Performance Analysis of Parallel Connected Inverters using Different Modulation Techniques

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***Abstract*:- Parallel connections of inverters are being used in medium and high power applications. They are used to increase the output power and also to enhance a reliable source of power especially to critical loads. In this project various modulation techniques are proposed to analyse the performance of the inverter, minimize the output voltage THD, enhance the output voltage as well as eliminate the circulating current between the inverters that may flow as a result of their interaction. A three phase induction motor is used as a load. The modulation techniques with better performance among the three modulation strategies adopted in this work is selected based on the harmonic spectrum and the r.m.s output voltage, in order to control the speed of the machine for use in variable speed application. The speed can be controlled by varying the applied voltage, as already known that the starting torque is low when the voltage is low. Thus, even when the voltage is sufficient to achieve a running torque the machine may not start. The methodologies adopted are: the carrier phase shifted sinusoidal PWM (cps-spwm), third harmonic injection PWM and the SPWM with zero sequence signals. The system was simulated using matlab/simulink and the results was analysed and discussed.**

Keywords: Circulating current, CPS-SPWM, Parallel inverter, Third Harmonic injection, Induction motor.

1. INTRODUCTION

Parallel connected inverters in which both the ac and dc sides are connected in parallel finds applications in medium and high power applications due to their advantages that includes; modular connection of inverters, simplicity in maintenance, reduced cost, reduced THD and facilitate load power sharing between individual modules [1-7]. However, despite the numerous advantages of parallel connection of inverters, still they have their own short comings among which are; the circulating current that may be produced as a result of the inter module interaction, output current synchronization problem and equal load power sharing [5,6]. Similarly paralleling technique defends on a relatively large inductors applied between the inverter poles and the point of common coupling for current sharing. The objective of the paper is to analyse the performance of different modulation techniques proposed on parallel inverters based on THD and to achieve load current sharing between the inverter modules as well as the output voltage waveform. The three modulation techniques used to achieve the circulating current control, the load current sharing and the THD minimization are; the Carrier phase shifted SPWM, the third Harmonic injection PWM and the SPWM with the zero sequence signal [1-10].

With induction motor as a load to the inverter, the machine can draw large current while starting which produce voltage dips oscillatory torque and also generate harmonics in the power systems especially during transient operation. Due to such factors the modulation techniques with better performance among the three modulation strategies adopted in this project is selected based on the harmonic spectrum and the r.m.s output voltage, in order to control the speed of the machine for use in variable speed application. The speed can be controlled by varying the applied voltage, as already known that the starting torque is low when the voltage is low. Thus, even when the voltage is sufficient to achieve a running torque the machine may not start [10-17]. As such this method of controlling speed can be best used in applications that require little starting torque. Several control strategies for parallel connected inverters were proposed in many literatures based on applications [1-7]. The techniques mostly used are; the CPS–SPWM, space vector modulation, voltage/frequency droop control and master and slave control strategies. Both this control methods are applied based on applications. Space vector modulation without zero sequence current and with a strong current loop for power factor correction is proposed in [3, 4]. The master and slave control technique is usually employed for load current sharing especially among inverters with different power ratings. The idea is that the inverter with highest output current will be the master inverter where as the rest of the inverters will be the slave inverters [5, 6]. All the techniques proposed take the advantages of some features of parallel inverters in order to eliminate the circulating current between the inverters and the THD of the output voltage.

The paper is divided into five sections the first section gives the general introduction of the concept and the review of the related literature the second section explains the concept and the principle of operation of parallel inverters the third section discussed the different modulation techniques used to achieve the operation of the inverter, the simulation results is given in the fourth section and the last section gives the conclusion and future scope of the work.

2. OPERATING PRINCIPLE

The block diagram shown in Fig. 1 depicts a three phase VSI connected in parallel from both the input and the output side and then connected to a three phase induction machine as a load. The two inverters are directly connected at both the input and the output without a transformer and they are controlled separately [1]. Parallel connected inverters can be operated in two modes viz: The synchronous mode (non-circulating current mode) Asynchronous mode (The circulating current mode) of operation.

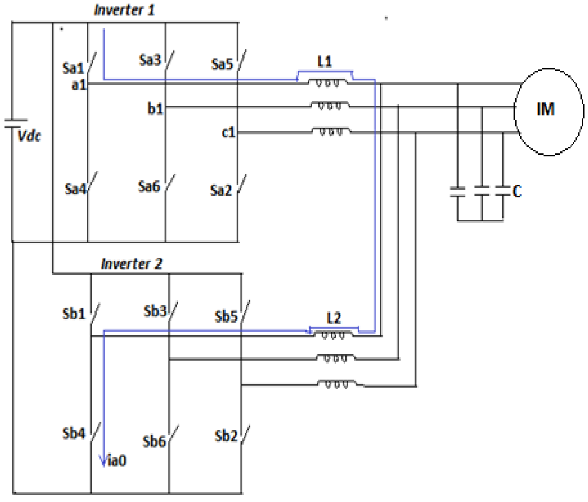


Fig.1 Parallel connected three phase VSI

(a) *The Synchronous mode*

This mode is otherwise called the non circulating current mode. When the power electronic switches between the parallel connected inverters are switched on at the same time, then there will be no circulating current flow between the inverters. However, the output phase voltage of the two inverters should have the same amplitude and phase voltage.

(b) *Asynchronous mode*

The circulating current mode, when the switching action of the power electronic switches is not synchronous meaning it is not at the same time then definitely circulating current will flow between the inverter modules. For example if an upper switch Sa1 of inverter #1 is On and a lower switch Sb2 of inverter #2 is On then, this provides a circulating current paths that will flows between the inverters through the source, as shown using the blue line in the diagram.

3. MODULATION TECHNIQUES

(a) CPS SPWM REALIZATION

As already stated CPS-SPWM is mostly used in medium and high power applications in order to reduce the circulating current, output current THD, and improve the output voltage waveform. A CPS-SPWM is a switch modulated SPWM applied to multilevel inverters and combination inverters for high power applications [4]. The principles and mode of application have been employed in many literatures [4, 5 & 9]. In this project the technique is applied to a three phase grid connected parallel connected inverters.

Figure below shows a CPS-SPWM strategy of the inverters shown above. The inverters are assumed to have same reference signals and same carrier frequency but are shifted between different modules. The reference equations are given below [1][9].

Phase a: $V_{ra}(t) = \frac{\pi}{2}[M\sin(\omega t)]$

Phase b: $V_{rb}(t) = \frac{\pi}{2}[M\sin(\omega t - \frac{2\pi}{3})]$ (4)

Phase c: $V_{rc}(t) = \frac{\pi}{2}[M\sin(\omega t + \frac{2\pi}{3})]$

The carrier initial phase angles of the inverters are given in [1].

$\Delta\emptyset_{c\_a1} = 0$ $\Delta\emptyset_{c\_b1} = -\frac{2\pi}{3}$ $\Delta\emptyset_{c\_c1} = \frac{2\pi}{3}$

$\Delta\emptyset_{c\_a2} = \pi$ $\Delta\emptyset_{c\_b2} = -\frac{2\pi}{3} + \pi$

$\Delta\emptyset_{c\_c2} = -\frac{2\pi}{3} + \pi$ (5)

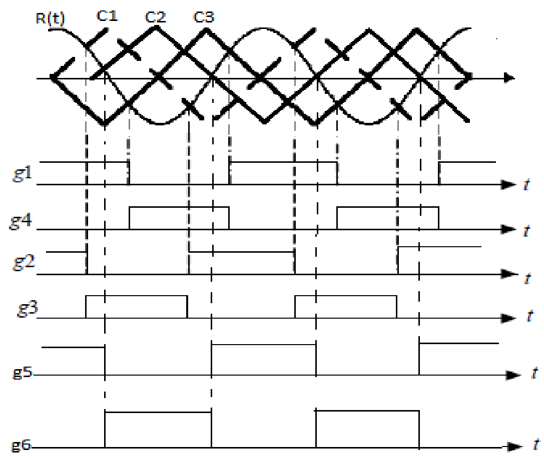


Fig. 2 CPS-SPWM for a three phase inverter

As shown in fig above the three carriers C1, C2 & C3 have the same amplitude but with different phase angle and they are compared with a sinusoidal reference signal R(t). The gating signals for the switches are generated from g1-g6. Signal g1 is used to turn on switch s1 and g4 to turn its complementary switch s4, similarly g3 & g6 and g2 & g5 will be triggered in the same way.

(b) THIRD HARMONIC INJECTION

This technique is implemented in the same way with the sinusoidal PWM, the difference is that the reference ac waveform is not sinusoidal but consists of both the fundamental component and the third harmonic component as shown in the figure below. The peak to peak amplitude of the resulting reference does not exceed the dc supply voltage. The fundamental component is higher than the available supply. The presence of exactly the same third harmonic component in each phase results in an effective cancellation of the third harmonic component in the neutral terminal and the line to line voltages. Third harmonic PWM provides better utilization of the dc supply voltage than the SPWM [18].

Fig. 3 below illustrates the principle of this PWM scheme, where the modulating wave v_{mA} is composed of a fundamental component v_{m1} and a third harmonic component v_{m3}, making v_{mA} somewhat flattened on the top. As a result, the peak fundamental component V_{m1} can be higher than the peak triangular carrier wave V_{cr}, which boosts the fundamental voltage v_{AB1}. In the meantime the peak modulating wave V_{mA} can be kept lower than V_{cr}, avoiding the problems caused by over modulation. The

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 8 Issue 05, May-2019

maximum amount of v_{AB1} that can be increased by this scheme is 15.5% [18].

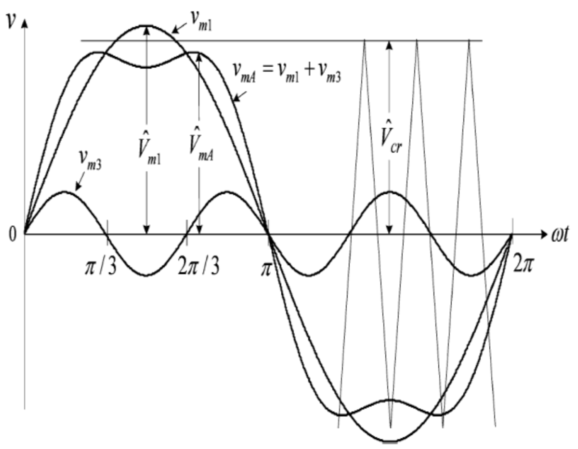


Fig. 3 Third Harmonic Injection PWM technique

(c) *SINUSOIDAL PWM WITH ZERO SEQUENCE SIGNALS*

The method takes the instantaneous average of the maximum and minimum of the three reference voltages (V_a, V_b, V_c) and subtracts the value from each of the individual reference voltages to obtain the modulation waveforms [8]:

$$V_{off} = (\max[va, vb, vc] + \min[va, vb, vc]/2 \qquad (6)$$

$$V_{azs} = V_a - V_{off}$$

$$V_{bzs} = V_b - V_{off} \qquad (7)$$

$$V_{bzs} = V_C - V_{off}$$

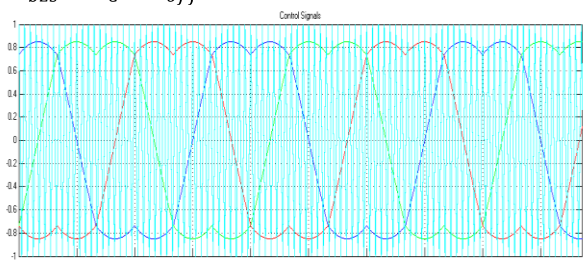


Fig.4 ZS-SPWM Generation

4. SIMULATION RESULTS

The circuit and its control process were simulated in a matlab/simulink for the CPS-SPWM, ZS-SPWM and the third harmonic injected SPWM. Three phase induction motor load was used. The simulation was carried out using different modulation index and the results were compared as shown in the table below. The output wave forms and the THD spectrum for different PWMs were also shown.

Table 1.1 THD and AC voltage for different modulation indexes

Modulation Index (m)	CPS-SPWM		ZS-SPWM		THISPWM	
	THD (%)	Vac (v)	THD (%)	Vac(v)	THD (%)	Vac(v)
1	5.22	426	14.63	500	7.18	500
0.85	5.30	366.3	15.35	460	15.64	460
0.7	5.65	360	17.27	410	23.13	410
0.5	6.75	216.2	21.73	249.7	70.77	27.43

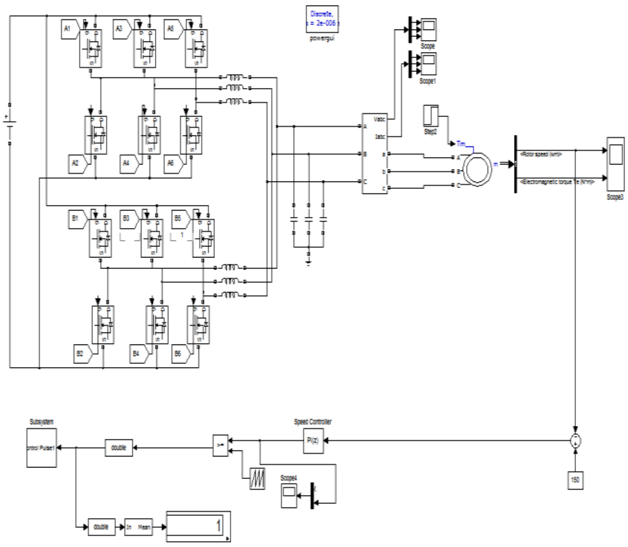
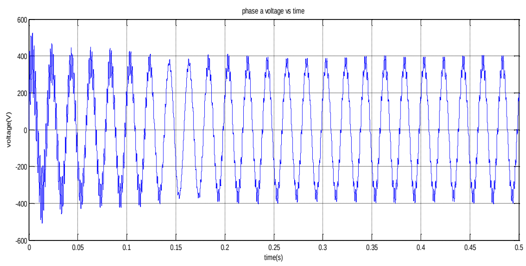
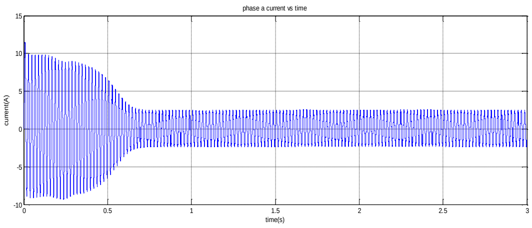


Fig. 5 Simulation model of the system

Fig. 6 shows the output waveforms and the harmonic spectrum for the CPS-SPWM



(a)



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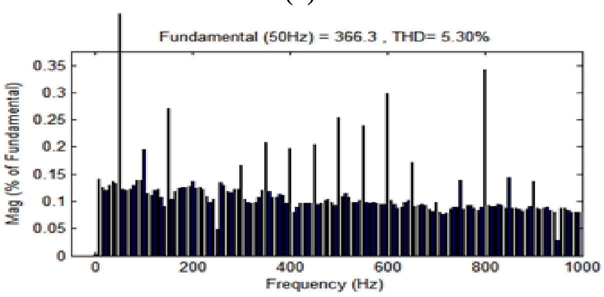
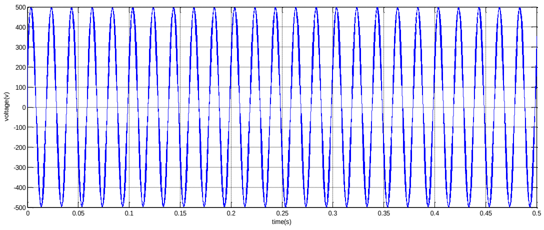


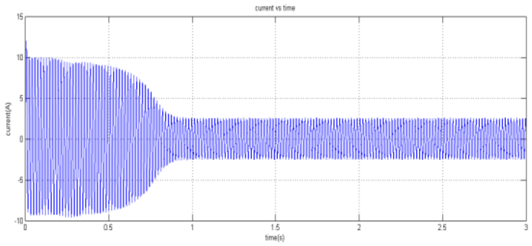
(c)

Fig. 6 (a) output voltage (b) load current & (c) harmonic spectrum for the CPS-SPWM

Fig. 6 shows the output waveforms and the harmonic spectrum for the THIPWM



(a)



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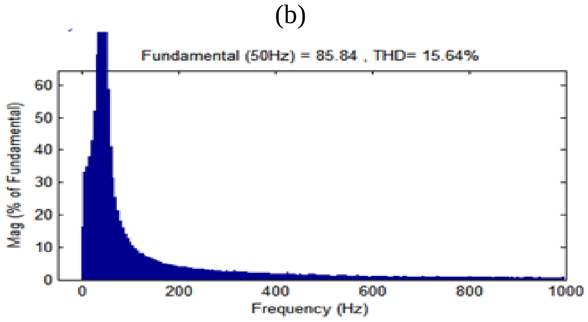
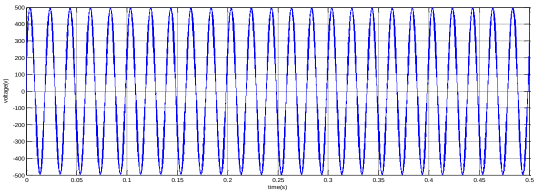


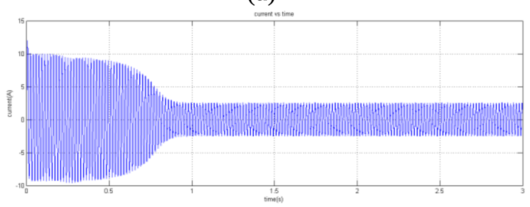
(c)

Fig. 7 (a) output voltage (b) load current & (c) harmonic spectrum for the THIPWM

Fig. 8 shows the output waveforms and the harmonic spectrum for the ZS-SPWM.



(a)



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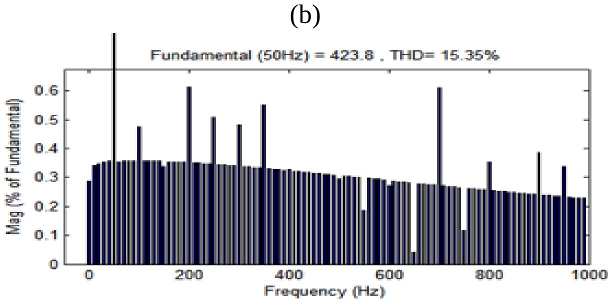
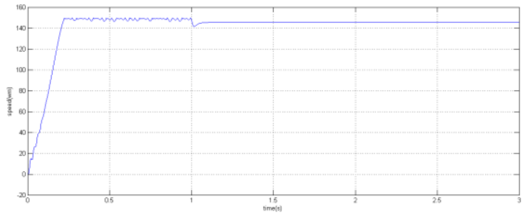


(c)

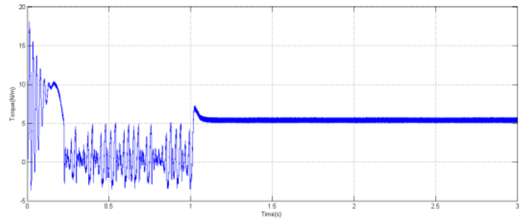
Fig. 8 (a) output voltage (b) load current & (c) harmonic spectrum for the ZS-SPWM

SIMULATION RESULT FOR CLOSED LOOP CONTROL OF IM

Fig. 9 below shows the simulation results for the closed loop control of Induction motor using parallel inverters. The modulation technique with robust performance among the three techniques is selected for the control induction motor. This allows the machine to be used in variable speed applications such as in Fans and blowers.



(a)



(b)

Fig. 12 (a) Speed (b) Torque

CONCLUSION

The simulation results were obtained by simulating the circuit both using the three modulation technique on matlab/simulink. From the results obtained we can conclude that for various modulation indexes the carrier phase shifted SPWM has better THD performance with parallel inverters. And the rest of the methods proved their effectiveness in better utilization of the dc voltage. The paralleling technique of a three phase VSI can also be used in variable speed application to control the speed of the machine.

FUTURE SCOPE

The inverters can be controlled so as to achieve minimum requirement for the output inductors while still allowing safe operation and maintaining equal load sharing among the inverters. Here only two inverters are connected for simplicity; however N number of inverters can be connected in future.

APPENDIX

Table 1.2 System Parameters

Parameters	Values
Input DC Voltage	500v
Load current	2.58A
Carrier Frequency	4KHz
Inverter Rating	1.5Kw
Output Inductance	0.32e-3H
Output Capacitor	4e-3μF
Kp And Ki	0.9 And 0.005

Table 1.3 Machine Parameters

Parameters	Values
Power	1867.5Kw
Voltage	415v
Torque	3Nm
Frequency	50Hz
Pole pairs	2
Stator Resistance	6.03 Ω
Stator Inductance	0.0299H
Rotor Inductance	0.0299H
Mutual Inductance	0.4893H
Rotor Resistance	6.085Ω
Inertial constant	0.011787J/Kg/M^2

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