Eng. & Tech. Journal, Vol.28, No.17, 2010

Analysis of Z-Source Inverter For Space Vector PWM Fed 3-Phase Induction Motor

Dr. Majid K. Al-Khatat *

Received on: 22/2/2010
Accepted on: 2/9/2010

Abstract

This paper presents analysis of operation and implementation of Z-source space vector pulse width modulation (SVPWM) inverter fed three phase induction motor. The Z-source is an alternative power conversion topology that can both buck and boost the input voltage using only passive components. It uses a unique LC impedance network in the DC link between rectifier and inverter fed induction motor. It also allows the use of the shoot-through switching state, which eliminates or reduces the dead-times that are used in the conventional inverters. Therefore, the Z-source inverter can buck and boost voltage to a desired output voltage that is greater than the available input voltage. In addition, it reduces the harmonics, improves power factor, increases reliability ,low cost and highly efficient single-stage structure for buck and boost power conversion.
Theoretical analysis and simulation studies using PSIM software have been performed to demonstrate these new features.

Keywords: Z-Source Inverter,SVPWM,Implementation,Shoot-through, Induction Motor

تحليل عاكس مصدر Z بتضمين عرض النبضة للمتجه الفضائي يغذي محرك حثي ثلاثي الطور

الخلاصة

يقدم هذا البحث التحليل و التمثيل لعمل محرك حثي ثلاثي الطور بأستخدام عاكس مصدر Z بتقنية تضمين عرض النبضه للمتجه الفضائي. عاكس مصدر Z يعتبر بديل هندسي لتحويل وتغيير الطاقة حيث يقلل ويعزز الفولتية الداخلة باستخدام مكونات غير فعالة.كما يستعمل ممانعة فريده ذات شبكة محاثية سعوية في وصلة التيار المستمر بين المعدل والعاكس التي تغذي الماطور الحثي.كذلك يسمح باستخدام حالة توصيل بين المفاتيح والتي تؤدي لالغاء او تقليل وقت الاطفاء الذي يستخدم بالعاكس التقليدي.ولذلك عاكس مصدر Z يمكن يقلل ويعزز الفولتية باكثر من الفولتية المتاحه الداخلة .بالاضافه يقلل التوافقيات ويحسن معامل القدره ويزيد الوثوقية وبكلفة واطئة وكفاءة عاليه ويسيطر على تحويل القدرة بهيكلية احاديه. تم تحليل نظري ودراسة تمثيلية باستخدام برنامج PSIM لتوضيح هذة الخصائص الجديدة.

1. Introduction:

SVPWM method is an advanced, Computation-intensive PWM method is possibly the best among all the PWM techniques for voltage source inverter, its advantage like good Dc utilization and less harmonics distortion in the output waveform, it has been finding widespread application in recent years [1,2].

* Electrical and Electronic Engineering Department, University of Technology / Baghdad

https://doi.org/10.30684/etj.28.17.4
2412-0758/University of Technology-Iraq, Baghdad, Iraq

In order to overcome the limitation and the problems of SVPWM inverter, a Z-source inverter (ZSI) which uses the Z-network to replace traditional dc link was introduced and studied [3,4, 5]. The ZSI is a single stage voltage inverter which has the unique feature that it can buck & boost the dc voltage by using the shoot through operating mode; two switches in the same phase legs can be gated on simultaneously and without DC/DC converter & bulky transformers . Also, it improves the reliability of inverter. In addition the ZSI provides a simple approach for applications of any dc source(photovoltaic cell, or fuel cell,battrey,and diode rectifier) .

The Z-source SVPWM drive induction motor is shown in fig.1. It consists of voltage source from the rectifier supply, impedance network, three phase inverter and three phase induction motor. The ac voltage is rectified to dc voltage by the rectifier. The rectifier output dc voltage fed to the Z- impedance network, which consists of inductors(L_1 and L_2) connected in series arms and capacitors($C_1$and C_2) connected in X shape. The impedance network is used to buck or boost the input dc voltage depending on boosting factor (B). This network also act as a second order filter and it should require less inductance and less capacitance. The inverter main circuit consists of six switches.

2. Traditional SVPWM Inverter:

Figure (2) shows the eight space vector ,where V_1 to V_6 are active vectors and V_0,V_7 are zero vectors in the origin.

In SVPWM the space reference voltage moves from state-1 to state-2 by time sharing PWM between V_1 and V_2. For example if the vector"V_{ref}" lies in sector-1, the PWM adjusted between V_1(100) and V_2(110) by duty cycle of each being T_1 and T_2 respectively, and the zero vectors V_o(000) and V_7(111) of duty cycle T_o .Therefore in linear modulation regions the reference voltage V_{ref} of figure (2) can resolved as two components in sector1

$$V_a = \frac{2}{\sqrt{3}} V_{ref} \sin(60° - \alpha)$$

$$V_b = \frac{2}{\sqrt{3}} V_{ref} \sin(\alpha) \qquad (1)$$

$$V_{ref} = V_a + V_b = V_1\ T_1/T_s + V_2\ T_2/T_s + V_o\ T_o/T_s$$

$$T_1 = \frac{V_a}{V_1} T_s \ ; \qquad V_1 = 2V_{dc}/3$$

$$T_2 = \frac{V_b}{V_2} T_s \ ; \qquad V_2 = 2V_{dc}/3$$

$$T_o = T_s - T_1 - T_2 \qquad (2)$$

That led to:

$$T_1 = \sqrt{3} T_s (V_{ref}/V_{dc}) \sin(60° - \alpha) \qquad (3)$$

$$T_2 = \sqrt{3} T_s (V_{ref}/V_{dc}) \sin(\alpha) \qquad (4)$$

Where V_{dc}- supply dc voltage

The time interval T_1 and T_2 satisfy the reference voltage, but T_0 fills up the remaining gap in T_s [1,2].

The representation ,modeling, and implementation of SVPWM technique was given detail in reference [6].

3.Z-Source Inverter(ZSI):

The most important features of Z-Source inverter is dc boosting voltage. With a unique impedance network of inductors and capacitors, the Z-Source inverter utilizes the shoot through states by gating on both the upper and lower switches in the same phase legs, to buck and boost voltage to the desirable output voltage .

Accordingly the Z-source SVPWM technique, it has extra one switching vector as compared to the traditional ones, nine switching vectors. Six active vectors, V_1-V_6, (impress the DC-link voltage on the motor); two zero vectors, V_0 and V_7, (do not impress the DC-link voltage to the motor) and one more vector (shoot through zero vector known as third zero state). The third zero state operates when the load terminals are shorted through i.e. both switches on a single leg or any 2-phase legs or all three-phase legs. A boosted voltage depends on the total shoot through duration, T over one switching period, T_s. The Z source network makes the shoot-through zero state efficiently utilized throughout the operation. The unique feature of the Z source inverter is that the output ac voltage can be any value between zero and infinity regardless of dc voltage [7,8,9].

the new Z- source SVPWM has an additional shoot-through time T besides time intervals T_1, T_2, T_0. The zero voltage period T_0 should be diminished for generating a shoot through time T. The shoot through time should be not increased the duration of the zero voltage period T_0 because the voltage must be remain symmetrical ,therefore the active state times T_1,T_2 are not changed as shown in switching pattern, Fig.3(b) .

Fig,3 shows the new switching pattern for ZSI at sector 1.Unlike the traditional SVPWM ,Fig.3(a) ,the new SVPWM has an additional shoot-through time T.

Accordingly equation (2) become

$$T_s=T_1+T_2+T^*+T \qquad (5)$$

Where $T^*=T_0-T$

The switching time of the upper switches and the lower switches in a ZSI is summarized in Table I. Its clear when the shoot-through duration (T) is equal to zero, the switching time of each power switch for the ZSI is exactly the same as that for the normal one[10].

3.1.State of operation:

Z-source inverter has a special impedance network between the inverter bridge and the input voltage source(Vi). This circuit structure makes ZSI has an additional shoot-through switching state. Normally that inductor L_1 and capacitor C_1 are equal to inductor L_2 and capacitor C_2, respectively. Two operation states should be obtained, the shoot-through zero vectors state when the two inductors are being charged by the capacitors as shown in fig.4(a) and in non-shoot-through active vector state as shown in Fig.4(b) when the inductors and input DC source transfer energy to the capacitors and motor. The following equations can be written:

Case1: shoot through state

$$V_{c1} = V_{c2} = V_C = V_{L1} = V_{L2} = V_L$$

$$V_{dc} = V_L + V_C = 2V_c \qquad (6)$$

$$Vi = 0$$

Case2: non shoot through state

$$V_L = V_{dc} - V_C$$

$$Vi = V_{dc}$$

$$Vi = V_C - V_L = 2V_C - V_{dc} \ldots\ldots. (7)$$

Assuming that the average voltage of the inductors over a switching period(0 toTs) is equal to zero in steady state:

$$V_C = T_{active} .Vi / (T_{active} - T) \qquad (8)$$

Where T_{active} =time of non shoot-through active interval.

It is clear that V_C can be used to regulate the DC-link voltage. The peak DC-link voltage across inverter bridge can be calculated using (7) and (8)

$$Vi = 2V_C - V_{dc} = V_{dc} /(1-2T/T_s) \qquad (9)$$

$$Vi = B.\ V_{dc} \qquad (10)$$

Where, $B = 1 / (1- 2T/T_s)$ i.e. > 1

The peak ac output phase voltage of inverter for Z- source SVPWM is

$$Vp_{an} = M.2Vi / \pi = B.M.2V_{dc}/\pi \qquad (11)$$

where M is modulation index.

The Buck - Boost factor (B.M) is determined by the modulation index M and the Boost factor B,which preferably should be set to unity ($T/T_s = 0$) for voltage-buck operation and B > 1 for voltage-boost operation.[10,11] .

The linear region in under modulation range of tradional SVPWM is larger than that of other types of PWM techniques, where the modulation index approaches to(90.7). The maximum modulation index can be obtained when V_{ref} equal to the radius of the inscribed circle:

$$(V_{ref})_{max} = \frac{2}{3} V_{dc} (30^o) = 0.577 V_{dc}$$

Therefore,

$$m_{max} = 0.577V_{dc}/(2V_{dc}\ \pi) = 0.907$$

It means that 90.7 percent of the square wave fundamental voltage is available in the linear region of SVPWM.

Also the peak ac output phase voltage in traditional SVPWM inverter,

$$Vpac=M.2.V_{dc}/\pi.$$

The SVPWM inverter fed induction motor restricts the drive operation in constant torque region only and also limits its speed because of output voltage limitation. But in ZSI state ,the ac voltage varies from zero to infinity depend on boosting factor B (equation.11).

3.2 Z-source impedance calculation:

The Z- impedance network contains $L_1=L_1$ and $C_1=C_2$ storage elements . The purpose of the inductor is to limit the current ripple through the devices during boost mode with shoot-through state and the purpose of the capacitor is to absorb the current ripple and maintain a fairly constant voltage . Choosing the parameters of Z-network elements will affect the inverter behavior , performance and harmonic distoration.Also could be optimally designed to lower the cost and size. Therefore, when attempting to size the parametric values of the chosen impedance network, procedures that are well established for traditional SVPWM inverter sizing can be used as brief guides for choosing capacitance and and inductance .Besides that for their second passive values, additional considerations must be taken. A review for calculating these parameters is presented in [12,13].Following the design guidelines presented in paper with a small ripple in capacitor voltage and inductor current, the capacitor and inductor can be calculated as :

$$C\geq (I_L .T/Ts) /2.Fs.\ \Delta V_c \qquad (12)$$

where, I_L, T/Ts, Fs, ΔV_c are, the average current of the Z-network inductor, the shoot-through duty ratio, the switching frequency and the value of capacitor voltage ripple at peak power. The maximum capacitor voltage ripple was taken as 5% in calculation. And

$$L \geq (V_c.T/Ts) /2Fs.\ \Delta I_L \qquad (13)$$

Where Vc, ΔI_L are the average capacitor voltage and the value of inductor current ripple at peak power. The maximum ripple current was taken as 5%.

4. Simulation of Proposed System:

The traditional SVPWM inverter fed induction motor was built and detailed analysis in [6]. It can be considered as a brief guidelines for the new ZSI which is presented in this research. Also the data of motor,MOSFET bridge ,and single phase rectifier were taken the same.

The performance analysis, system implementation, and simulation has established using PSIM program package.

PSIM program provides a powerful and efficient environment for power electronics and motor control simulation. PSIM's graphic user interface is intuitive and very easy to use. A circuit can be easily setup and edited. The simulation results can be analyzed easily using various post-processing function in the waveform display program .

The blocks and their parameters of modified Z-source SVPWM inverter are given in the followings:

1-Space vector calculation, vector location, and time interval calculation blocks are shown in fig.5(a).The shoot through is also setting in the model, that shoot through time (T) can be selected. The maximum value must be $T \le T_0/2$(see mono-stable box in fig.5(a)).

2- The circuit of voltage source Inverter drive induction motor consist of three phase induction motor ,A three –phase voltage source PWM inverter which consist of power bridge devices with three output legs, each consisting of two power switches and two freewheeling diodes, the inverter is supplied from DC voltage Vi through dc link passive Z-impedance .The dc link is supplied by dc voltage V_{dc} from singl phase rectifier as shown in figure 5(b).

5- Results and Discussion:

The analytical and operating principle of the new Z-source inverter has been verified with simulation.

The name plate of the motor shows: 3-phase IM,380volt ,1100watt,2pole, 2800rpm,50Hz.Rs=6Ω,Xs=25Ω,Rr=15 Ω, ,Xr=12.5 Ω,and Xm=300 Ω .

AC supply voltage is (220) volt with respect to the rated frequency (50Hz). The parameters are as follows:

Z-source-network: L1=L2=450uH, C1=C2=880 uF

Switching frequency: Fs=2 kHz, modulation index M=0.8,and output frequency of inverter=40 Hz.

The following theoretical calculation when shoot through duty cycle (T/Ts) is 0.115.

$B=1/(1-2.T/Ts)=1.3$.

$Vi=M.B.2V_{dc}/\pi=405V$.

$Vp_{an} = B.M.2V_{dc}/\pi$ =206V(fundamental/ Phase) and 356V(fundamental/ line).

While theoretical calculation in traditional inverter is : Vi=311V, $Vp_{an} = M.2V_{dc}/\pi$=158V,and =274V for line .

The above values are quiet consistent with simulation results as shown in figs.6 ,7,8,9.

Figs.6 show simulation voltage waveforms under the nominal phase voltage of 220Vac.The magnitude of the output voltage is boosted to 175V(phase) and 304V(line).However ,its impossible to produce this voltage in case of traditional SVPWM inverter as shown in figs.7.The magnitude of Vphase is 135V and Vline is 233V.

The average dc voltage across the inverter bridge, is boosted to 405V as shown in fig.6(d) and should be limited below the device voltage rating .While is 311 V at traditional one (figs.7(d).Its clear the boosting factor B=405/311 =1.3.

Figures10 shows the line current of motor and ac supply current ,it is noted that the line current contains much less harmonics than the traditional SVPMW inverter fed induction motor as shown in fig.11. It can clearly observed from FFT analysis of the above two mentioned currents and also the total harmonic distortion THD in fig.12 is lower than THD in fig.13 that is the fundamental is higher and the amplitude of harmonics is lower in case of ZSI than in tradional SVPWM inverter as shown in fig.12 and fig.13 respectively.

The transient period of rotor speed for induction motor in Z-source SVPWM system is about 0.13sec. while in traditional SVPWM is 2 sec. as shown in fig.14(a,b) respectively.

It can be deduced the dynamic response in Z-source is better.

Figs.15shows simulation voltage waveform during 20% voltage sag(the ac voltage drop to 176V (rms).Again the values for the phase, line voltages of the output inverter and average DC voltage across the inverter as shown in Figs.15(a,b,c,d) respectively, are as previous case(fig.6) . But the boosting factor has been increased to 1.6.

6-Conclusions

This paper has demonstrated that the Z-source(SVPWM) inverter topology is a good alternative technology to the traditional inverter. The Z-source inverter is suited for control three phase induction motor. Due to output voltage limitation in (SVPWM) inverter ,the power and speed region of motor drive should be limited. this restrict in ZSI has been cancelled. The Z-source rectifier/inverter system can produce an output voltage greater than the ac input voltage by controlling the boost factor, which is impossible for the traditional(SVPWM) inverter .

A SVPWM technique is modified to realize the shoot-through zero vectors that boost the dc-link voltage.

To validate the effectiveness of the proposed model system with a three phase motor is simulated using PSIM program under varies operating condition. simulation studies are performed .The results verified the effectiveness of the proposed new Z-source SVPWM inverter fed induction motor.

Additionally, the general improvement has been presented:

Buck and boost voltage, harmonics reduction(line &load side),realibilty,fast responce,dead time can be removed, power factor , cost reduced, and voltage sag removed.

References:

[1] Bimal K. Bose, " *Modern Power Electronic and AC Drives*", Prentice Hall, 2002.

[2] Muhammed H. Rashid, " *Power Electronics, Circuits, Derives and applications"*, Pearson Education Inc. 2004.

[3] Fang Zheng Peng; "Z-source inverter", Industry Applications, IEEE Transactions on, Volume: 39 Issue: 2,Mar/Apr 2003, Page(s):504-510.

[4] Peng, F.Z; Xiao-ming Yuan; Xu-Fang; Zhao-ming Qian; "Z-source inverter for adjustable speed drives", Power Electronics Letters, IEEE, Volume: 1 Issue: 2, June 2003, Page(s): 33 –35.

[5] Q. Tran, T. Chun, J. Ahn, and H. Lee, "Algorithms for controlling both the dc boost and ac output voltage of Z-source inverter," IEEE Trans. Ind. Electron., vol. 54, no.5, pp. 2745-2750, Oct. 2007.

[6] Majid K. Al-Khatat, Fadhil Abbas Hassan."Modeling and Implementation of Space Vector PWM Driver of 3-Phase Induction Motor"Eng.&Tech.Vol.27,No.10,2009,Iraq,Bagdad.

[7] S. Thangaprakash, Dr. A. Krishnan "Z-source Inverter Fed Induction Motor Drives – a Space Vector Pulse Width Modulation,Based Approach" Journal of Applied Sciences Research, 5(5): 579-584, 2009, INSInet Publication

[8] Jin-WooJung, and Ali Keyhani. "Control of a Fuel Cell Based Z-SourceConverter".IEEE Transactions, Soner Energy Conversion,VOL.22,NO.2,JUN,2007

[9] Amitava Das, Debasish Lahiri and Barnali Kar. " Space Vector PWM Based AC Output Voltage Control of Z – Source Inverter". INTERNATIONAL CONFERENCE ON "CONTROL, AUTOMATION,

COMMUNICATION AND ENERGY CONSERVATION -2009, 4th-6th June 2009.

[10]A.Keyhani,andJin-WooJung. "Distributed Energy Systems". Journal of Iranian Association of Electrical and Electronics Engineers - Vol.1 - No.2 - Summer & Fall 2004.

[11] Rathika, S.; Kavitha, J.; Paranjothi, S.R."Embedded control Z-source inverter fed induction motor" INCACEC 2009. 2009 International Conference on Control, Automation, Communication and Energy Conservation, 2009.

[12] S. Rajakaruna and Y. Jayawickrama:"Designing Impedance Network of Z-Source Inverters",IEEE,Power Engineering Conference, Nov. 2005. pp. 1-6.

(13) Ellabban, O.; Van Mierlo, J.; Lataire, P.;"Comparison between different PWM control methods for different Z-source inverter topologies".Power Electronics and Applications, 2009. EPE '09. 13th European Conference on 8-10 Sept. 2009 Page(s):1 – 11

Sector	Upper (S1, S3, S5)	Lower (S4, S6, S2)
1	S1 = T1 + T2 + T0/2 + T S3 = T2 + T0/2 S5 = T0/2 - T	S4 = T0/2 S6 = T1 + T0/2 + T S2 = T1 + T2 + T0/2 + 2T
2	S1 = T1 + T0/2 S3 = T1 + T2 + T0/2 + T S5 = T0/2 - T	S4 = T2 + T0/2 + T S6 = T0/2 S2 = T1 + T2 + T0/2 + 2T
3	S1 = T0/2 - T S3 = T1 + T2 + T0/2 + T S5 = T2 + T0/2	S4 = T1 + T2 + T0/2 + 2T S6 = T0/2 S2 = T1 + T0/2 + T
4	S1 = T0/2 - T S3 = T1 + T0/2 S5 = T1 + T2 + T0/2 + T	S4 = T1 + T2 + T0/2 + 2T S6 = T2 + T0/2 + T S2 = T0/2
5	S1 = T2 + T0/2 S3 = T0/2 - T S5 = T1 + T2 + T0/2 + T	S4 = T1 + T0/2 + T S6 = T1 + T2 + T0/2 + 2T S2 = T0/2
6	S1 = T1 + T2 + T0/2 + T S3 = T0/2 - T S5 = T1 + T0/2	S4 = T0/2 S6 = T1 + T2 + T0/2 + 2T S2 = T2 + T0/2 + T

Table (1) Switching time duration

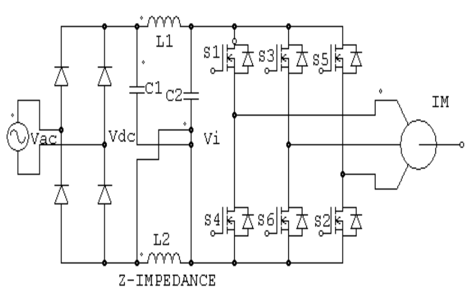


Figure (1)Z-Source *SVPWM Inverter.*

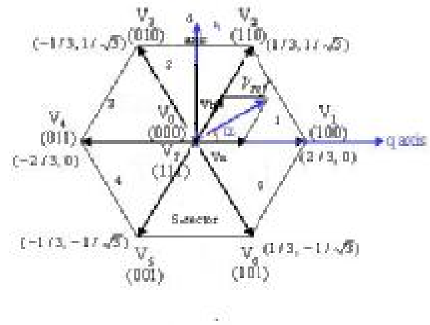
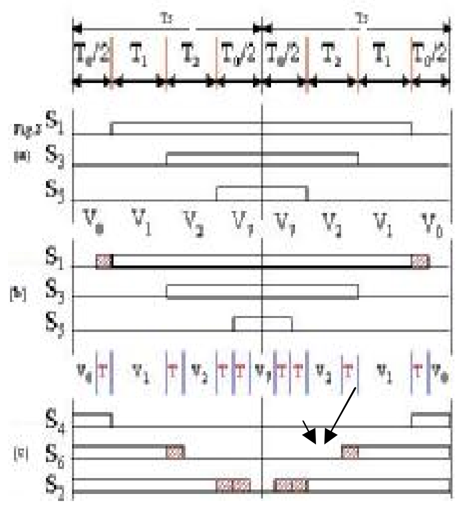


Figure (2) Basic& switching patterns of space vecto

Sector 1



Shoot-Through T

Figure(3)ZSI.implementation.(a)Traditional SVPWM.(b)ZSI.upper switch.(c)ZSI,lower switch.

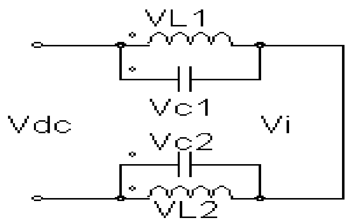


Figure 4(a) Equivalent circuit of Z— Source in the shoot through state.

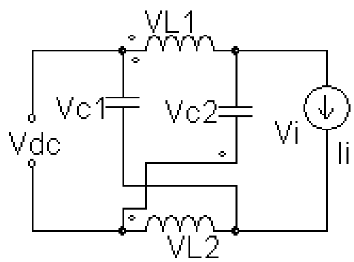


Figure 4(b).Equivalent circuit of Z Source in the non shoot through state.

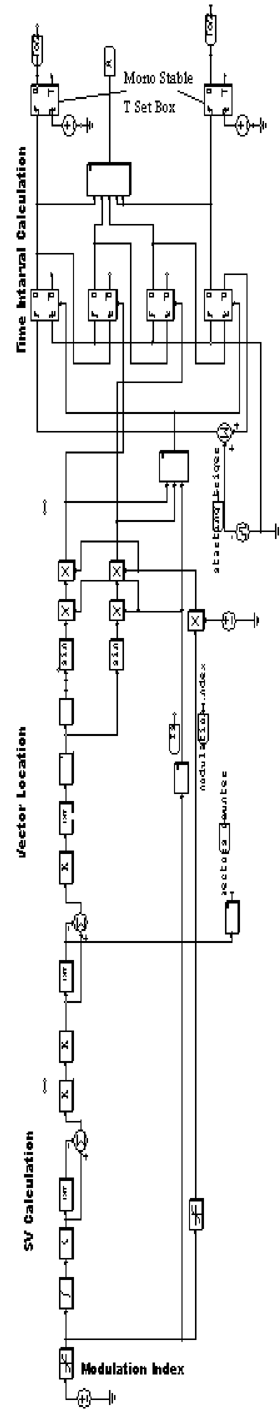


Figure 5(a):SVPWM Calculation,location,and time interval with shoot-through simulation.

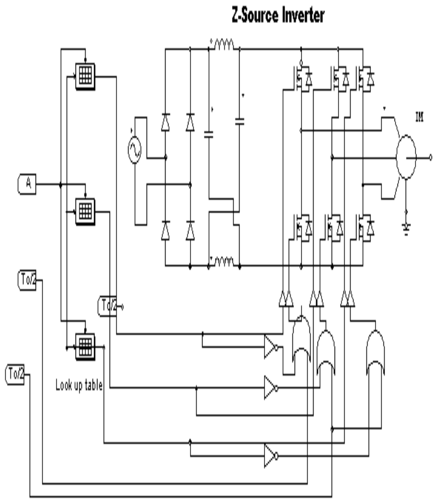


Figure 5(b) ZSI fed induction motor simulation.

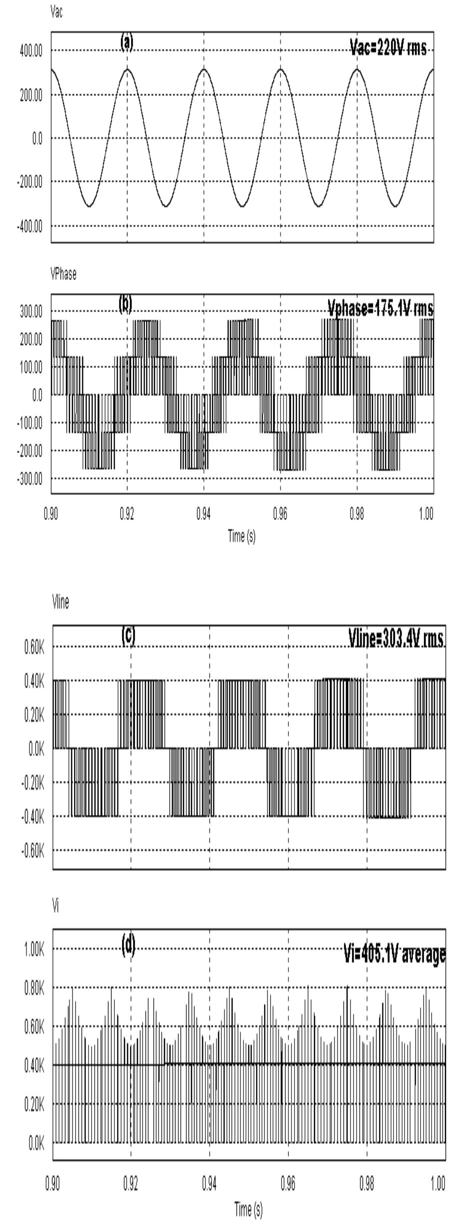


Figure (6)Voltage Waveforms of ZSI.(a)Input phase voltage to rectifier .(b) Output phase voltage of inverter.(c) Output line voltage of inverter .(d)Input dc voltage.

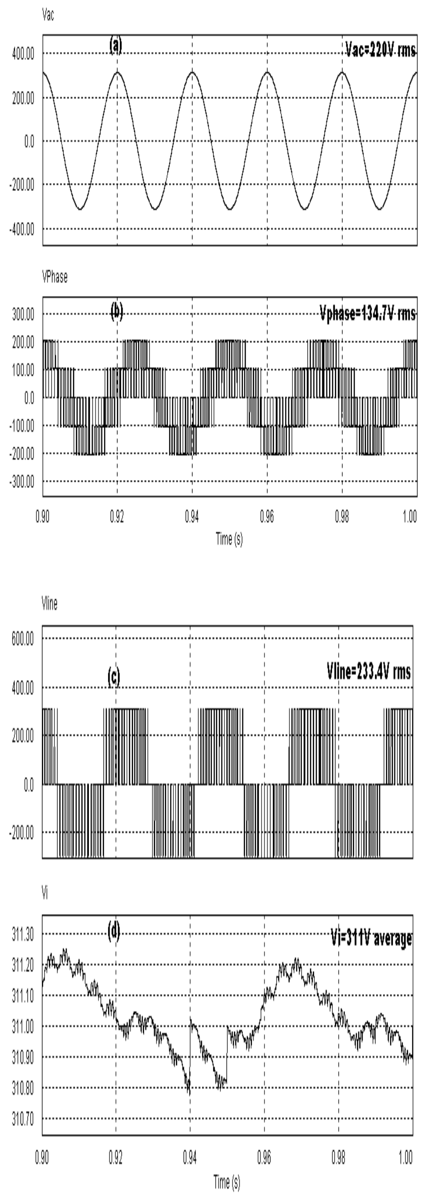


Figure (7)Voltage Waveforms of Traditional Inverter.(a)Input phase voltage to rectifier .(b) Output phase voltage of inverter.(c) Output line voltage of inverter .(d)Input dc voltage.

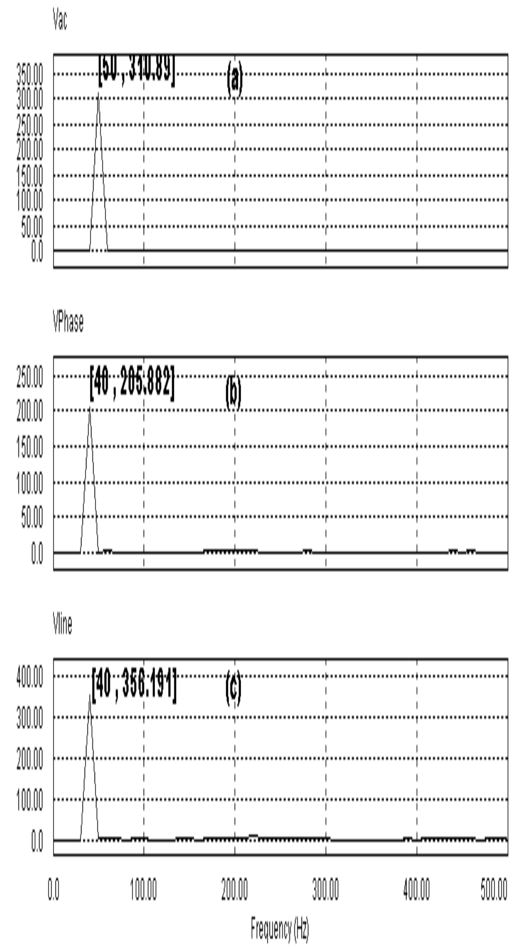
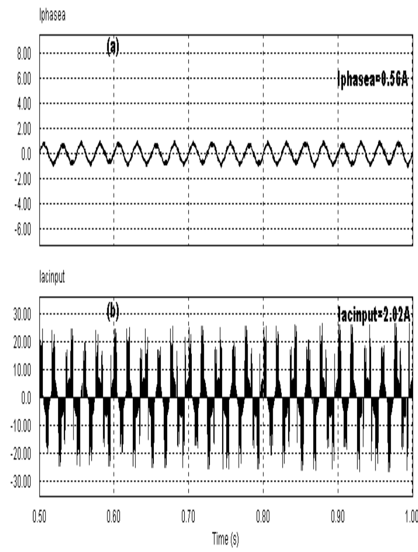
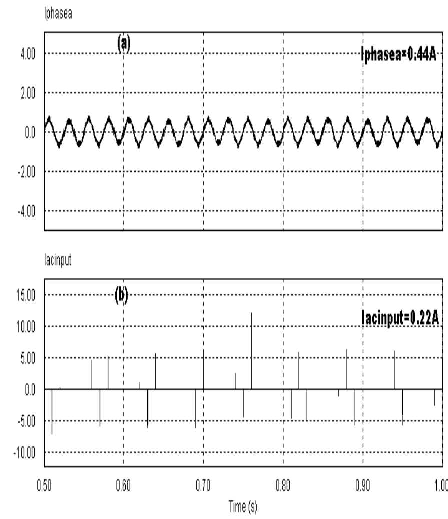


Figure (8)FFT Results of voltage in ZSI. (a)Input phase voltage of rectifier.(b)Output phase voltage of inverter.(c) Output line voltage of inverter.

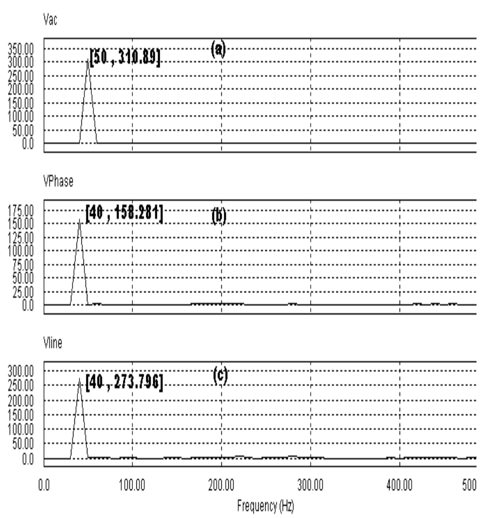


Figure(10)Current Waveforms in ZSI:(a)Line current of motor.(b) Supply Current

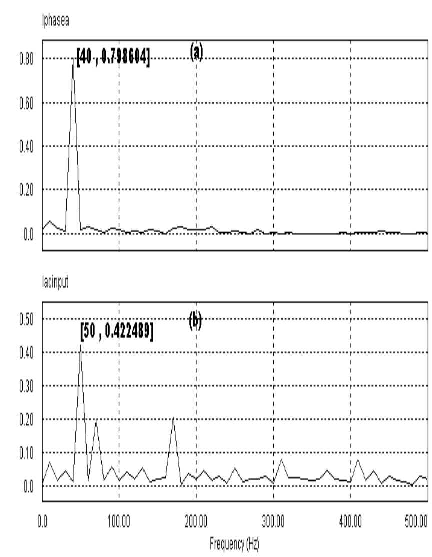


Figure(11)Current Waveforms in traditional inverter:(a)Line current of motor.(b) Supply Current

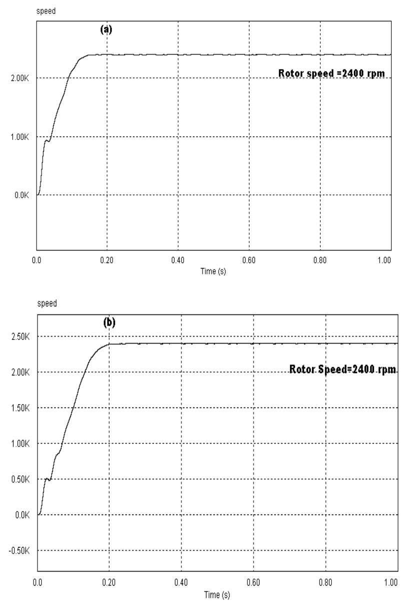
.



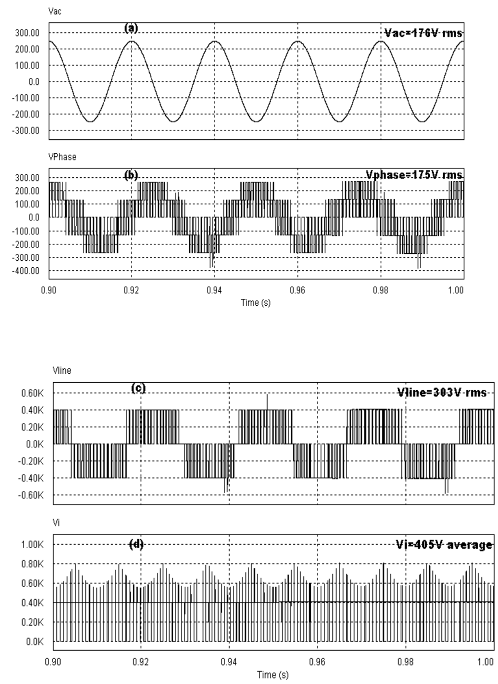
Figure(9)FFT Results of voltage in traditional. (a)Input phase voltage of rectifier.(b)Output phase voltage of inverter.(c) Output line voltage of inverter.



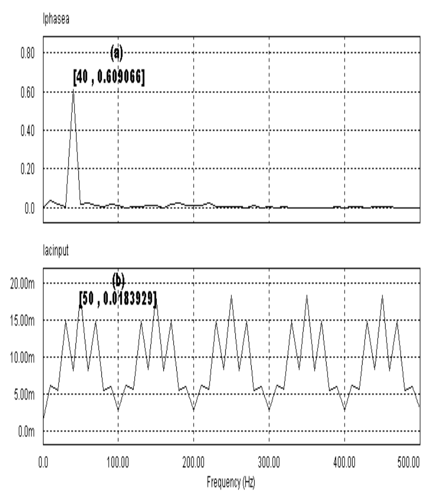
Figure(12)FFT Current Analysis In ZSI:(a)Line current of motor.(b) Supply Current.



Figure(14)Rotor speed :(a) ZSI.(b) Traditional Inverter.



Figure(15)Voltage Waveforms of ZSI For 20% voltage sag.(a)Input phase voltage to rectifier .(b) Output phase voltage of inverter.(c) Output line voltage of inverter .(d)Input dc voltage.



Figure(13)FFT Current Analysis In Traditional Inverter:(a)Line current of motor.(b) Supply Current.