

## Space Vector Modulation based Speed Control of Induction Motor Fed by Z-Source Inverter using PI controller

<sup>1</sup>P.Elangovan, <sup>2</sup>Dr.C.Kumar, <sup>3</sup>V.Suresh

<sup>1, 2, 3</sup> Department of Electrical & Electronics Engineering, SKP Engineering College, Tiruvannamalai

### Abstract

This paper presents a speed control system of Induction motor fed by Z-source Inverter with implementation of Proportional plus Integral (PI) controller in the feedback path. The Z-source inverter system uses a unique LC network in the dc link and a small capacitor on the ac side of the diode front end. The Z-source inverter will produce output voltage greater than the line voltage which shows the advantage over the conventional Voltage source Inverter. The comparison analysis is made between space vector modulation and sinusoidal pulse width modulation (PWM) Z-source Inverter fed Induction motor with the implementation of PI controller. From the analysis of Total harmonic distortion (THD) in the inverter current, Space Vector Modulation (SVM) technique was found to be better than Sinusoidal Pulse Width Modulation (SPWM) technique. Instead of using any artificial intelligence technique in the speed control system, the PI controller is used which avoids system complication. Analysis and simulation results will demonstrate the features of the system.

**Keywords** – PI controller, Sinusoidal PWM technique, Space vector modulation technique, Total Harmonic Distortion, Z-source Inverter.

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### I. INTRODUCTION

The conventional adjustable speed drive (ASD) system is based on the voltage source inverter, which consists of a diode rectifier front end, dc link capacitor and inverter bridge as shown in Fig.1.

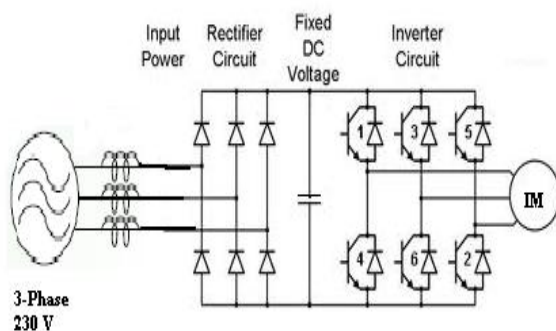


Fig.1 Conventional variable speed drive system

To improve power factor, either an ac inductor or dc inductor is normally used. The voltage at dc link is equal to 1.35 times the line voltage because of which the conventional voltage source inverter can only produce an ac voltage limited by the dc link voltage.

Some of the problems and limitations by which the voltage source inverter based ASD system will suffer are as follows,

#### Reduced Output Voltage:

The derivable voltage is limited below the input line voltage [1]. For light load operation or small drives with no significant inductance, the line current becomes discontinuous “double-pulse” and the dc voltage is closer to 1.41 times the line-to-line input voltage. For that 1.41 times of line-to-line input voltage, the inverter can produce maximum voltage which cannot drive the motor or the low obtainable output voltage significantly limits output power that is proportional to the square of the voltage.

#### Voltage Sags:

Voltage sags can interrupt an ASD system and shut down critical loads and processes. The power quality related problems around 90% is due to voltage sags of 10 – 50% below nominal. The energy storage element present in the dc link of ASD system is relatively small and it cannot hold dc voltage above the operable level under such voltage sags. [1]-[5] demonstrates the serious problem accompanied with lack of ride-through capacity for sensitive loads driven by ASDs.

The industries that uses ASD system goes with the option using flyback converter or boost converter with energy storage or diode rectifier to achieve ride-through. But it increases the complexity in the control circuit and come with penalties of cost, size and weight.

**Harmonic Current:**

High inrush and harmonic current from the diode rectifier can pollute the line. Low power factor is another issue of the conventional ASD system.

**Switching Losses:**

In the conventional ASD system, the voltage source inverter uses six switches and six gate control circuit which leads to high switching losses and increases the complexity in gate control circuit.

**II. PULSE WIDTH MODULATION IN INVERTERS**

Output voltage from an inverter can be adjusted by exercising a control within the inverter itself. The most efficient method of doing this is by pulse-width modulation control used within an inverter.

In this method, a fixed dc input voltage is given to the inverter and a controlled ac output voltage is obtained by adjusting the on and off periods of the inverter components. PWM inverters are quite popular in industrial applications. PWM techniques are characterized by constant amplitude pulses. The width of these pulses is however modulated to obtain inverter output voltage control and to reduce its harmonic content.

The commonly used PWM techniques to control the output voltage of an inverter are as under:

- Sinusoidal Pulse width modulation
- Space vector modulation

**2.1 SINUSOIDAL PWM TECHNIQUE**

Instead of maintaining the width of all pulses the same as in the case of multiple – pulse modulation, the width of each pulse is varied in proportion to the amplitude of a sine wave evaluated at the center of the same pulse.

The generation of gating signals with sinusoidal PWM are shown in fig.2. There are three sinusoidal reference signal corresponding to a phase to generate the gating signals for that phase [6]. Comparing the carrier signal with the reference phases  $V_{oa}$ ,  $V_{ob}$  and  $V_{oc}$  produces the gating signals. The instantaneous line-to-line output voltage is  $V_{ab} = V_s(g_1 - g_2)$ . The output voltage as shown in Fig.2 is generated by eliminating the condition that two switching devices in the same arm cannot conduct at the same time.

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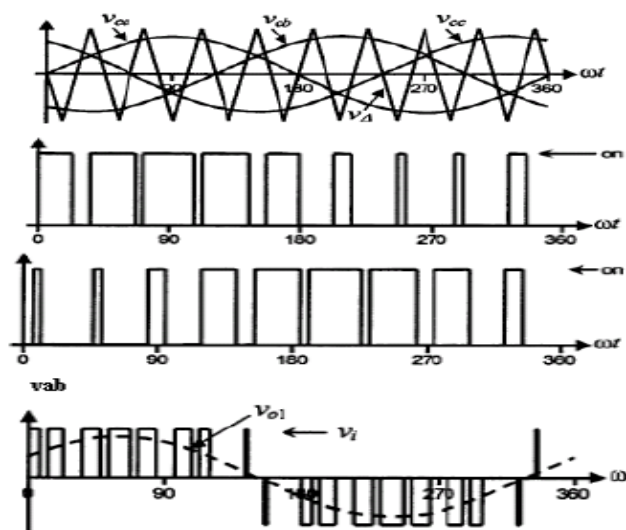


Fig.2 SPWM for three phase inverter

Comparing the carrier signal with the reference phases  $V_{oa}$ ,  $V_{ob}$  and  $V_{oc}$  produces the gating signals. The instantaneous line-to-line output voltage is  $V_{ab} = V_s(g_1 - g_2)$ . The output voltage as shown in Fig.2 is generated by eliminating the condition that two switching devices in the same arm cannot conduct at the same time.

The normalized carrier frequency  $m_f$  should be odd multiple of three. Thus, all phase-voltage are identical, but  $120^\circ$  out of phase without even harmonics; moreover, harmonics at frequencies multiple of three are identical in amplitude and phase in all phases. For instance, if the ninth harmonic voltage in phase a is

$$V_{aN9}(t) = \tilde{v}_9 \sin(9\omega t) \dots \dots \dots (1)$$

the corresponding ninth harmonic in phase b will be,

$$V_{b9}(t) = \tilde{v}_9 \sin(9(\omega t - 120^\circ)) = \tilde{v}_9 \sin(9(\omega t - 180^\circ)) = -\tilde{v}_9 \sin(9\omega t) \dots \dots (2)$$

Thus, the ac output line voltage  $v_{ab}$  does not contain the ninth harmonic. Therefore, for odd multiples of three times

the normalized carrier frequency  $m_f$ , the harmonics in the ac output voltage appear at normalized frequencies  $f_h$

$$\text{centered around } m_f \text{ and its multiples, specifically, at } N = jm_f \pm k \dots \dots \dots (3)$$

For nearly sinusoidal ac load current, the harmonics in the

$$\text{dc link current are at frequencies given by } n = jm_f \pm k \pm 1 \dots \dots \dots (4)$$

**2.2 Space Vector Modulation Technique**

The desired three phase voltages at the output of the inverter could be represented by an equivalent vector  $V$  rotating in the counter clock wise direction as shown in Fig.3. The magnitude of this vector is related to the magnitude of the output voltage and the time of this vector takes to complete one revolution is the same as the fundamental time period of the output voltage.

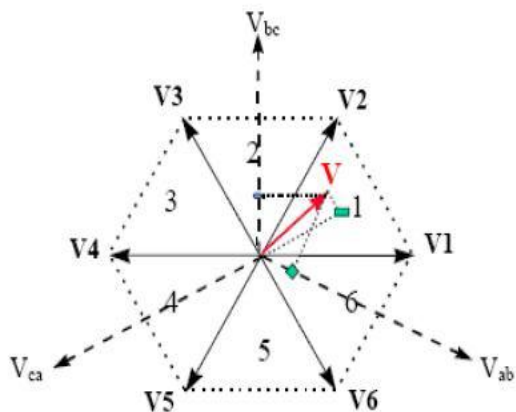


Fig.3 Output voltage vector in the plane  
Let us consider the situation when the desired line to-line output voltage vector **V** is in sector 1 as shown in Fig.4.

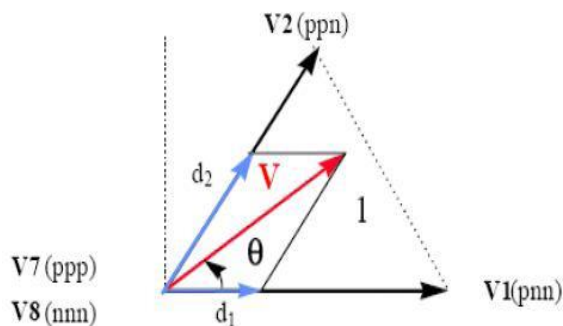


Fig.4 Synthesis of the required output voltage vector in

Sector 1

This vector could be synthesized by the pulse width modulation (PWM) of the two adjacent SSV's **V1** (pnn) and **V2** (ppn), the duty cycle of each being  $d_1$  and  $d_2$ , respectively, and the zero vector( **V7**(nnn) / **V8**(pp) ) of duty cycle  $d_0$ :

$$d_1V_1 + d_2V_2 = V = mV_{ge} \dots \dots \dots (5)$$

$$d_1 + d_2 + d_0 = 1 \dots \dots \dots (6)$$

Where,  $0 \leq m \leq 0.866$ , is the modulation index. This would correspond to a maximum line-to-line voltage of  $1.0V_g$ , which is 15% more than conventional sinusoidal PWM as shown.

All SVM schemes and most of the other PWM algorithms use Eqns. (5) and (6) for the output voltage synthesis. The modulation algorithms that use non-adjacent SSV's have been shown to produce higher THD and/or switching losses and are not analyzed here, although some of them, e.g. hysteresis, can be very simple to implement and can provide faster transient response. The duty cycles  $d_1$ ,  $d_2$ , and  $d_0$ , are uniquely determined from Eqns. (5) and (6), the only difference between PWM schemes that use adjacent vectors is the choice of the zero vector(s) and the sequence in which the vectors are applied within the switching cycle.

### III. Z-Source Inverter Equivalent Circuit And Operating Principle

The equivalent circuit of z-source inverter is shown in Fig.5.

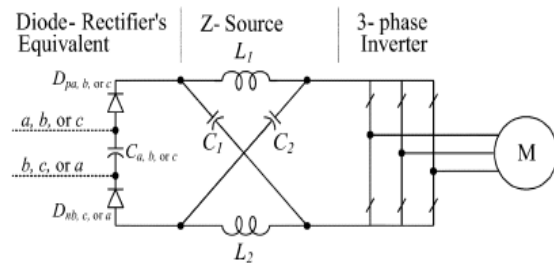


Fig.5 Equivalent circuit of the diode bridge viewed from the Z-source network.

The basic operating principle and control of the Z-source inverter fed by a dc source such as fuel cell stack have been detailed in [7].

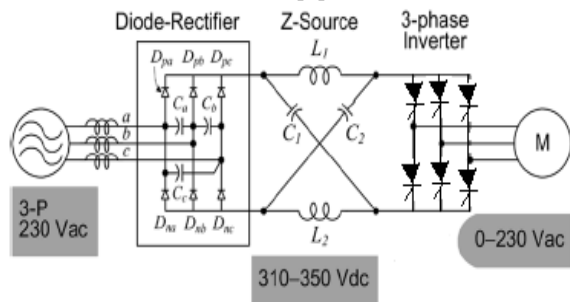


Fig.6 Proposed Z-source inverter fed Induction motor.

In the proposed ASD system in Fig. 6, a diode rectifier bridge with input capacitors ( $C_a$ ,  $C_b$  and  $C_c$ ) serves as the dc source feeding the Z-source network. The input capacitors are used to suppress voltage surge that may occur due to the line inductance during diode commutation and shoot-through mode of the inverter, thus requiring a small value of capacitance. At any instant of time, only two phases that have the largest potential difference may conduct, carrying current from the ac line to the dc side. Fig. 7 shows the rectifier's six possible conduction intervals per cycle.

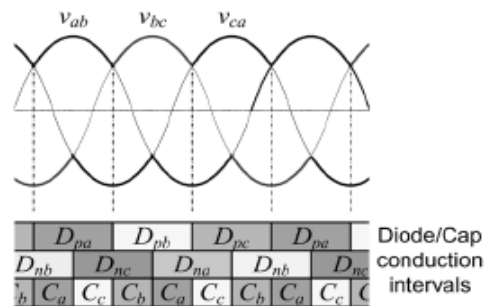


Fig.7 Six possible conduction intervals per fundamental cycle.

The two diodes ( $D_{pa}, D_{pb}$  or  $D_{pc}$  and  $D_{na}, D_{nb}$  or  $D_{nc}$ ) conduct as a pair with the corresponding capacitor ( $C_{a,b}$  or  $c$ ) respectively. Therefore, as viewed from the Z-source network, the diode bridge can be modeled as a dc source in series with two diodes, as shown in Fig.5. Note that the order of the suffixes corresponds with their six combinations, e.g.,  $D_{pa}$  and  $D_{nc}$  conducting as a pair with capacitor and conducting as a pair with capacitor  $C_b$ , and so on. Furthermore, the two diodes conduct in a pair and in series acting like one when viewed from the Z-source network. As a result, the proposed Z-source ASD system is reduced to the basic Z-source inverter that has been presented in [7] and illustrated in Fig.7 of [7].

### 3.1 Modes of Operation of Z-Source Inverter

In [8] & [9], the different modes of operation of z-source inverter was clearly explained. There are three different modes in which the z-source inverter will operate and are as follows,

#### Mode – I:

The inverter bridge is operating in one of the six traditional active vectors, thus acting as a current source viewed from the Z-source circuit. The diodes ( $D_{pa}$  and  $D_{nb}$ ) conduct and carry currents. Fig.8 shows the circuit of this mode. In the conventional ASD system, the diode bridge may not conduct depending on the dc capacitor voltage level. However, the Z-source circuit always forces diodes ( $D_{pa}$  and  $D_{nb}$ ) to conduct and carry the current difference between the inductor current and inverter dc current as shown in Fig.8.

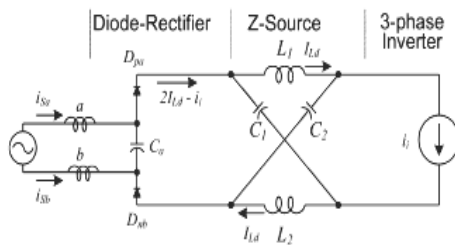


Fig.8 Mode-I Circuit configuration

#### Mode – II:

In this mode, one of the two traditional zero vectors carries the inverter bridge operation and shorting through either the upper or lower three devices, thus acting as an open circuit viewed from the Z-source circuit. The diodes ( $D_{pa}$  and  $D_{nb}$ ) conduct and carry currents.

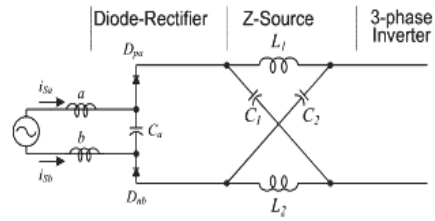


Fig.9 Mode – II Circuit Configuration.

Fig.9 shows the circuit for this mode. Again, under this mode, the two diodes ( $D_{pa}$  and  $D_{nb}$ ) have to conduct and carry the inductor current, which contributes to the line current's harmonic reduction.

#### Mode – III:

In this mode, the inverter bridge is operating in one of the seven shoot-through states. During this mode, both diodes are off, separating the dc link from the ac line. The line current flows to the capacitor  $C_a$ .

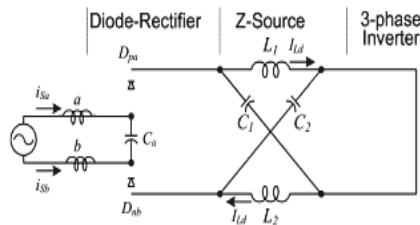


Fig.10 Mode – III Circuit configuration.

Fig.10 shows the resultant circuit. This is the shoot-through mode to be used every switching cycle during the traditional zero vector period generated by the PWM control. Depending on how much a voltage boost is needed, the shoot-through interval ( $T_0$ ) or its duty cycle ( $T_0/T$ ) is determined [7]. It can be seen that the shoot-through interval is only a fraction of the switching cycle; therefore it needs a relatively small capacitor  $C_a$  to suppress voltage.

### 3.2 ANALYSIS OF Z-SOURCE NETWORK

The analysis of z-source network is carried out by redrawing the network shown in Fig.5.

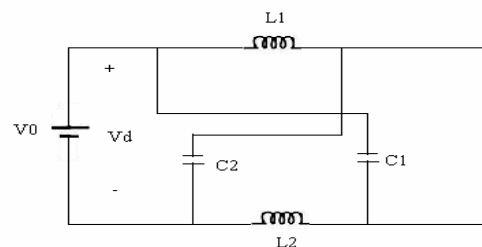


Fig.11 Equivalent circuit of z-source network  
The redrawn equivalent circuit of z-source network is shown in Fig.11. The voltage across the capacitors  $C_1$  and  $C_2$  are  $V_{c1}$  and  $V_{c2}$ . The current through the inductors  $L_1$  and  $L_2$  are  $I_{L1}$  and  $I_{L2}$ . Assume the

inductors (L1 and L2) and capacitors (C1 and C2) have the same inductance and capacitance values respectively. From the above equivalent circuit:

$$V_{c1} = V_{c2} = V_c \dots \dots \dots (7)$$

$$V_{L1} = V_{L2} = V_L \dots \dots \dots (8)$$

$$V_L = V_c, V_d = 2V_c$$

$$V_i = 0$$

During the switching cycle T:

$$V_L = V_o - V_c \dots \dots \dots (9)$$

$$V_d = V_o$$

$$V_i = V_c - V_L = V_c - (V_o - V_c) \dots \dots \dots (10)$$

$$V_i = 2V_c - V_o$$

where,  $V_o$  is the dc source voltage and:

$$T = T_o + T_1 \dots \dots \dots (11)$$

The average voltage of the inductors over one switching period (T) should be zero in steady state:

$$V_L = V_L = T_o \cdot V_c + T_1(V_o - V_c) / T = 0$$

$$V_L = (T_o \cdot V_c + V_o \cdot T_1 - V_c \cdot T_1) / T = 0$$

$$V_L = (T_o - T_c) V_c / T + (T_1 \cdot V_o) / T \dots \dots \dots (12)$$

$$V_c / V_o = T_1 / T_1 - T_o$$

Similarly the average dc link voltage across the inverter bridge can be found as follows.

From Eq. 10:

$$V_i = V_i = (T_o \cdot 0 + T_1 \cdot (2V_c - V_o)) / T \dots \dots \dots (13)$$

$$V_i = (2V_c \cdot T_1 / T) - (T_1 V_o / T)$$

$$2V_c = V_o$$

From Eq. 12:

$$T_1 \cdot V_o / (T_1 - T_o) = 2V_c \cdot T_1 / (T_1 - T_o)$$

$$V_c = V_o \cdot T_1 / (T_1 - T_o)$$

The peak dc-link voltage across the inverter bridge is:

$$V_i = V_c - V_L = 2V_c - V_o = T / (T_1 - T_o) \cdot V_o = B \cdot V_o \dots \dots \dots (14)$$

Where:

$$B = T / (T_1 - T_o) \text{ i.e., } \geq 1$$

B = A boost factor

The output peak phase voltage from the inverter:

$$V_{ac} = M \cdot V_i / 2 \dots \dots \dots (15)$$

where, M is the modulation index.

In this source:

$$V_{ac} = M \cdot B \cdot V_o / 2 \dots \dots \dots (16)$$

In the traditional sources:

$$V_{ac} = M \cdot V_o / 2$$

For Z-Source:

$$V_{ac} = M \cdot B \cdot V_o / 2$$

The output voltage can be stepped up and down by choosing an appropriate Buck-Boost factor (BB):

$$BB = B \cdot M \text{ (it varies from 0 to } \alpha \text{)} \dots \dots \dots (17)$$

The capacitor voltage can be expressed as:

$$V_{c1} = V_{c2} = V_c = (1 - T_o / T) \cdot V_o / (1 - 2T_o / T) \dots \dots \dots (18)$$

The buck-boost factor BB is determined by the modulation

index m and the boost factor B[11]. The boost factor B can be controlled by duty cycle of the shoot through zero state over the non-shoot through states of the PWM inverter. The shoot through zero state does not affect PWM control of the inverter, because it equivalently produces the same zero voltage to the load terminal. The available shoot through period is limited by the zero state periods that are determined by the modulation index.

#### IV. Pi Controller

Instead of using the controller involved with artificial intelligence, the Proportional plus Integral (PI) controller was used to control the speed of the induction motor. Since, it avoids the complexity that was present in control circuit, it is highly preferable for the industries using ASD system.

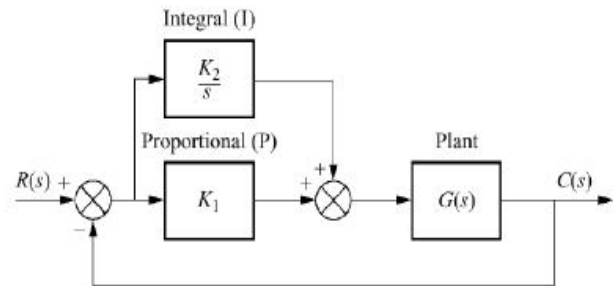


Fig.12 Block Diagram of PI controller

Fig. 12 shows the Proportional-Integral (PI) controller block diagram. The speed error  $E_N$  between the reference speed  $N_R$  and the actual speed  $N$  of the motor is fed to the PI controller, and the  $K_1$  and  $K_2$  are the proportional and integral gains of the PI controller.

The P-I controller has the form

$$E_1(S) / E_N(S) = (K_1 S + K_2) / S \dots \dots \dots (19)$$

This is a phase-lag type of controller with the pole at the origin and makes the steady-state error in speed zero. The transfer function between the output speed  $N$  and the reference speed  $N_R$  is given by:

$$N(S) / N_R(S) = (AK_1 + AK_2 S) / (K_1 S^2 + K_2 S + K_3) \dots \dots \dots (20)$$

Where,

$$A = C_1 K_{CH} K$$

$$K_1 = R_A B T_M + C_1 K_{CH} B T_M$$

$$K_2 = R_A B + K_2 + C_1 K_{CH} B + A K_P$$

$$K_3 = A K_I$$

$$T_M = J / B$$

$K_1$  and  $K_P$  are controller gains, and  $R_A$ ,  $B$ ,  $T_M$ , etc., are motor and feedback constants shown in table 1. The above equation introduces a zero and therefore a higher overshoot is expected for a step change in speed reference.

#### 5. RESULTS AND DISCUSSION

In order to validate the efficiency and the effectiveness of the proposed network for the speed



Fig.17 shows the line voltage and current output from the inverter and also it shows the torque response of the induction motor. The waveforms shown in Fig.17 are relatively close with the conventional waveforms. However, the voltage stresses on the inverter switches and the common mode voltage which leads to the motor bearing current is highly eliminated.

## V. Conclusion

This paper is intended to evaluate the speed control of Induction motor fed from Z-source inverter. In this paper, the performance evaluation of SPWM and SVPWM techniques also determined based on the Total harmonic distortion in the inverter output current. From the simulation results, it is concluded that SVPWM technique is more preferable than SPWM technique to control the output voltage and current of the Z-source inverter.

It is observed that PI controller is highly preferable to control the speed of the Induction motor where not much load change involved or not much speed change is required.

Finally, the conclusion made on the usage of Z-source inverter to drive the Induction motor. The Z-source inverter avoids a stage to boost the inverter output voltage whereas in conventional voltage source inverter, a separate stage is needed to boost the output voltage of the inverter. Hence, the Z-source inverter is highly preferable to drive the Induction motor..

## ACKNOWLEDGEMENTS

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P.Elangovan received the B.E. degree in Electrical and Electronics Engineering from Anna University, Chennai, India in 2007, M.E. degree in Power Electronics and Drives from Anna University, Chennai, India in 2011 and currently pursuing the PhD degree at Anna University, Chennai, India.

He is presently working as Assistant Professor of EEE department at SKP Engineering college, Tiruvannamalai, India. His research interests are Power Electronics, motor drives and control systems.



Dr.C.Kumar is working as Director – Academics in SKP Engineering College, Tiruvannamalai, India. He is having 48 years of teaching experience, out of which two years as Director Academic, and 26 years as Principal. He has received the B.E. degree in Electrical and

Electronics Engineering from Alagapaa Chattiar College of Engineering and Technology, Karaikudi, India in 1975, M.Sc (Engg.) degree in Power Systems from Thiagarajar college of engineering Madurai, India in 1979 and the PhD degree from Madurai Kamarajar University, Madurai, India in 2001. His current research includes Electrical engineering, Power systems, Power Electronics and Drives.



V.Suresh received the B.E. degree in Electronics and instrumentation Engineering from Anna University Chennai, India in 2005, M.E. degree in Power Electronics and Drives from Anna University, Chennai, India in 2012 and he is presently working as Assistant Professor of EEE department at SKP Engineering college, Tiruvannamalai, India. His research interests are Power Electronics, Electrical drives and controllers.