A Simplified Modulation Strategy for Three-leg Voltage Source Inverter Fed Unsymmetrical Two-winding Induction Motor

Saliltip Sinthusonthishat[†] and Nontawat Chuladaycha*

Abstract – This paper presents a simplified modulation strategy for the three-leg VSI fed two-winding induction motor. The strategy provides independent unbalanced voltage control for the main and auxiliary windings. This make the motor can be reversed rotation through the range of motor speed operation without limitation of voltage boost of the auxiliary winding. To study the advantages of the proposed drive, the experimental results such as voltage stresses, hysteresis band of the currents in locus, and also acoustic noise levels of the three-leg VSI are compared with those of the conventional two-leg topology. The results obviously show that the proposed technique achieves superior performance compared with the traditional scheme in case of dramatic increase of DC bus utilization, effective reduction of harmonic voltages content, and also significant enhancement of motor efficiency.

Keywords: Three-leg voltage source inverter, Two-phase drive, Unsymmetrical two-winding induction motor, Unbalanced output voltage

1. Introduction

Single-phase squirrel-cage induction motor is one of the most widely used types of low power AC motors for residential households and commercial applications. Since the mostly installed motor volume into the field is the typical standard single-phase induction motor. In case of desirably variable speed, classical techniques such as mechanical or electrical equipments are utilized. These methods do not accomplish continuous speed control and energy saving viewpoint because the motor operates with constant voltage and constant frequency sources. Importance of energy saving issue and the decrease in the cost of the power electronic circuitry has substantially stimulated interest in the investigation of different single-phase motor drive topologies.

Variable speed control for single-phase induction motor (SPIM) with a single-phase drive has several serious problems especially at low speed such as low efficiency and average torque, great ripple torque and speed pulsation when compared with a two-phase drive [1-5]. The two-phase drive system can be classified as inverter topologies in three types: two-leg, three-leg, and four-leg inverters. The two-leg inverter is the most favorite type of the drive system because control strategies for each motor winding can be designed independently [6-10]. However, the generated bipolar or two-level pulse width modulation (PWM) pattern of the two-leg drive has numerous

harmonic voltages. The additional losses of the motor are taken placed. Motor efficiency is greatly reduced. The four-leg type is hardly concerned. Although the independent control with unipolar or three-level PWM pattern is given, more switching devices significantly provide more cost, higher switching and conduction losses, and also lower system reliability. Therefore, few researchers [11-13] use the three-leg inverter. Even though the quality of PWM scheme is nearly the four-leg type, a special modulation strategy is dramatically required. To disregard the difficulty in the modulation methodology, a symmetrical two-winding motor is considered [14]. However, the motor must be rewound or redesigned. The proper ways to attain the optimal motor performance, low-cost drive circuits, and appropriate inverter strategies may be the three-leg topology with an uncomplicated control technique.

In [13, 15], the unsymmetrical two-winding induction motor drive with unbalanced voltage control method have been presented as shown in Fig.1. Capacitors connected in series with an auxiliary winding are removed. V_{D1} and V_{Q1} are the fundamental output voltage of the auxiliary winding and the main winding, respectively. a is turns ratio of the auxiliary winding to the main winding. Since "a" of SPIM is normally depended on type and rated power of the motor. This voltage control method achieves the best motor performance for both starting and running status.

This paper presents a simplified modulation strategy for two-phase drive system using a three-leg voltage source inverter (VSI) feeding standard single-phase induction motors which are composed of unsymmetrical two stator windings. The proposed strategy offers completely unbalanced voltage control at a wide range of speed operation, and also no limitation of rotating direction of

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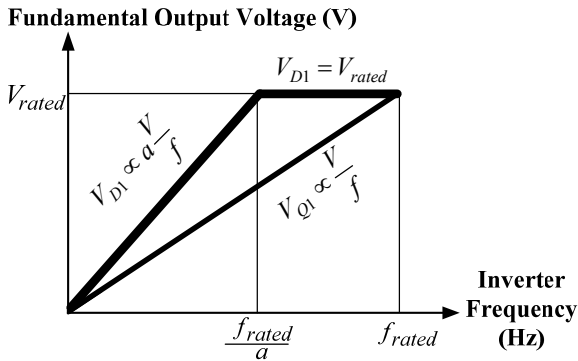**Fundamental Output Voltage (V)**

Fig. 1. The relationship between inverter frequency and fundamental output voltage for each winding

motor shaft. The results of three-leg VSI with the proposed strategy are compared with those of the conventional two-leg drive. Harmonic voltages content in case of voltage stress, loci current, acoustic noise, and motor efficiency are investigated. The experimental results clearly show that the proposed modulation strategy is better than the classical two-leg scheme in terms of DC bus voltage utilization, harmonic voltage content, and motor performance.

2. Conventional Two-leg Modulation Strategy

The main structure of PWM inverter fed unsymmetrical two-winding induction motor using the conventional two-leg inverter is shown in Fig. 2. The drive system consists of a single-phase voltage doubler circuit, two series filter capacitor, and two-leg of an IGBT pair. The one end of the main and auxiliary windings are joined to the two-leg inverter. The other ends are connected together with the center-tap of the filter capacitors. A capacitor for permanent split capacitor SPIM or two capacitors for the motor type of two-value capacitor SPIM must be removed. The fundamental voltage for both windings must be displaced with 90 electrical degree differences. The principle of generating PWM output voltages is based on a comparison between a reference sinusoidal and a common triangular wave, so called a sinusoidal pulsewidth
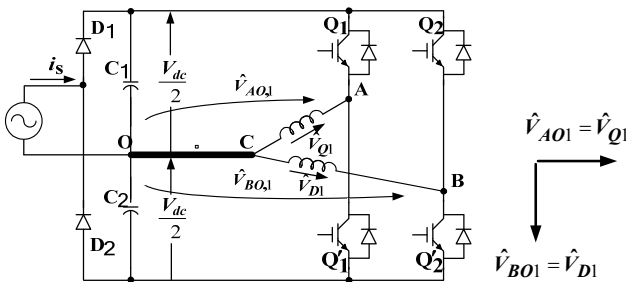

Fig. 2. Main power circuit and voltage vector of a conventional two-leg VSI

modulation (SPWM). If $v_{a,2-leg}$ and $v_{b,2-leg}$ are reference modulating functions of control signals on phase a and b, respectively, those functions for the two-leg system are as follows:

$$\left. \begin{aligned} v_{a,2-leg} &= V_{m1} \sin (\omega_r t), \\ v_{b,2-leg} &= V_{m2} \sin (\omega_r t - \frac{\pi}{2}). \end{aligned} \right\} \tag{1}$$

where V_{m1} and V_{m2} denote as the voltage amplitude.

Let V_{dc} is DC link voltage. Thus, the instantaneous fundamental output voltage of the auxiliary winding $\left(v_{D1,2-leg} \right)$ and that of the main winding $\left(v_{Q1,2-leg} \right)$ are

$$\left. \begin{aligned} v_{D1,2-leg} &= \frac{M_1 V_{dc}}{2} \sin(\omega_r t), \\ v_{Q1,2-leg} &= \frac{M_2 V_{dc}}{2} \sin(\omega_r t - \frac{\pi}{2}). \end{aligned} \right\} \tag{2}$$

From (2), it is obviously indicated that $v_{D1,2-leg}$ and $v_{Q1,2-leg}$ can be individually adjusted by modulation index M_1 and M_2, consecutively.

3. The Proposed Three-leg Modulation Strategy

The three-leg VSI is modification of the two-leg VSI by adding a leg of IGBT pair as well as inserting a modulating control signal. If each modulating function is

$$\left. \begin{aligned} v_1 &= V_m \sin (\omega_r t), \\ v_2 &= V_m \sin (\omega_r t - \frac{\pi}{2}), \\ v_3 &= V_m \sin (\omega_r t - \pi). \end{aligned} \right\} \tag{3}$$

Where v_1, v_2, and v_3 are applied to leg1, leg2, and leg3 of the three-leg inverter, consecutively. All control signals have the same voltage amplitude V_m and contain 90 electrical degree phase shifting. These offer three configurations of winding placement and inverter connection which can be depicted as shown in Figs. 3 to 5. The appropriate wiring should be according to Fig. 4 because V_{D1} and V_{Q1} are orthogonal. Unfortunately, control signals in (3) cannot contribute to unbalanced voltage control. To overcome this problem, modification of the modulating function is required. Let

$$\left. \begin{aligned} v_{a,3-leg} &= v_1 - d \left(v_2 + v_3 \right), \\ v_{b,3-leg} &= v_2, \\ v_{c,3-leg} &= v_3 + q \left(v_1 + v_2 \right). \end{aligned} \right\} \tag{4}$$
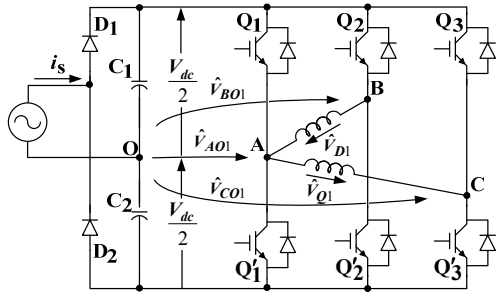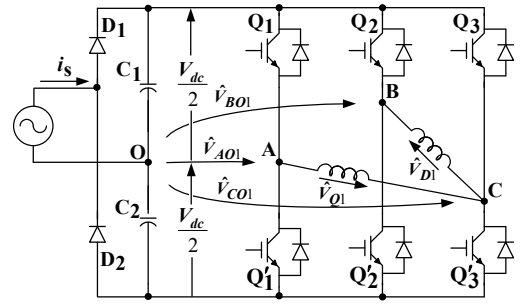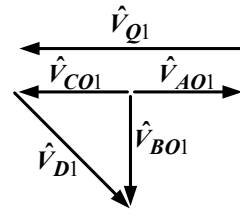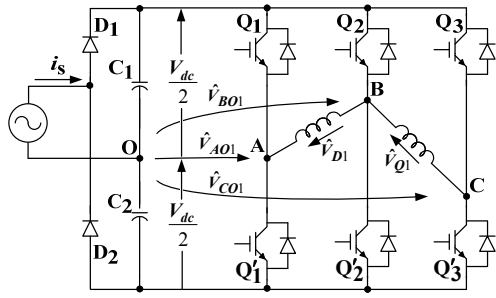
(a) main power circuit of a three-leg VSI
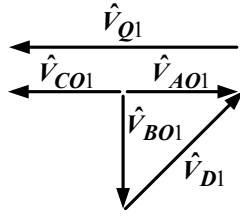
(b) voltage vectors

Fig. 3. Stator winding connected together at A point
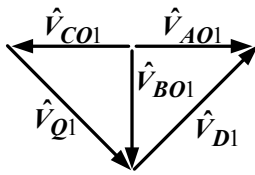

(a) main power circuit of a three-leg VSI

(b) voltage vectors

Fig. 4. Stator winding connected together at B point

When d and q are constant values, therefore,

$$
\left.
\begin{aligned}
v_{a,3-leg} &= V_m \sin(\omega_r t) - dV_m \sin\left(\omega_r t + \frac{\pi}{4}\right), \\
v_{b,3-leg} &= V_m \sin\left(\omega_r t - \frac{\pi}{2}\right), \\
v_{c,3-leg} &= V_m \sin(\omega_r t - \pi) + qV_m \sin\left(\omega_r t - \frac{\pi}{4}\right).
\end{aligned}
\right\}
\tag{5}
$$

The control signals across the auxiliary winding $\left(v_{ab,3-leg}\right)$ and that across the main windings $\left(v_{bc,3-leg}\right)$ are

(a) main power circuit of a three-leg VSI

(b) voltage vectors

Fig. 5. Stator winding connected together at C point

$$
\left.
\begin{aligned}
v_{ab,3-leg} &= v_{a,3-leg} - v_{b,3-leg} = \sqrt{2}(1-d)V_m \sin\left(\omega_r t + \frac{\pi}{4}\right), \\
v_{bc,3-leg} &= v_{b,3-leg} - v_{c,3-leg} = \sqrt{2}(1-q)V_m \sin\left(\omega_r t - \frac{\pi}{4}\right).
\end{aligned}
\right\}
\tag{6}
$$

The fundamental output voltages of the auxiliary winding $\left(v_{D1,3-leg}\right)$ and the main winding $\left(v_{Q1,3-leg}\right)$ can be expressed as

$$
\left.
\begin{aligned}
v_{D1,3-leg} &= V_{AN} - V_{BN} = \frac{\sqrt{2}(1-d)MV_{dc}}{2}\sin\left(\omega_r t + \frac{\pi}{4}\right), \\
v_{Q1,3-leg} &= V_{BN} - V_{CN} = \frac{\sqrt{2}(1-q)MV_{dc}}{2}\sin\left(\omega_r t - \frac{\pi}{4}\right).
\end{aligned}
\right\}
\tag{7}
$$

In (7), the fundamental output voltages of the auxiliary winding and of the main winding can be separately adjusted by d and q, respectively. It can be seen that there are two different parameters used for the voltage control which are similar to those of the two-leg drive as prior described in (2). However, the DC bus utilization equals to $\sqrt{2}$ times of that used by the two-leg drive. The proposed modulating strategy is simple and makes achievement of unbalanced voltage control of the three-leg drive system. In case of reverse direction, $v_{D1,3-leg}$ and $v_{Q1,3-leg}$ can be switched. Voltage amplitude for each winding can be governed by q and d again. This method is found to be superior to [13] in terms of voltage control in case of reversible rotation. Since [13] has only the additional modulating function in phase C. The strategy according to [13] cannot maintain voltage boost with "*a*" times of the auxiliary winding when reverse direction is
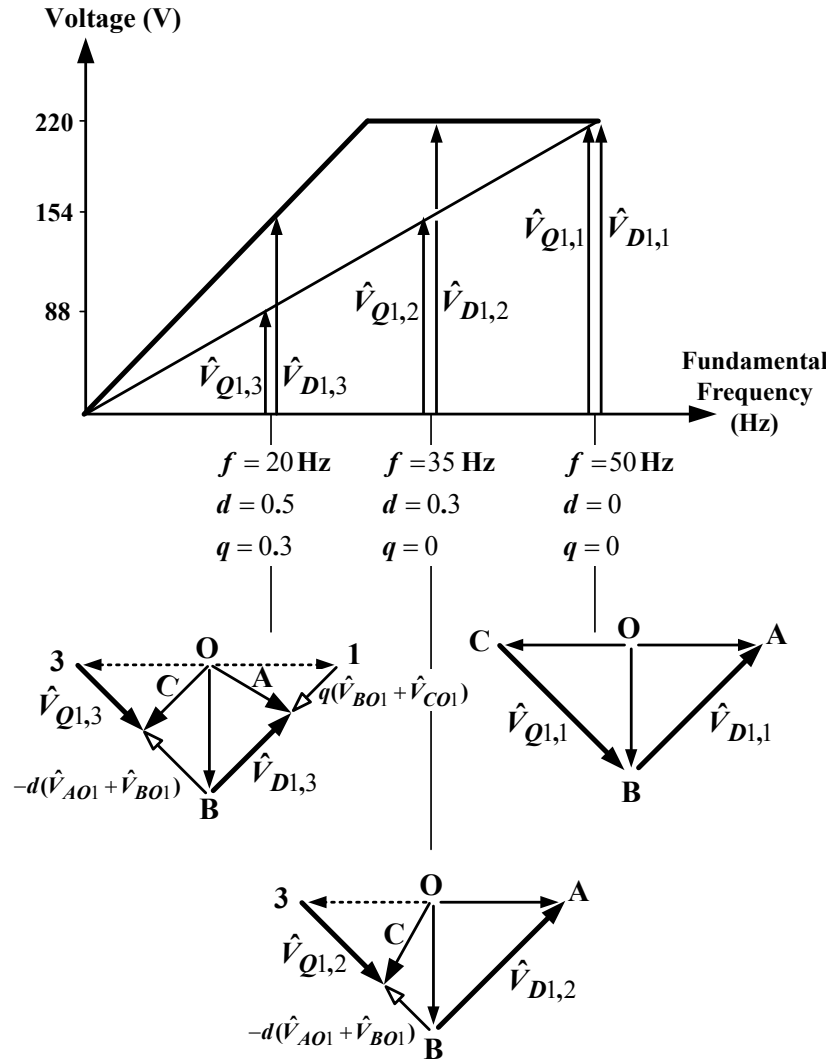
Fig. 6. Phasor diagram of the modified modulating functions for unbalanced output voltages of three-level VSI

required.

In order to better understand the proposed PWM modulation strategy, an authentic information of a tested motor such as the 220-V rated voltage, 50-Hz rated frequency, 1.7 turns ratio, and $\frac{V_{rated}}{f_{rated}} = \frac{220}{50} = 4.4$, was substituted in Fig. 1. The relationship between both winding voltages and fundamental frequency of inverter (f) can be rewritten as illustrated in Fig. 6. There are divided into three cases as follows:

Case 1: at $f = f_{rated}$, $V_{D1} = V_{Q1} = V_{rated}$, thus,

$$f = 50 \text{ Hz}, V_{D1,1} = V_{Q1,1} = 220 \text{ V},$$

Case 2: at $\frac{f_{rated}}{a} \leq f < f_{rated}$, $V_{D1} = V_{rated}$,

$$V_{Q1} \propto \frac{V_{rated}}{f_{rated}}, \text{ so } f = 35 \text{ Hz}, V_{D1,2} = 220 \text{ V},$$

$$V_{Q1,2} = 154 \text{ V},$$

Case 3: at $f < \frac{f_{rated}}{a}$, $V_{D1} \propto \frac{a \times V_{rated}}{f_{rated}}, V_{Q1} \propto \frac{V_{rated}}{f_{rated}},$

hence, $f = 20$ Hz, $V_{D1,3} = 149.6$ V, $V_{Q1,3} = 88$ V.

It can be noticed that in case 1 there is no need of d and q. Case 2 uses only q to regulate voltage amplitude of the main winding. In the final case, both d and q are required to adjust the desired voltage amplitude. Voltage vectors of each case are strongly verified a success of the proposed modulation strategy for unbalanced voltage control method of the two-phase drive system using the three-leg VSI.

4. Results and Discussion

The performance of the proposed modulation strategy is

verified by the experiment of which the simplified block diagram is illustrated in Fig. 7. A 370-W 2.56-Nm 220-V 2.66-A 1375-rpm 50-Hz 4-pole permanent split capacitor motor with turns ratio of 1.7 is used in the investigation. A running capacitor in series with the auxiliary winding is not necessary in the proposed circuit. In order to study the advantages of the proposed technique, the three-leg VSI is compared with the conventional two-phase drive. The motor is fed by two types of two-phase inverters constructed by 25-A 1200-V IGBT Intelligent Power Module power switching device. The inverter patterns are asynchronously natural-sampled PWM signals which are generated by comparing a triangular carrier wave with the sinusoidal reference modulating functions generated from a
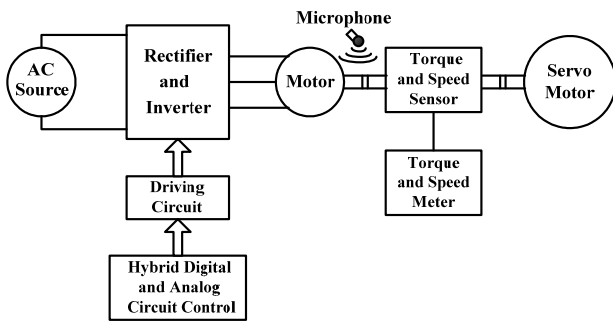
microcontroller. A 1000 W servo motor connected with the motor is served as a dynamic load. Motor shaft torques and speeds are measured by torque-speed sensor. Experimental results of motor input are recorded using the PZ4000 Power Harmonics Analyzer. Noise signals are detected by an installed microphone at a distance of 3 cm. from the motor. Acoustic noise spectra are extracted from the measured noise by using a spectrum analysis program. Fig. 8 shows a photograph of the experimental setup.
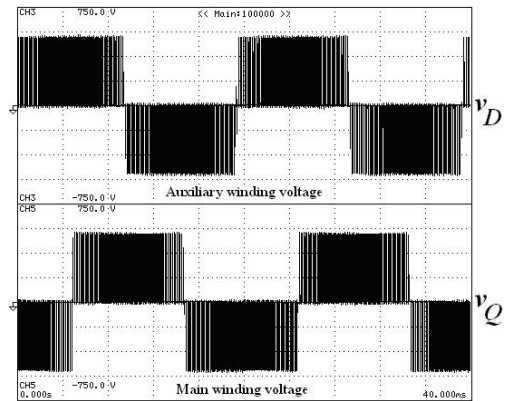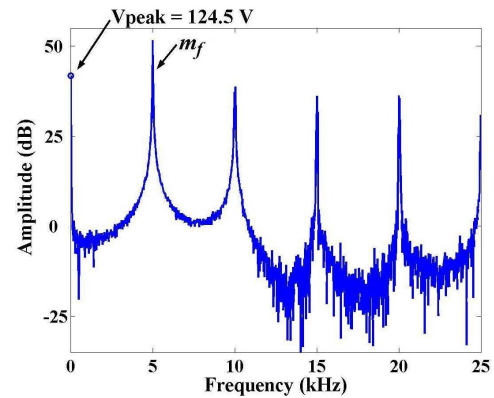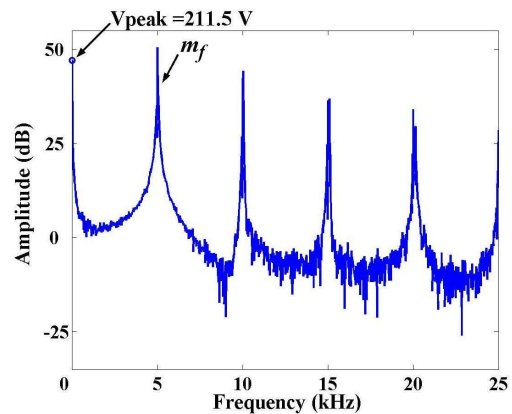

Fig. 7. Block diagram of experimental system
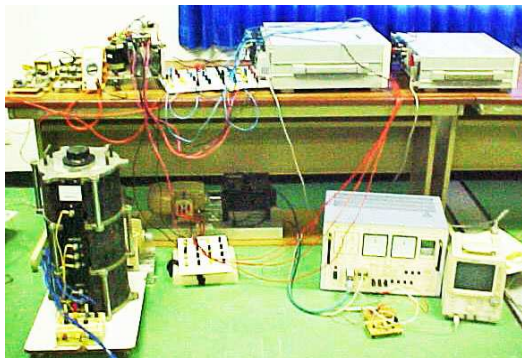
Fig. 8. Photograph of the experimental setup
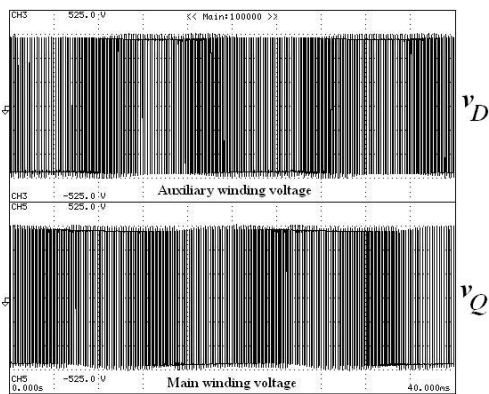
Fig. 9. PWM output voltages for the two-leg VSI

Fig. 10. PWM output voltages for the three-leg VSI
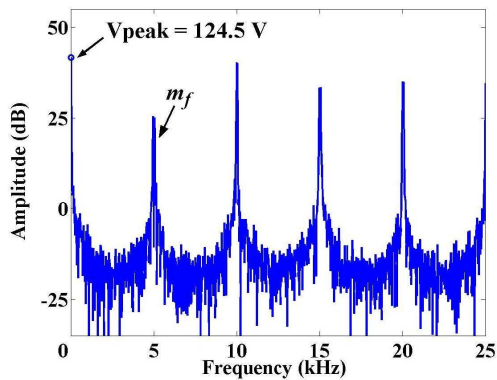

(a) main winding
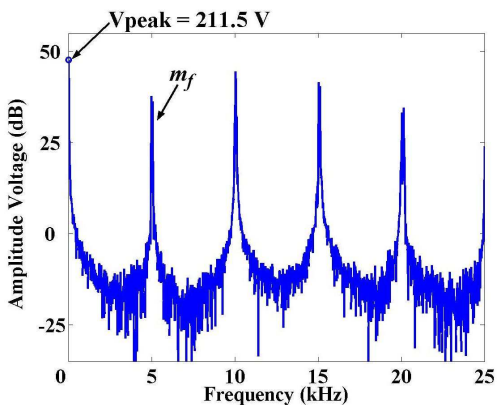

(b) auxiliary winding

Fig. 11. Voltage stress of the two-leg VSI at 20-Hz frequency

The experimental results of PWM output voltages across motor windings at rated frequency of 50 Hz for the two-leg and three-leg VSIs are shown in Figs. 9 and 10, respectively. They are indicated that at the same dc bus voltage of 525 V and modulation index of 0.8 for both drive systems, the two-leg VSI provides 525-V two-level PWM output voltage across each winding while the three-leg VSI supplies 750-V three-level one. This confirms that, at the same dc bus voltage and modulation index, the three-leg drive provides higher output voltage about 1.4 times of that provided by the two-leg VSI.

To inspect the harmonic voltage contents and its effect on motor performance, especially in the complete voltage boost region, the sinusoidal reference frequency of 20 Hz and the compromise triangular carrier frequency of 5 kHz are selected. The fundamental peak voltage of the main winding is about 124.5 V while that of the auxiliary winding is approximately 211.5 V. The motor load is kept at rated torque. The harmonic voltage stress of the two-leg and three-leg VSIs are demonstrated in Figs. 11 and 12, consecutively. The figures show that the three-leg drive with the proposed modulating function offers the lower harmonic voltage stresses, particularly at the first harmonic voltage of carrier frequency or m_f. Figs. 13 and 14 illustrate
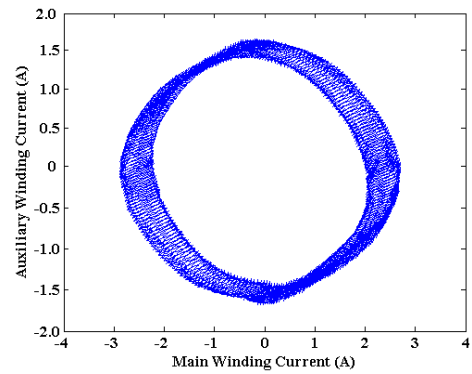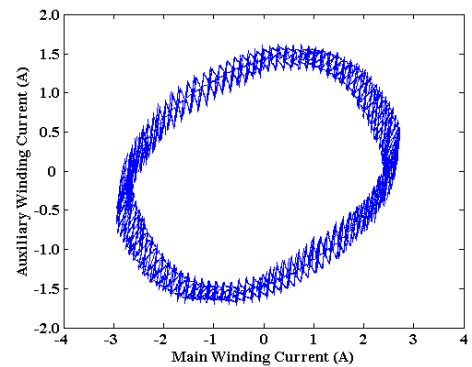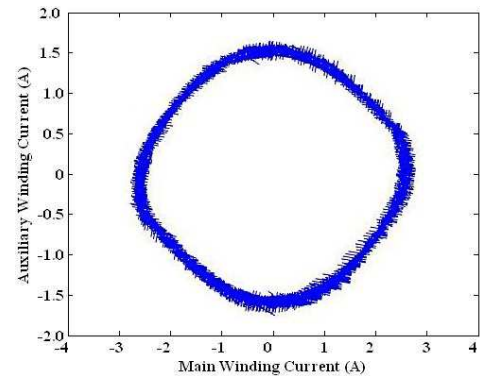

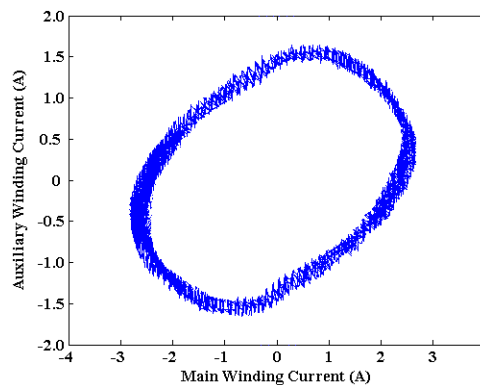(a) inverter frequency of 20 Hz

(b) inverter frequency of 50 Hz

Fig. 13. Loci current for the two-legVSI

(a) inverter frequency of 20 Hz

(b) inverter frequency of 50 Hz

Fig. 14. Loci current for the three-leg VSI

(a) main winding

(b) auxiliary winding

Fig. 12. Voltage stress of the three-leg VSI at 20-Hz frequency

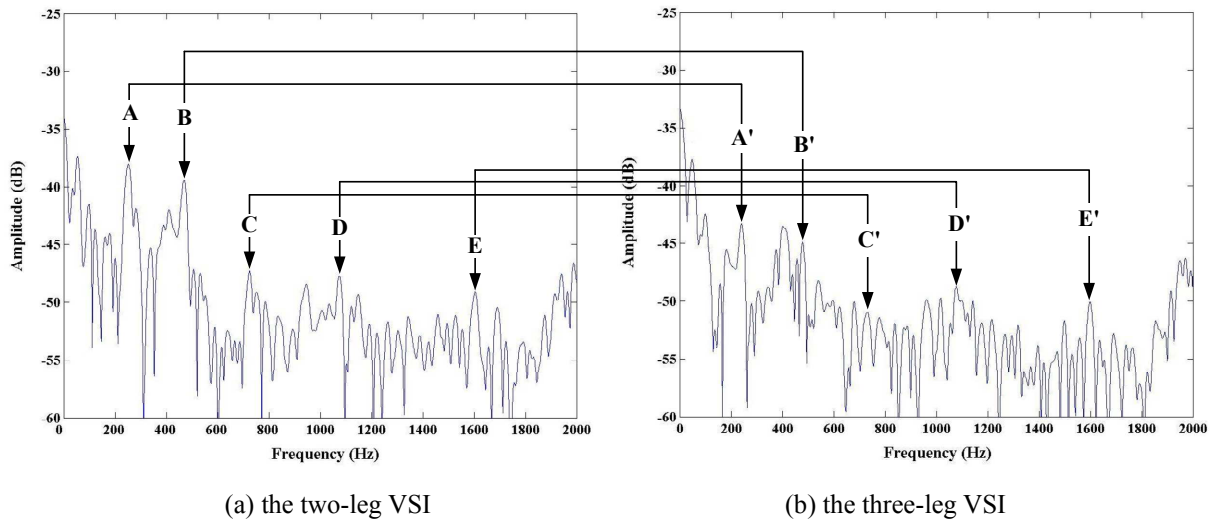(a) the two-leg VSI   (b) the three-leg VSI

Fig. 15. Acoustic noise with both drive systems at inverter frequency of 20 Hz

loci current of the two-leg, and three-leg VSIs. It can be seen that current hysteresis band of the two-leg inverter is greater than that of the 3-leg. Acoustic noise spectra with the two-leg and three-leg inverter fed the induction motor are depicted in Fig. 15. For low and medium motor speed, mechanical and aero-dynamical noises can practically be neglected [16-17]. Therefore, only electromagnetic noise is presented. It can be apparently seen that the noise components of the three-level PWM are mostly attenuated. Motor efficiencies for each inverter topologies are demonstrated in Table 1. It is obviously shown that motor efficiencies of the three-leg VSI are better than those of the two-leg VSI as a result of higher order harmonic current due to unipolar and bipolar PWM patterns of the three-leg and the two-leg VSIs. The average and ripple torques of the motor do not exist. Ordinarily, the average torques for both drives are identical because of the same fundamental output voltage. Harmonic voltages typically create only harmonic of ripple torque.

Table 1. Motor efficiency

Drive system	The 2-leg				The 3-leg			
f (Hz)	20	30	40	50	20	30	40	50
Efficiency (%)	50.5	61.4	72.3	73.7	54.6	63.2	75.2	78.6

5. Conclusion

This paper focuses on a simplified modulation strategy for a three-leg drive system fed typical single-phase induction motors. The proposed strategy requires only three reference voltage vectors which have the same amplitude and 90 electrical degree phase difference and the modified modulating function. This provides completely independent two-phase voltage control for both motor windings. With the modified modulating function, the

reverse rotation at a wide range of speed operation can be achieved. The experimental results of the three-leg topology are compared with those of the traditional two-leg drive. The experimental results noticeably show that the three-leg drive offers dramatically lower harmonic voltages than the two-leg VSI. Consequently, the electromagnetic forces created in the motor are significantly minimized. The result of higher harmonic voltage order makes decrease of harmonic currents and also decline in the acoustic noise volume. The more reduction in harmonic current results in the higher motor efficiency.

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