STANDARD THREE-LEG INVERTER SUPPLYING INDEPENDENTLY TWO INDUCTION MACHINES

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***Abstract* – This paper proposes two motor drive system topologies. The proposed configurations have been designed for applications in which it is necessary to control two motors independently, by using a single conventional three-leg inverter. The proposed two-motor drive system is seen as a potentially viable industrial solution for applications that demand one high-power and one low-power machines. The pulse-width modulation techniques and the control strategies are investigated. The main characteristics of the drive systems are also presented. Experimental results verify the theoretical studies.**

***Keywords* – Induction motor, motor drive system, reduced components, independent control of two motors.**

I. INTRODUCTION

A standard ac motor drive system is constituted by an input rectifier, a capacitor bank for providing the dc-link, an inverter, an electrical motor and a microcomputer based control system. In industrial applications that demand multiple electrical motors, the standard solution consists in replicating such standard configuration. One alternative for reducing costs in this case is to use a common dc-link for all motor drive systems installed in the shop-floor. A second alternative to further reduce installation costs is to use converter topologies with a minimized number of power switching devices [1] - [15].

The objective of this paper is to propose two motor drive system topologies. One proposed configuration is designed for the three-phase machine in a wye connection [see Fig. 1(a)], while the other one is designed for the three-phase machine in a delta connection [see Fig. 1(b)], in both topologies the three-phase machine is connected to a single-phase machine. The configurations have been assumed for applications which it is necessary to control two motors independently, by using a single conventional three-leg inverter. The two-motor drive systems of the proposed structure is seen as a potentially viable industrial solution for applications requiring one high-power (three-phase machine) and one low-power machine (single-phase machine). Such topologies can be applied, for instance, with motors for traction and compression in automotive applications [8], [9], [16] and [17]. All the proposed solutions employ conventional three-leg converters and thus have less power devices than the typical solution for multi-machine drive systems, in which the number of power switches is proportional to number of the machines.

In addition, the paper aims to present relevant characteristics of the converter, such as: i) voltage capability and capacitor currents; ii) pulse-width modulation techniques based on scalar approaches; iii) control strategies for providing voltage and current control; and iv) experimental results.

II. MOTOR DRIVE SYSTEM

Both proposed configurations comprise six switches, a dc-link constituted by a capacitor bank with mid-point connection and two induction motors (three-phase and single-phase ones). The converter is composed by switches q_1, $\bar{q}_1$, q_2, $\bar{q}_2$, q_3 and $\bar{q}_3$. The switch-pairs q_1-$\bar{q}_1$, q_2-$\bar{q}_2$ and q_3-$\bar{q}_3$ are complementary. In all cases, the conduction state of all switches can be represented by binary variable q_1, q_2 and q_3 where q=1 indicates a closed switch while q=0 indicates an open one.

A. Three-phase motor model

A typical three-phase machine has been used in this work. Adopting a fixed coordinate reference frame, the mathematical model that describes the dynamic behavior of the three-phase induction machine is given by

$$v_{sdq} = r_s i_{sdq} + \frac{d}{dt}\phi_{sdq} \tag{1}$$

$$v_{rdq} = r_r i_{rdq} + \frac{d}{dt}\phi_{rdq} - j\omega_r \phi_{rdq} \tag{2}$$

$$\phi_{sdq} = l_s i_{sdq} + l_{sr} i_{rdq} \tag{3}$$

$$\phi_{rdq} = l_{sr} i_{sdq} + l_r i_{rdq} \tag{4}$$

$$v_{so} = r_s i_{so} + l_{ls}\frac{d}{dt} i_{so} \tag{5}$$

$$v_{ro} = r_r i_{ro} + l_{lr}\frac{d}{dt} i_{ro} \tag{6}$$

$$T_e = P l_{sr}\left(i_{sq} i_{rd} - i_{sd} i_{rq}\right). \tag{7}$$

Where $v_{sdq} = v_{sd} + jv_{sq}$, $i_{sdq} = i_{sd} + ji_{sq}$ and $\phi_{sdq} = \phi_{sd} + j\phi_{sq}$ are the voltage, current, and flux dq vectors of the stator, respectively; $v_{sho} = v_{sh} + jv_{so}$, $i_{sho} = i_{sh} + ji_{so}$ and $\phi_{sho} = \phi_{sh} + j\phi_{so}$ are voltage, current and flux ho homopolar no-torque vectors of the stator, respectively (the equivalent rotor variables are obtained by replacing the subscript s by r); T_e is the electromagnetic torque; ω_r is the angular frequency of the rotor; r_s and r_r are the stator and rotor resistances; l_s, l_{ls}, l_r and l_{lr} are the self and leakage inductance of the stator and rotor, respectively; l_{sr} is the mutual inductance and P is the number of pole pairs.

The dqo stator variables can be determined from the 123 variables by using the transformation given by [10]:

$$w_{123} = Aw_{dqo}. \tag{8}$$

With $w_{123} = \begin{bmatrix} w_1 & w_2 & w_3 \end{bmatrix}^T$, $w_{dqo} = \begin{bmatrix} w_d & w_q & w_o \end{bmatrix}^T$ e

$$A = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 & \frac{\sqrt{2}}{2} \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} & \frac{\sqrt{2}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & \frac{\sqrt{2}}{2} \end{bmatrix}. \tag{9}$$

Vectors w_{123} and w_{dqo} can be currents, voltages or flux vectors, and $A^{-1} = A^T$.

B. Single-phase motor model

A permanent-capacitor single-phase motor has a capacitor series connected with the auxiliary winding in order to generate the rotating magnetic field. Choice of the capacitor value is made to achieve minimum electromagnetic torque oscillation at rated speed. Despite of be designed to operate under constant frequency it can be shown that there exist a frequency range in which it is possible to vary its speed [21].

III. CONFIGURATION Y

The proposed topology, named Configuration Y, is shown in Fig 1(a).

A. Model

The converter pole voltages can be written as a function of phase voltage of the three-phase and single-phase machines, or as a function of conduction state of the switches, as follow

$$v_{10} = v_{s1} - v_{s3} = q_1 v_{c1} - (1 - q_1) v_{c2} \tag{10}$$

$$v_{20} = v_{s2} - v_{s3} = q_2 v_{c1} - (1 - q_2) v_{c2} \tag{11}$$

$$v_{30} = v_l = q_3 v_{c1} - (1 - q_3) v_{c2}. \tag{12}$$

From (10)-(12) can obtain the machines voltages, as follows

$$v_{s1} = \frac{2}{3} v_{10} - \frac{1}{3} v_{20} \tag{13}$$

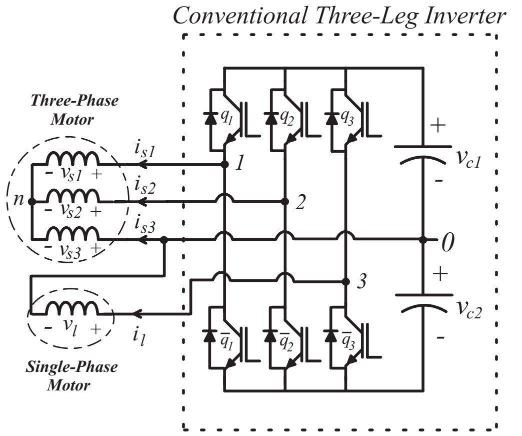
$$v_{s2} = -\frac{1}{3} v_{10} + \frac{2}{3} v_{20} \tag{14}$$

$$v_{s3} = -\frac{1}{3} (v_{10} + v_{20}) \tag{15}$$

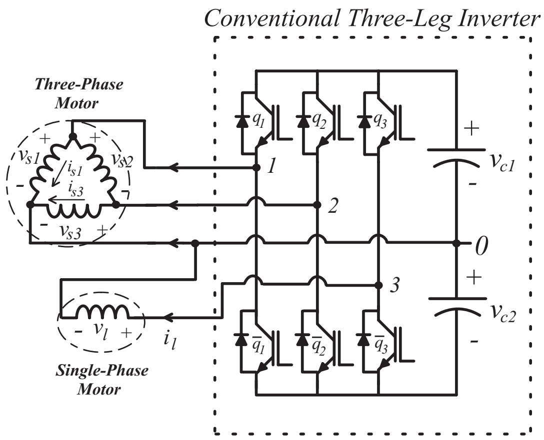
$$v_l = v_{30}. \tag{16}$$

B. PWM Control

From now on the desired machine phase voltages are specified by $v_{s1}^*, v_{s2}^*, v_{s3}^*$ and v_l^*.



(a)



(b)

Fig. 1. Conventional inverter supplying independently two inductions motors: (a) Three-phase machine with wye connection (Configuration Y). (b) Three-phase machine with delta connection (Configuration D).

Therefore, the voltage referred to the mid-point '0' can be expressed by

$$v_{10}^* = v_{s1}^* - v_{s3}^* \tag{17}$$

$$v_{20}^* = v_{s2}^* - v_{s3}^* \tag{18}$$

$$v_{30}^* = v_l^*. \tag{19}$$

Once the mid-point voltage (v_{10}^* to v_{30}^*) have been determined, pulse widths τ_1 to τ_3 are calculated by using

$$\tau_j = \left(\frac{T}{2} + \frac{T}{E} \right) v_{j0}^* \quad \text{for} \quad j=1 \text{ to } 3 \tag{20}$$

where $E = v_c^*$ (total dc-link voltage), T is the switching period and gating signals (τ_1 to τ_3) are generated with programmable timers. Alternatively, gating signals can be generated comparing modulating reference signals v_{10}^* to v_{30}^* with a high frequency triangular carrier signal.

On the other hand, to eliminate the error due to the capacitor unbalance resultant from the capacitor midpoint connection, the expression (20) is no longer valid, because this one uses the reference value of the dc-link voltage. To compensate the capacitor unbalanced, pulse widths must be computed by using (21). The new expression for τ_1 to τ_3 is given by

$$\tau_j = \left(v_{j0}^* + v_{c2}\right)\frac{T}{v_{c1} + v_{c2}} \quad \text{for } j = 1 \text{ to } 3. \tag{21}$$

Note that it is necessary to measure v_{c1} and v_{c2}. This expression was obtained in [20].

C. Control Strategy

Control block diagram of the system is shown in Fig. 2. In these figures IM 1 represents the three-phase machine, while IM 2 represents the single-phase machine.

Volts/Hertz control and torque control has been applied for the single-phase and three-phase motor, respectively. The PWM block has been implemented by equations obtained in the previous section.

Block R_{dq} implements the dq currents control. When the torque control is accomplished by controlling the dq voltages, the diagram of Fig. 2 can be directly adapted. In this case, the torque controller outputs are the voltages v_{sdq}^* (controller R_{dq} is eliminated).

IV. CONFIGURATION D

The proposed configuration, named Configuration D is shown in Fig 1(b). In view of dc-link voltage reduction importance, three-phase machine with delta connection is more indicated. Since the dc-link voltage is defined by three-phase motor line-voltages.

A. Model

As in the case of Configuration Y, the converter pole voltages can be written as a function of phase voltage of the three-phase and single-phase machines, or as a function of conduction state of the switches, as follow

$$v_{10} = v_{s1} = q_1 v_{c1} - (1 - q_1)v_{c2} \tag{22}$$

$$v_{20} = v_{s3} = q_2 v_{c1} - (1 - q_2)v_{c2} \tag{23}$$

$$v_{30} = v_l = q_3 v_{c1} - (1 - q_3)v_{c2}. \tag{24}$$

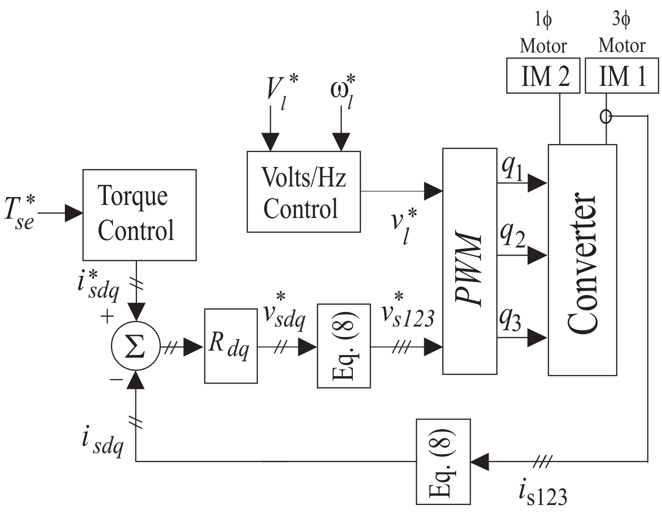


Fig. 2. Control system block diagram.

From (22)-(24) can obtain the machines voltages, as follows

$$v_{s1} = v_{10} \tag{25}$$

$$v_{s2} = v_{10} - v_{20} \tag{26}$$

$$v_{s3} = v_{20} \tag{27}$$

$$v_l = v_{30}. \tag{28}$$

B. PWM Control

The voltage referred to the mid-point ‘0’ can be expressed by

$$v_{10}^* = v_{s1}^* \tag{29}$$

$$v_{20}^* = v_{s3}^* \tag{30}$$

$$v_{30}^* = v_l^*. \tag{31}$$

Once mid-point voltage (v_{10}^* to v_{30}^*) have been determined, pulse width τ_1 to τ_3 are also calculated from (20) or (21).

C. Control Strategy

Control strategy for Configuration D is given as done for Configuration Y. In terms of control strategy, the unique difference between two configurations is obtained in PWM block, for Configuration Y has been used equations (17)-(19), while for Configuration D has been used equations (29)-(31).

V. COMPARISON BETWEEN THE CONFIGURATIONS

A. Voltages Analysis

The voltage limits can be determined by considering that all voltages are purely sinusoidal. Since $v_{j0}^* \le E/2$ (j = 1 to 3), the dc-link voltage necessary for Configuration Y is determined as follow

$$E \ge 2\left(\sqrt{3}V_s\right) \tag{32}$$

$$E \ge 2(V_l) \tag{33}$$

$$E \ge \sqrt{3}V_s + V_l \tag{34}$$

where V_s, V_l are the amplitude of three-phase and single-phase machines, respectively. The dc-link voltage necessary for Configuration D is determined, as follow

$$E \ge 2V_s \tag{35}$$

$$E \ge 2(V_l) \tag{36}$$

$$E \ge V_s + V_l. \tag{37}$$

Then, comparing (32)-(34) to (35)-(37) has been observed that Configuration D is more indicated than Configuration Y, specifically in terms of dc-link voltage criteria.

B. Capacitor Current

The average value (over the switching period T) of the current flowing though the upper side capacitor (i_{cup}) of the capacitor bank is an important issue for the proposed configurations. This current for Configuration Y and Configuration D is given, respectively by

$$\bar{i}_{cup} = \frac{1}{2}\left(i_{s3} - i_l\right) \tag{38}$$

$$\bar{i}_{cup} = \frac{1}{2}\left(-i_{s1} - i_{s3} - i_l\right). \tag{39}$$

Then, comparing (38) to (39) has been observed that Configuration Y is more indicated than Configuration D, in the current analysis.

Therefore, the comparison between both proposed structures can be done in terms of dc-link voltage or dc-link currents. Equations (32)-(37) and (38)-(39) highlight the differences in these two criterions, i.e., in terms of dc-link voltage, Configuration D is more interesting, while in terms of capacitor currents, Configuration Y has more advantage.

VI. EXPERIMENTAL RESULTS

The topology presented in Fig. 1 has been implemented experimentally in the laboratory. The set-up (Fig. 3) used in the experimental tests is based on a microcomputer (PC-Pentium) equipped with appropriate plug-in boards and sensors.

Fig. 4 presents selected experimental results for Configuration Y [see Fig. 1(a)]. These results were obtained with Volts/Hertz control applied to single-phase machine while current control was applied to three-phase machine.

Fig. 4(a) shows steady-state single-phase and three-phase currents operating at 40Hz and 25Hz, respectively. Fig. 4(b) shows a transitory in amplitude and frequency of the three-phase current. Both results indicate an independent control for each machine, even in presence of abrupt variations of the three-phase machine current.

According to expected results, the experimental tests obtained for Configuration D is similar to that of Configuration Y.

VII. CONCLUSION

This paper has presented two reduced switch count ac drive systems for combinations between a three-phase and single-phase machines. Both proposed topologies employ a single standard three-leg inverter. Their operating principles were presented and it has been shown that their overall performance is adequate. The experimental results have demonstrated the feasibility of the proposed topologies.

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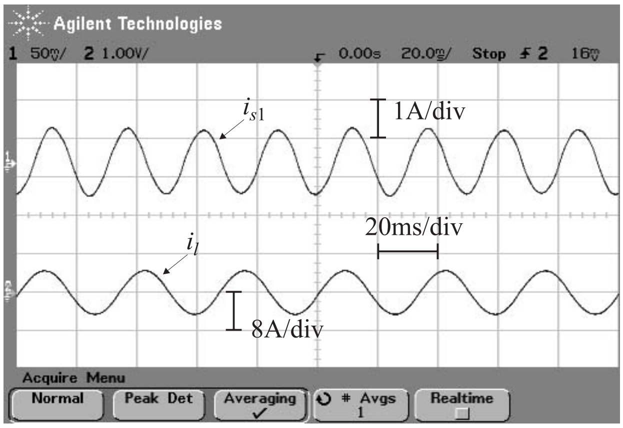
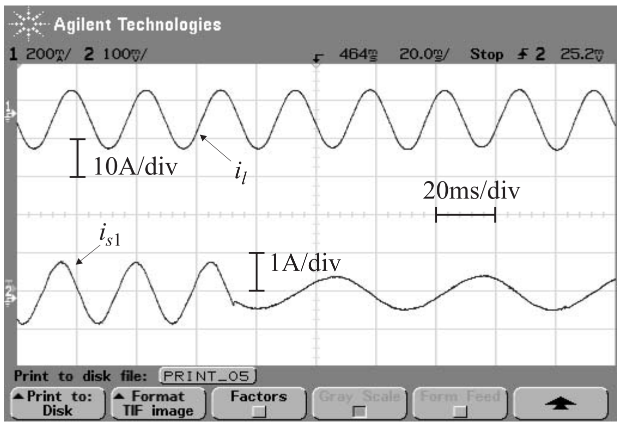
Fig 3. Experimental set-up.



(a)



(b)

Fig. 4. Experimental results of Configuration Y obtained from oscilloscope: (a) three-phase machine current and single-phase machine current, operating at 40Hz and 25Hz, respectively, (b) single-phase machine current and three-phase machine current with transitory in the amplitude and frequency of the currents.

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