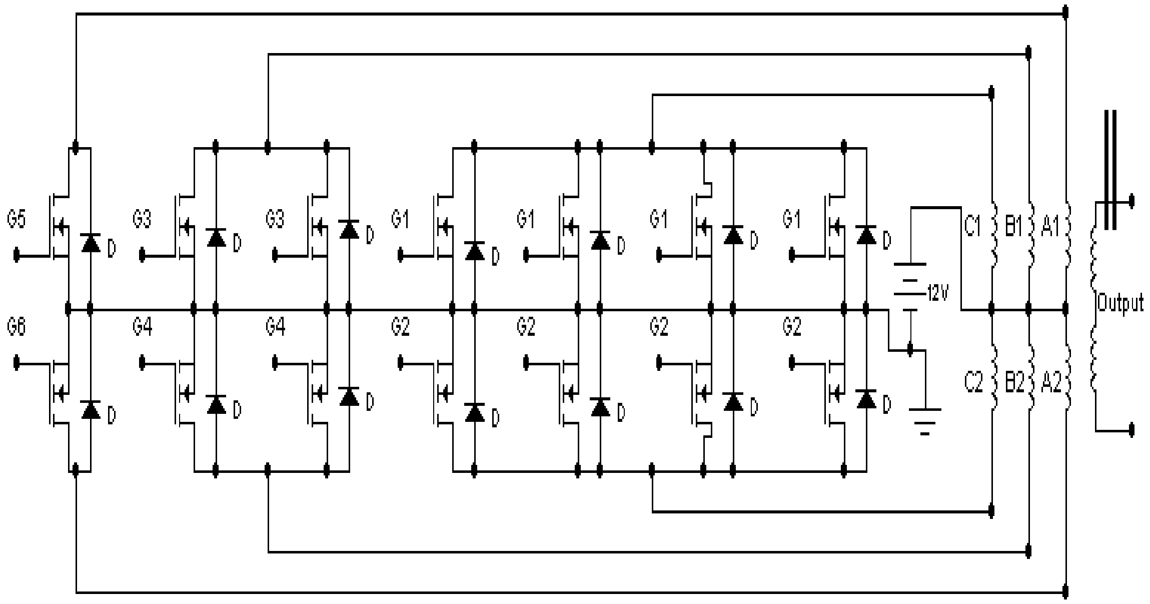

Figure 12. The proposed parallel operation of the switching devices.

The controller output is such connected to the MOSFET inputs so that it cannot conduct all the coils in all situations. A load will receive the power according to its impedance value provided that the rms voltage of the ac system is constant. For any load condition at first impedance measurement is taken, than the required power for the load is calculated and it is compared with the reference values by the comparators. The output signal of the comparator is digital. As the coils are split into three different rated coils so the maximum possible combination is eight including no load condition and full load condition. An encoder having seven input lines and three output lines is used in this controller to make proper selection of winding(s) according to the load (B. L. Theraja, 2003; Albert, 2001). All the inputs of the MOSFET bridges are connected to the output terminals of logic AND gates having two inputs. One of the two logic inputs of a logic AND gate is connected with the PWM signal generator output and another terminal of the logic inputs is connected to the output of the encoder. So if the encoder sets zero to any one of the two inputs of any one of the logic AND gates the PWM inverter cannot trigger the corresponding MOSFET Bridge and thus the corresponding coil is unable to conduct. The load is categorized into eight steps. The subsystem of the controller is shown in Figure 13. From the impedance the power drawn by the load is calculated and this is compared with different references by comparators. The encoder circuit consists of three output channels which are connected with three primary windings which are split through the breakers (static relay switches). The MOSFET bridges are connected with other terminals of the breakers. The load is connected to the connection 4 and 5. In no load and overload condition the controller disconnects all the coils and thus it is helpful for the system to minimise the magnetizing current and also for the protection of the system.

At no load condition the output of the encoder is 000. When a load ranges from 0 to 100 watt than the output of the encoder is 001. When a load is greater than 100 watt and within 200 watt than the output of the encoder is 010 and so on. The digital logic circuit is so designed that in overload condition the output of the encoder circuit is 000. The winding A is connected with the least significant bit and winding C is connected with the most significant bit through the static relay switches. According to load which coils are permitted to conduct through MOSFETs and the output channels of the encoder with different loads which is categorized is shown in Table 1.

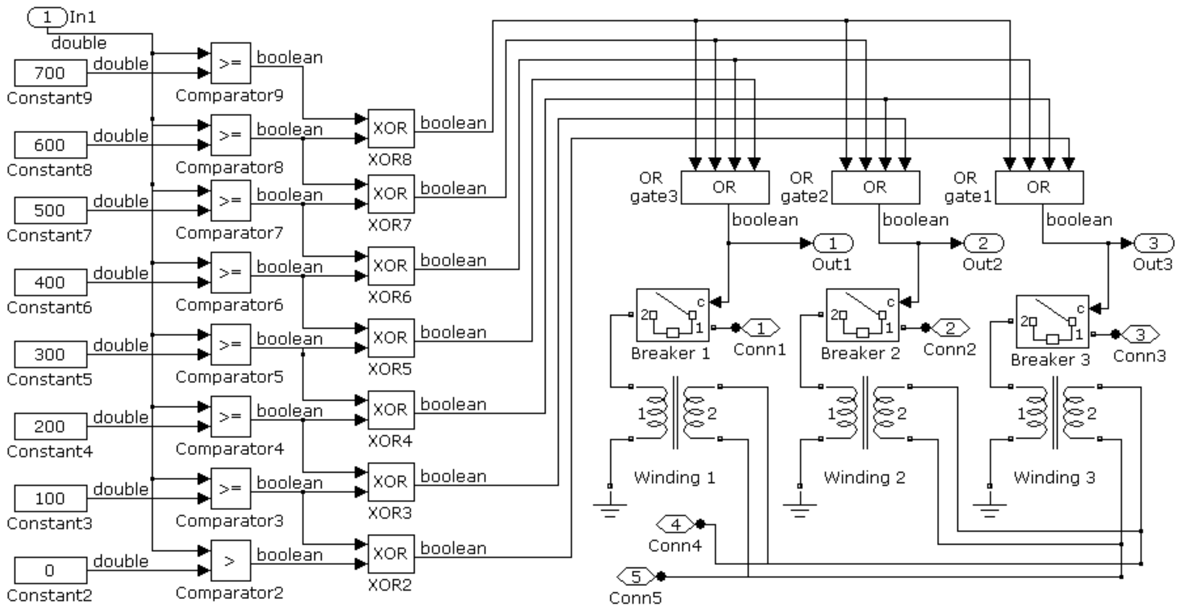

Figure 13. The subsystem of the controller

Table 1. Conduction of different coils switching through MOSFETs with **encoder value.**

Load (L)	Output of the encoder C B A	Status of MOSFET operation		Conduction of Coil	Percentage of full Load
		On	Off		
L = 0 (no load)	0 0 0	none	G1, G2, G3, G4, G5, G6	none	0
0 < L < = 100	0 0 1	G5, G6	G1, G2, G3, G4	A	14.28
100 < L < =200	0 1 0	G3, G4	G1, G2, G5, G6	B	28.57
200 < L < = 300	0 1 1	G3, G4, G5, G6.	G1, G2	A, B	42.85
300 < L < =400	1 0 0	G1, G2	G3, G4, G5, G6.	C	57.14
400 < L < =500	1 0 1	G1, G2, G5, G6	G3, G4	A, C	71.43
500 < L < = 600	1 1 0	G1, G2, G3, G4	G5, G6	B, C	85.71
600 < L < = 700	1 1 1	G1, G2, G3, G4, G5, G6	none	A, B, C	100
L > 700 (over load)	0 0 0	none	G1, G2, G3, G4, G5, G6	none	0

SIMULATION RESULTS AND DISCUSSION

For simulation work, let the maximum power handling capacity of the conventional and proposed inverter is 700 VA and the carrier frequency is 1 KHz. Figure 14 represents the output voltage and current waveshapes of the conventional inverter When 50 percent of full load is connected and Figure 15 represents the output voltage and current waveshapes of the proposed inverter at the same load. The ripple current and voltage of the proposed inverter are less than the conventional inverter in the same condition. Figure 16 represents the output voltage and current waveshapes of the conventional inverter when 25 percent of full load is connected and Figure 17 represents the output voltage and current waveshapes of the proposed inverter at the same load. The ripple current and voltage of the proposed inverter are less than the conventional inverter for 25 percent of full load condition.

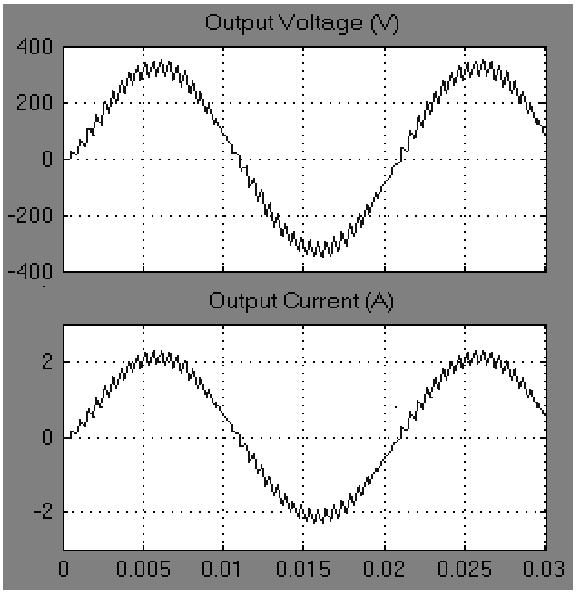

Figure 14. Output voltage and current waveshapes of the conventional PWM inverter with 50 percent load

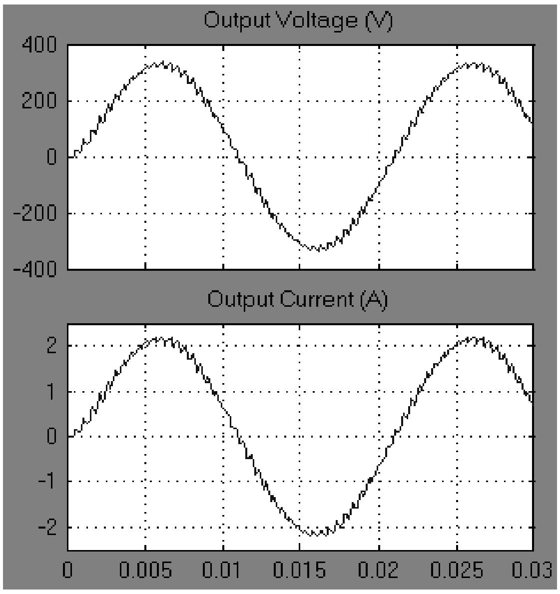

Figure 15. Output voltage and current waveshapes of the proposed PWM inverter with 50 percent load

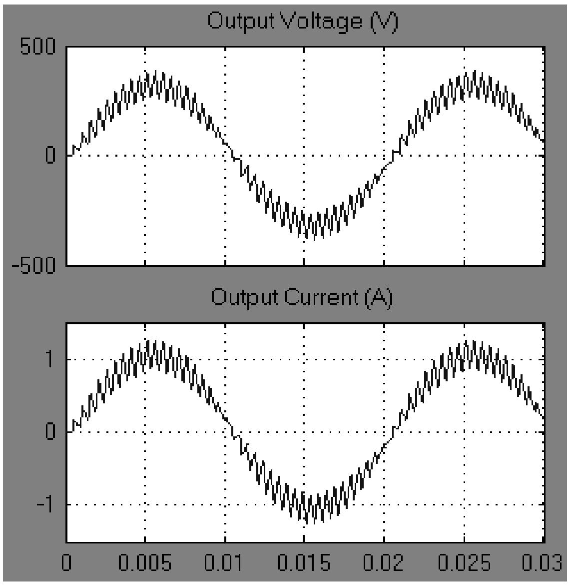

Figure 16. Output voltage and current waveshapes of the conventional PWM inverter with 25 percent load

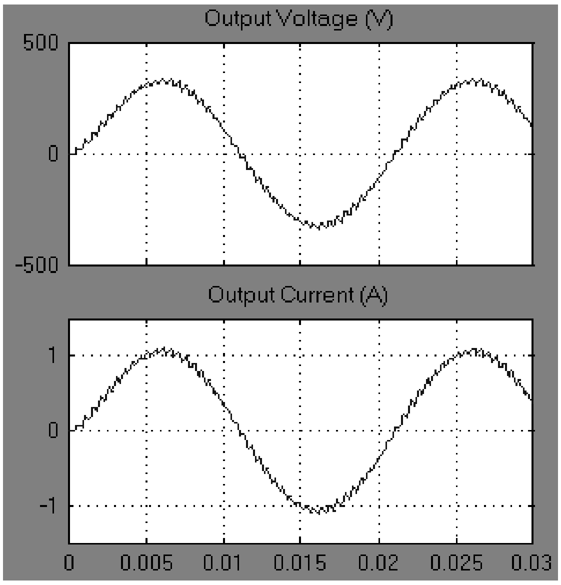

Figure 17. Output voltage and current waveshapes of the proposed PWM inverter with 25 percent load

Figure 18 represents the output voltage and current waveshapes of the conventional inverter when 15 percent of full load is connected and Figure 19 represents the output voltage and current waveshapes of the proposed inverter at the same load. For the above three load conditions the quality of output voltage and current waveshapes of the proposed inverter are much better than the conventional PWM inverter and the ripple current is quite low. The MATLAB simulation block diagram is shown in Figure 20. Three logic AND gates are connected to the gates of the MOSFET bridges of different power handling capacity. The rms voltage and current measurements are taken to calculate the impedance and power rating of the load. The feedback process of the proposed inverter is as usual. Depending on the difference between output rms voltage and the reference rms voltage, the value of modulation index, M is changed.

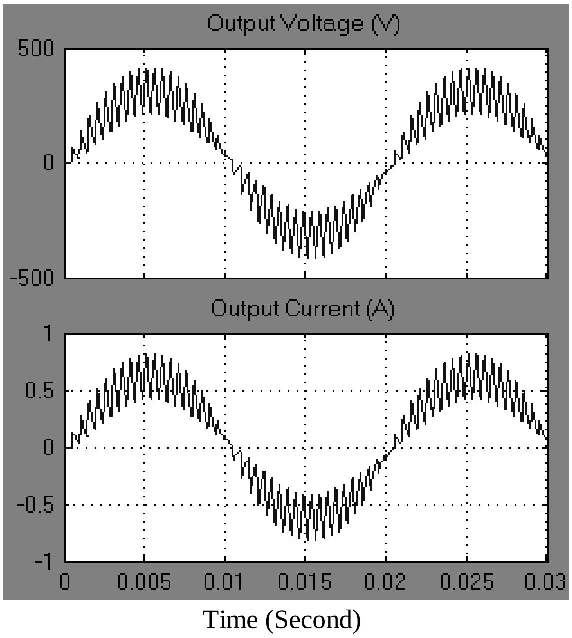

Figure 18. Output voltage and current waveshapes of the conventional PWM inverter with 15 percent load

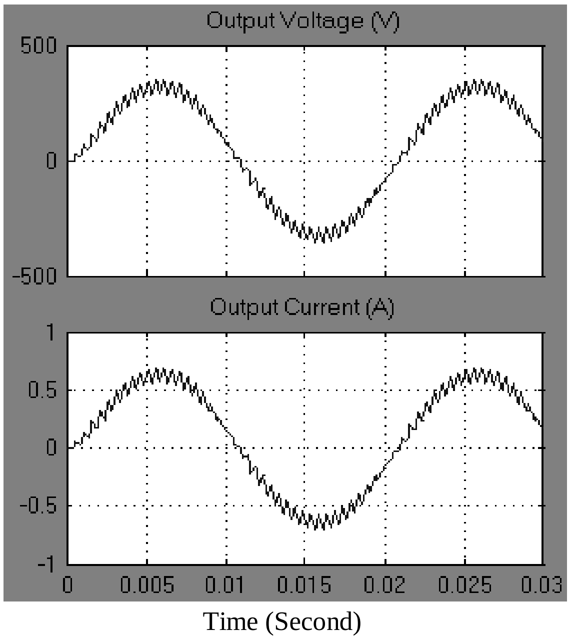

Figure 19. Output voltage and current waveshapes of the proposed PWM inverter with 15 percent load

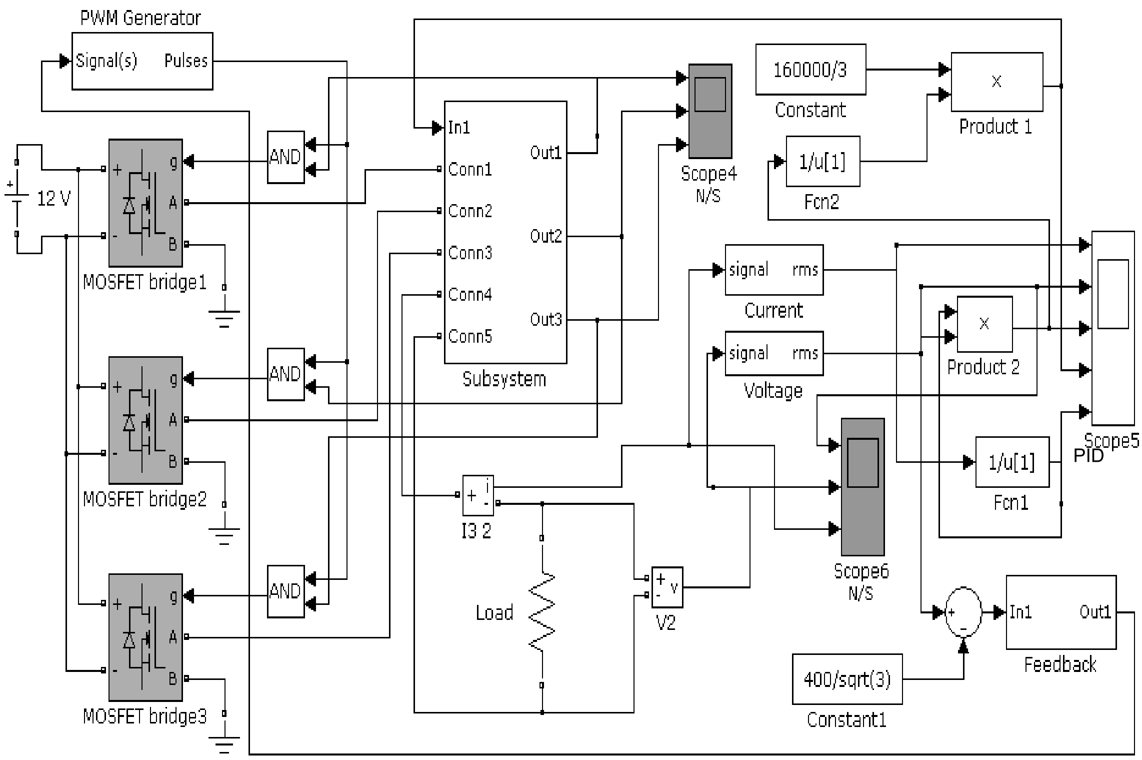

Figure 20. The MATLAB simulation block diagram

Figure 21 represents the flow chart of the proposed controller. Figure 22 and 23 represent the harmonic components of voltage of the conventional and the proposed inverter respectively when 25 percent of full load is connected. The harmonic components are less in the proposed inverter than the conventional inverter. The magnitude along Y axis is enlarged so that the harmonic components can be seen clearly and the scale is same in both cases. X axis represents the order of harmonic where the fundamental frequency is 50 Hz.

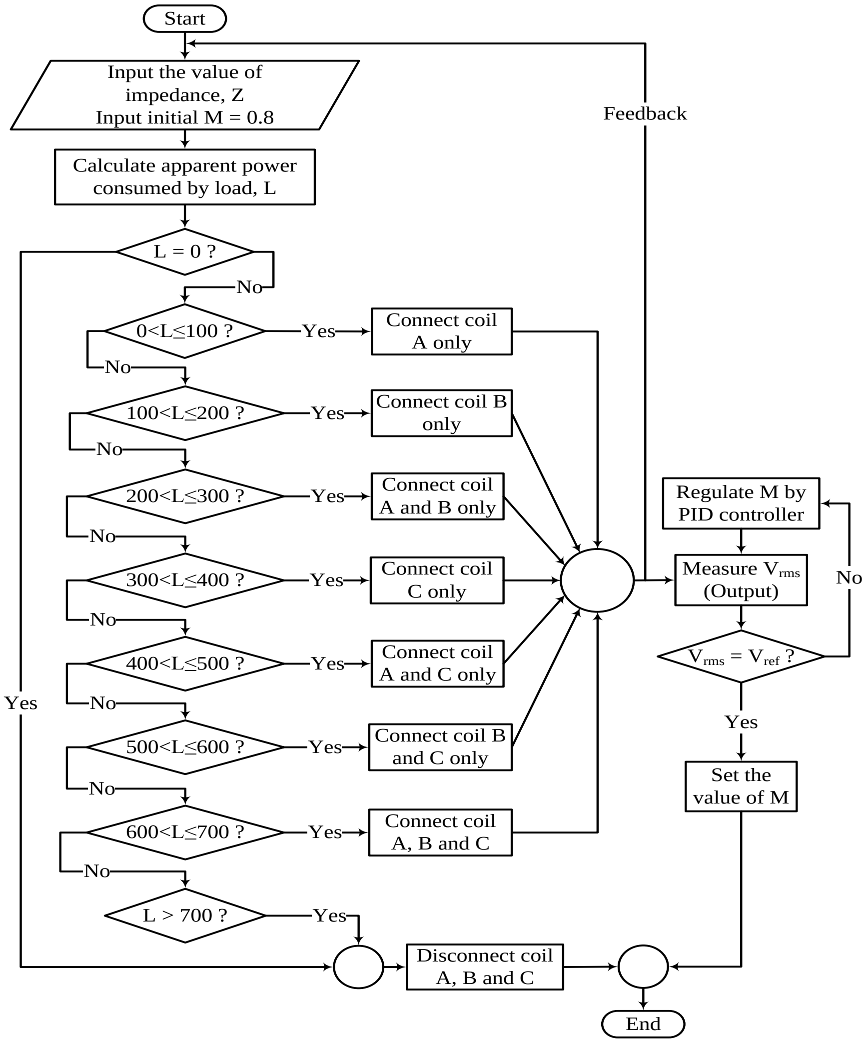

Figure 21. The Flow chart of the proposed controller

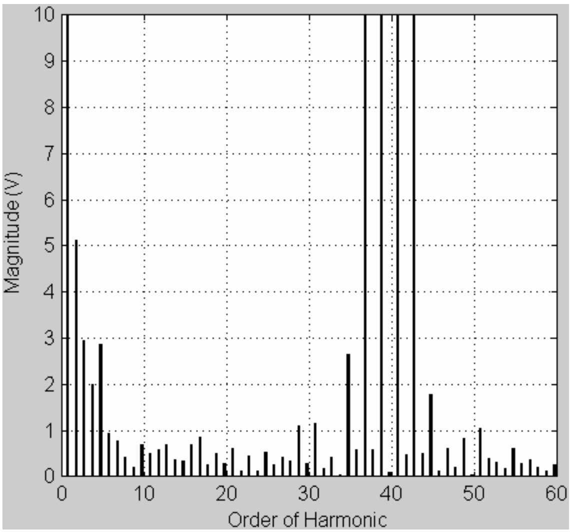

Figure 22. The harmonic components of the conventional PWM inverter with 25 percent load

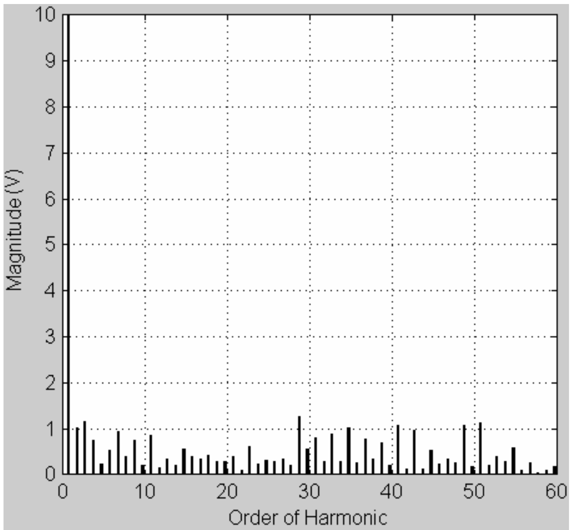

Figure 23. The harmonic components of the proposed PWM inverter with 25 percent load

DISCUSSION AND CONCLUSION

Though seven single arm MOSFET bridges are used in this experiment but any number of single or double arm MOSFET (or similar switching device) bridges can be used as the rating of all the inverters and MOSFETs are not the same. If the transformer is center tapped than single arm MOSFET bridges are used but if the transformer is not center tapped than in this case double arm MOSFET bridges are used. The overall cost of the proposed inverter is low because the high speedy control devices and switching devices are not essential as the value of carrier frequency used in this technique is low. The inverter is such designed that the ripple current, distortion factor and the harmonic components are low at different load conditions. The same technique is applicable in three phase PWM inverter. Though SPWM technique is used in the proposed controller, it can be used in any type of PWM technique like single PWM technique, multiple PWM technique, sinusoidal PWM technique, modified sinusoidal PWM technique and inverted sine carrier PWM technique etc. because it requires to change only the carrier signal; all other components should be unchanged. The windings of the transformer may be split into two, three or more coils according to necessity. The digital logic controller helps to protect overloading effect and makes proper selection of the necessary winding(s) while the PID controller sets the value of M very quickly to regulate the rms value. Ziegler–Nichols method is used for gain tuning of the PID controller.

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APPENDIX

System Frequency: 50 Hz; DC voltage: 12 V; Transformer rating: 700 VA, Rated voltage: 10/250V (RMS), Equivalent resistance: 0.004 p.u., Equivalent reactance: 0.1 p.u., Reference Voltage: $400/\sqrt{3}$ V (RMS); Carrier frequency: 1000 Hz; PID gain tuning method: Ziegler–Nichols method; MOSFET: IRF540N, Maximum drain current: 23 A, Static Drain-to-Source On-Resistance: 44 mΩ (when, V_{GS}=10 V, I_D=16A).