



Direct Torque Control of Two Series Connected Six-Three phases Motor Fed by Single Six Phases VSI Based on Optimum Vectors Selection

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ABSTRACT

In this paper, a direct torque control (DTC) is developed for a two series connected six-phase & three-phase motor drive (IMs) with sinusoidal distributed windings and fed by single six-phase voltage source inverter (VSI). Direct torque control also considered as a variable structure control strategy with simplicity, fast response and tolerance to motor parameter variations; it provides direct control of stator flux and torque by optimally selecting the inverter states in each sampling period. In case of multi-phase system drive, the increased number of voltages vectors offers greater flexibility in optimizing the selection of the inverter states. The technique elaborated in this work based direct torque control allows independently control of the system fed by single inverter. The effectiveness and capability of the proposed method are shown by computer simulation..

1. Introduction

During the last decade, the interest in multi-phase multi-motor drive system has substantially increased because of the potential advantages that they can offer for certain applications such electric ship propulsion, ‘more-electric aircraft’ and traction applications, electric vehicles, and

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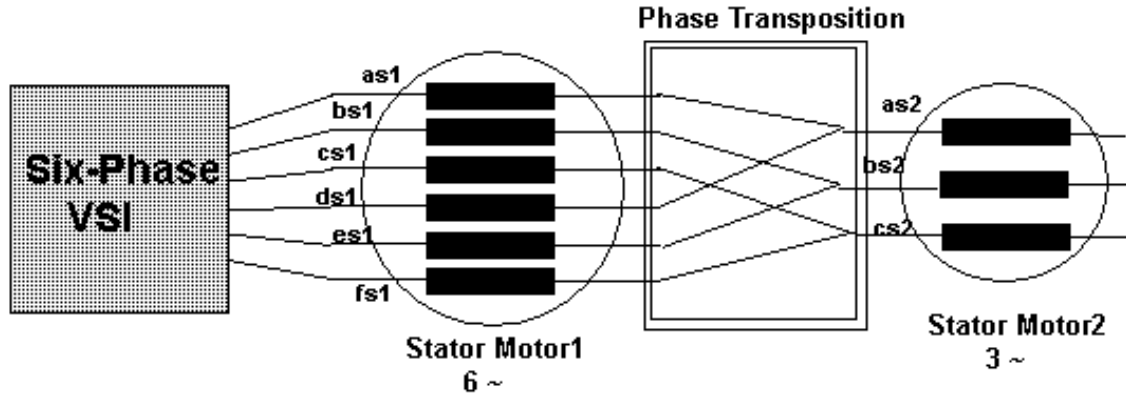
hybrid electric vehicles [1],[2]. The increase in number of phase voltages permits increasing power, reducing components cost, DC bus ripple and more efficient use of cable cross-sectional area which implies smaller number of electronic components and easy integration [4], [5]. Additional degree of freedom should be mentioned which allows us connecting in series two or more machines with an appropriate phase transposition [9]. The idea was first implemented for a five-phase series-connected two-motor drive system, but is now applicable to any number of phases more than or equal to five-phase, the number of series-connected machines is a function of the phase number of VSI. One specific case of such a drive system is a two-motor drive, comprising a symmetrical six-phase machine connected in series with a three-phase machine, an independent control of the two motors drive with respect to each other can be realized in such a way that the flux/torque producing current components of only one machine becomes non flux/torque producing currents for the other and vice versa [9], [14].

The major shortcoming of the series connected multi-phases motor drive is the increase in the stator windings losses since both machines are affected by currents flow even they produce or not flux/torque which limits its applications in general purpose drive [13]. However, it has been demonstrated in [16] when one machine in the group operates at low speed (low voltage) with high torque (high current) while the other machine operate at high speed (high voltage) with low torque (low current), the total stator copper losses remain less than or equal to the rated value.

Whereas the field oriented control (FOC) method maintains orthogonality between the rotor flux linkage and the stator torque producing current [3], direct torque control (DTC) directly controls the stator flux to affect torque control [6],[7], its operates in stationary reference frame and acts directly on the inverter switches to produce the necessary stator voltages. Hysteresis controllers are used to constrain the electrical torque and stator flux magnitude within certain bounds [8]. Unlike FOC, the well-known DTC does not require any regulator, coordinate transformations and pulse width modulation signal generators, thus it allows good and fast torque control in steady state and transient operating conditions. However, DTC presents some disadvantages such variable switching frequency and difficulty to control torque and flux at low speed [8], [11].

2. Modelling of the drive system

The drive system is composed of two series connected six- phase and three-phase squirrel cage induction motors as shown in (Fig.1) the two motors drive are connected in series with an



appropriate phase transposition and fed by single six-phase inverter [5],[14]. The relation between voltages and currents can be given as:

Fig 1. Two series six and three phase induction motor drive fed by single six phase inverter.

$$\begin{aligned}
 V_A &= v_{as1} + v_{as2} \\
 V_B &= v_{bs1} + v_{bs2} \\
 V_C &= v_{cs1} + v_{cs2} \\
 V_D &= v_{ds1} + v_{as2} \\
 V_E &= v_{es1} + v_{bs2} \\
 V_F &= v_{fs1} + v_{cs2}
 \end{aligned} \tag{1}$$

By using the decoupling Clark's transformation [1], the original phase variables are transformed to the new $(\alpha-\beta)$, $(x-y)$ and $(0+, 0-)$ variable as:

$$\begin{bmatrix} v_{\alpha}^{inv} \\ v_{\beta}^{inv} \\ v_x^{inv} \\ v_y^{inv} \\ v_{0+}^{inv} \\ v_{0-}^{inv} \end{bmatrix} = C \begin{bmatrix} v_{as1} + v_{as2} \\ v_{bs1} + v_{bs2} \\ v_{cs1} + v_{cs2} \\ v_{ds1} + v_{as2} \\ v_{es1} + v_{bs2} \\ v_{fs1} + v_{cs2} \end{bmatrix} = \begin{bmatrix} v_{as1} \\ v_{\beta s1} \\ v_{xs1} + \sqrt{2}v_{as2} \\ v_{ys1} + \sqrt{2}v_{\beta s2} \\ v_{o+s1} + v_{os2} \\ v_{o-s1} \end{bmatrix} \tag{2}$$

$$\begin{aligned}
 i_{\alpha}^{inv} &= i_{\alpha s1} \\
 i_{\beta}^{inv} &= i_{\beta s1} \\
 i_x^{inv} &= i_{xs1} = i_{as2}/\sqrt{2} \\
 i_y^{inv} &= i_{ys1} = i_{\beta s2}/\sqrt{2} \\
 i_{o+}^{inv} &= i_{o+s1} = i_{os2}/\sqrt{2} \\
 i_{o-}^{inv} &= i_{o-s1} = i_{\beta s2}/\sqrt{2}
 \end{aligned} \tag{3}$$

Where:

$$C = \sqrt{\frac{2}{6}} \begin{bmatrix} 1 & \cos(\alpha) & \cos(2\alpha) & \cos(3\alpha) & \cos(4\alpha) & \cos(5\alpha) \\ 0 & \sin(\alpha) & \sin(2\alpha) & \sin(3\alpha) & \sin(4\alpha) & \sin(5\alpha) \\ 1 & \cos(2\alpha) & \cos(4\alpha) & \cos(6\alpha) & \cos(8\alpha) & \cos(10\alpha) \\ 0 & \sin(2\alpha) & \sin(4\alpha) & \sin(6\alpha) & \sin(8\alpha) & \sin(10\alpha) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \end{bmatrix} \quad (4)$$

And ($\alpha = 2\pi/6$)

Since the (x-y) and zero-sequence components of the rotor voltages and currents are zero, the complete model in the stationary reference frame for the six-phase and the three-phase series connected machines consists of ten differential equations [2] as shown in developed form of inverter voltages equations:

$$v_{\alpha}^{inv} = R_{s1}i_{\alpha}^{inv} + (L_{ls1} + L_{m1})\frac{di_{\alpha}^{inv}}{dt} + L_{m1}\frac{di_{dr1}}{dt} \quad (5)$$

$$v_{\beta}^{inv} = R_{s1}i_{\beta}^{inv} + (L_{ls1} + L_{m1})\frac{di_{\beta}^{inv}}{dt} + L_{m1}\frac{di_{qr1}}{dt} \quad (6)$$

$$v_x^{inv} = R_{s1}i_x^{inv} + L_{ls1}\frac{di_x^{inv}}{dt} + \sqrt{2}\left\{\sqrt{2}i_x^{inv} + (L_{ls2} + L_{m2})\frac{d\sqrt{2}i_x^{inv}}{dt} + L_{m2}\frac{di_{dr2}}{dt}\right\} \quad (7)$$

$$v_y^{inv} = R_{s1}i_y^{inv} + L_{ls1}\frac{di_y^{inv}}{dt} + \sqrt{2}\left\{\sqrt{2}i_y^{inv} + (L_{ls2} + L_{m2})\frac{d\sqrt{2}i_y^{inv}}{dt} + L_{m2}\frac{di_{qr2}}{dt}\right\} \quad (8)$$

$$v_{o+}^{inv} = R_{s1}i_{o+}^{inv} + L_{ls1}\frac{di_{o+}^{inv}}{dt} + \sqrt{2}\left\{R_{s2}\sqrt{2}i_{o+}^{inv} + L_{ls2}\frac{d\sqrt{2}i_{o+}^{inv}}{dt}\right\} \quad (9)$$

$$v_{o-}^{inv} = R_{s1}i_{o-}^{inv} + L_{ls1}\frac{di_{o-}^{inv}}{dt} \quad (10)$$

Rotor voltage equations for six-phase machine are:

$$0 = R_{r1}i_{dr1} + L_{m1}\frac{di_{dr1}^{inv}}{dt} + (L_{lr1} + L_{m1})\frac{di_{dr1}}{dt} + \omega_{r1}(L_{m1}i_{\beta}^{inv} + (L_{lr1} + L_{m1})i_{qr1}) \quad (11)$$

$$0 = R_{r1}i_{qr1} + L_{m1}\frac{di_{qr1}^{inv}}{dt} + (L_{lr1} + L_{m1})\frac{di_{qr1}}{dt} + \omega_{r1}(L_{m1}i_{\alpha}^{inv} + (L_{lr1} + L_{m1})i_{dr1}) \quad (12)$$

Rotor voltage equations for three-phase machine are:

$$0 = R_{r2}i_{dr2} + \sqrt{2}L_{m2}\frac{di_x^{inv}}{dt} + (L_{lr2} + L_{m2})\frac{di_{dr2}}{dt} + \omega_{r2}(L_{m2}\sqrt{2}i_y^{inv} + (L_{lr2} + L_{m2})i_{qr2}) \quad (13)$$

$$0 = R_{r2}i_{qr2} + \sqrt{2}L_{m2}\frac{di_y^{inv}}{dt} + (L_{lr2} + L_{m2})\frac{di_{qr2}}{dt} + \omega_{r2}(L_{m2}\sqrt{2}i_x^{inv} + (L_{lr2} + L_{m2})i_{dr2}) \quad (14)$$

Torque equations for two-motor drive are given as:

$$T_{e1} = P_1L_{m1}(i_{dr1}i_q^{inv} - i_d^{inv}i_{qr1}) \quad (15)$$

$$T_{e2} = \sqrt{2}P_2L_{m2}(i_{dr2}i_y^{inv} - i_x^{inv}i_{qr2}) \quad (16)$$

3. DESIGN OF DIRECT TORQUE CONTROL OF THE DRIVE SYSTEM

3.1 Vectors selection Principle

For a two level six-phase inverter supplying the two-motor drive system under consideration there are 64 possible inverter states [5], [9]. According to equations (5), (6), (7) and (8), the six phase voltages of each inverter state are transformed into two voltages vectors (zero sequences voltages are omitted for further consideration):

$$\underline{v}_{\alpha\beta}^{inv} = \frac{2}{6} (v_a + \underline{a}v_b + \underline{a}^2v_c + \underline{a}^3v_d + \underline{a}^4v_e + \underline{a}^5v_f)$$

$$\underline{v}_{xy}^{inv} = \frac{2}{6} (v_a + \underline{a}^2v_b + \underline{a}^4v_c + v_d + \underline{a}^2v_e + \underline{a}^4v_f) \quad (17)$$

Where; $\underline{a} = \exp\left(j\frac{2\pi}{6}\right)$.

Voltages vectors are plotted in their associated $(\alpha-\beta)$ and $(x-y)$ sub-space as shown in (Fig 2). Each inverter plane comprises three decagons with magnitude of: $\frac{2}{3}v_{dc}$, $\frac{1}{\sqrt{3}}v_{dc}$, $\frac{1}{3}v_{dc}$. According to their magnitude, the voltages vectors in each plane are classified into four types: null, small, medium and large. In total, we count 64 vectors in each plane: ten with large magnitude, twelve with medium magnitude, thirty six with short magnitude and ten are null vectors. Inverter states which are given in binary form has been coded in octal system for better representation, for example state (111000) has been coded to (71) and so on.

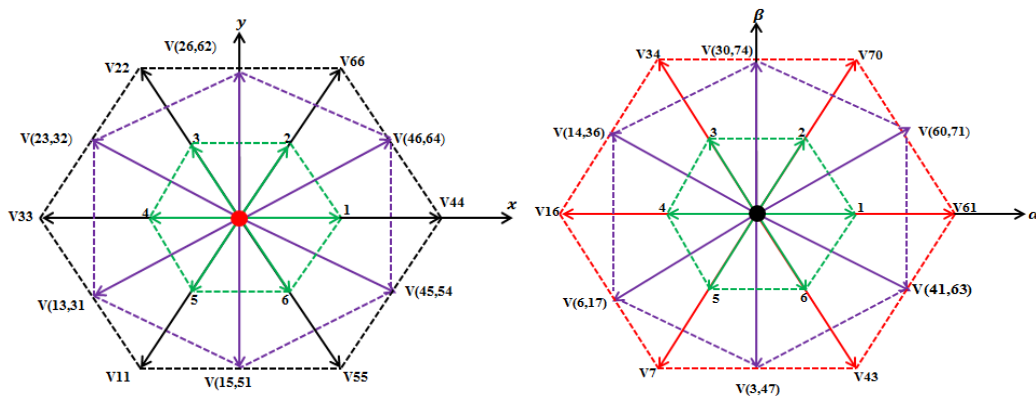


Fig 2. Projection of two level six-phase voltage space vectors in $(\alpha-\beta)$ plan and $(x-y)$ plan

To perfectly achieve the design, one should attentively analyze vectors mapping in each plan before building associated look up tables for each controller. The aim behind this to

independently control the two-motor, and moreover minimize torque and currents ripples caused by low harmonics order flowing in stator windings connected in series, consequently minimizing losses to obtain high efficiency.

Since the system under study is fed by single six-phase VSI, vectors generated must guaranties $(\alpha-\beta)$ components producing torque/flux for the first motor while eliminating $(x-y)$ components also it guaranties $(x-y)$ components producing Torque/flux for the second motor while simultaneously eliminates $(\alpha-\beta)$ components in every switching period. In case of large vectors taken as an example, Table 1 shows inverter states and associated vectors in each plane with their respective magnitude.

Table 1. Correspondent magnitude of large vectors in $(\alpha-\beta)$ and $(x-y)$ for selected inverter states

Inverter states	Abs($v_{\alpha\beta}$)	Abs(v_{xy})
{7, 16, 34, 43, 61, 70}	0.6667	0
{11, 22, 33, 44, 55, 66}	0	0.6667

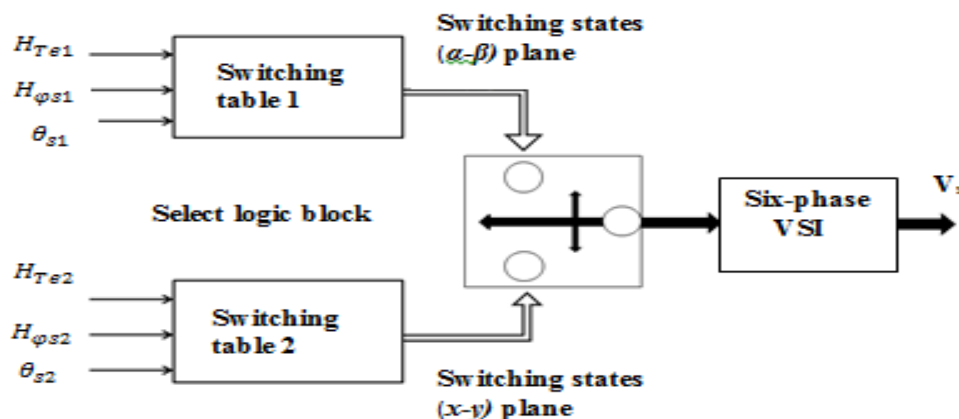


Fig 3. Principle of states selection.

One can observe that inverter states denoted (7, 16, 34, 43, 61, and 70) in Table 1 gives vectors with same Magnitude equal to 0.6667 in $(\alpha-\beta)$ plan, and simultaneously produces null vectors in $(x-y)$ plane. In turn, inverter states denoted (11, 22, 33, 44, 55, and 66) gives vectors with magnitude equal to 0.6667 in $(x-y)$ plane while simultaneously produce null vectors in $(\alpha-\beta)$ plane. That is, taking advantages of this situation one can perform DTC controller for the drive system by using vectors mapping in $(\alpha-\beta)$ plane to control the first machine and vectors mapping in $(x-y)$ plane to control the second machine, undesirable vectors in each table will be eliminated automatically as explained above. This is one of many positive points in multiphase-multimachines drive system; the increased number of voltages vectors offers greater flexibility

in optimizing the selection of the inverter states. In order to concretize the proposed technic, an added block is introduced between the two switching tables and the six-phase VSI as shown in (Fig 3). The block so called “select logic” permits appropriate inverter states selection in every switching period.

3.2 Torque and Flux Control Principle

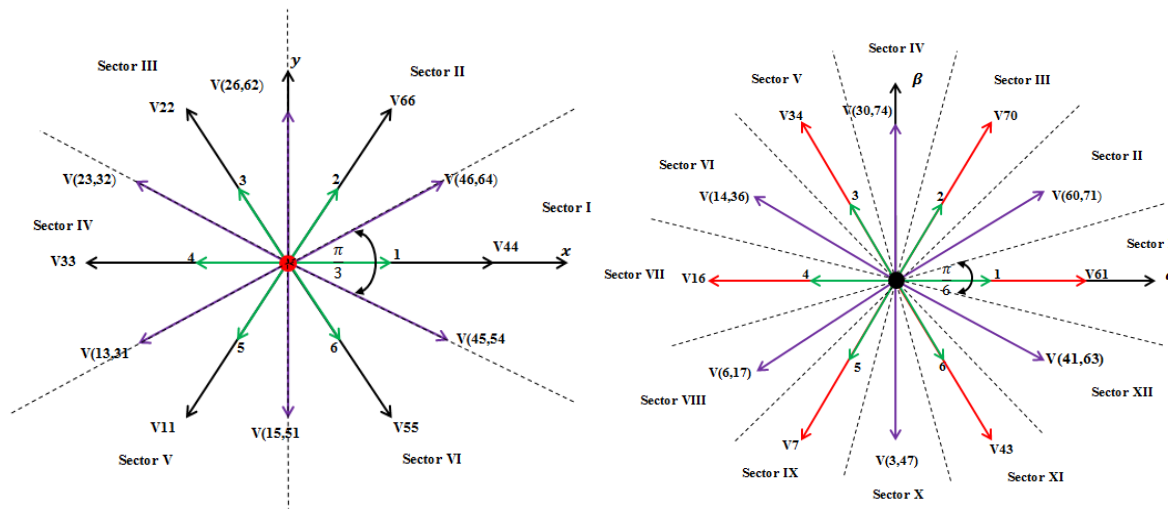
Regardless to the number of phase of the two-motor, respectively six-phase and three-phase, two different switching tables are built in concordance to the vectors selection criterion as shown in (Fig 4). The first switching table will use twelve active vectors to control the six-phase machine, that is, the $(\alpha-\beta)$ plane will be divided in twelve sectors (30 degrees/ sector), while the second switching table witch control the three-phase machine will use only six vectors, in turn, $(x-y)$ plane will be divided in six sectors (60 degrees/sectors). If we Consider the sector (1) for example, to control the torque and the flux of the six-phase motor IM1, the voltage vectors criterion stated as follow: If the torque and flux have to be increased, i.e., $HT_{e1} = +1$ and $H\phi_{s1} = +1$, the active virtual voltage (V_{60}) or (V_{71}) is selected; if the torque is to be increased and the flux is to be decreased, i.e., $HT_{e1} = +1$ and $H\phi_{s1} = -1$, then (V_{14}) or (V_{36}) is selected; if the torque is to be decreased and the flux is to be increased, i.e., $HT_{e1} = -1$ and $H\phi_{s1} = +1$ then (V_{41}) or (V_{63}) is selected; if the torque and the flux are to be decreased, i.e., $\Delta T_{e1} = -1$ and $H\phi_{s1} = -1$ then (V_6) or (V_{17}) is selected; if the torque error is within the error band, i.e., $HT_{e1} = 0$ the null voltage (V_0) or (V_{77}) is selected regardless of the flux control loop, All cases are summarized in Table 2. The same technique will be used for the second switching table by selecting four active virtual vectors in conjunction with null vector in each sector from $(x-y)$ plane as shown in Table 3.

Table 2. Voltage vector look up table for DTC Controller for three-phase motor.

		Sector number in $(\alpha-\beta)$ plan											
$\Delta\phi_{s1}$	ΔT_{e1}	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
+1	+1	V60	V70	V30	V34	V14	V16	V6	V7	V3	V43	V41	V61
	-1	V41	V61	V60	V70	V30	V34	V14	V16	V6	V7	V3	V43
-1	+1	V14	V16	V6	V7	V3	V43	V41	V61	V60	V70	V30	V34
	-1	V6	V7	V3	V43	V41	V61	V61	V60	V70	V30	V34	V14
+1	0	V0	V77	V0	V77	V0	V77	V0	V77	V0	V77	V0	V77
-1	0	V77	V0	V77	V0	V77	V0	V77	V0	V77	V0	V77	V0

Table 3. Voltage vector look up table for DTC Controller for three-phase motor.

$\Delta\phi_{s2}$	ΔT_{e2}	Sector number in (x-y) plan					
		I	II	III	IV	V	VI
+1	+1	V66	V22	V33	V11	V55	V44
	-1	V55	V44	V66	V22	V33	V11
-1	+1	V22	V33	V11	V55	V44	V66
	-1	V11	V55	V44	V66	V22	V33
+1	0	V0	V77	V0	V77	V0	V77
-1	0	V77	V0	V77	V0	V77	V0

Fig 4. Twelve active virtual vectors in $(\alpha-\beta)$ plan and $(x-y)$ plan

3.3 Stator Flux Estimation

As the design control of the two-motor drive system is based on vectors selection and flux position (sectors), the simplest way to calculate vector flux is the time integral of stator emf (\underline{e}_s), the technic is developed for the six-phase motor and can be easily extended for the three-phase motor:

$$\underline{e}_s = \underline{V}_s - (R_{s1} + R_{s2}) * \underline{I}_s \quad (18a)$$

For the six-phase motor (IM1):

$$e_{s\alpha} = v_{s\alpha} - (R_{s1} + R_{s2}) * i_{s\alpha} \quad (18b)$$

$$e_{s\beta} = v_{s\beta} - (R_{s1} + R_{s2}) * i_{s\beta} \quad (19)$$

However, these expressions, besides its simplicity, problems related to the signal integration such the dc-offset caused by non-perfect measurement of currents or/and voltages and the dc-drift which can be caused by initial condition of the integral [8]. In the literature, many several solutions are discussed to overcome this drawback by using: low pass filter (*LPF*), high pass filter (*HPF*), voltage-current model. Among the proposed structures of estimators, the adopted one used in this paper is shown in (Fig 5). The used block works as follow: If the frequency of input signal is much higher than the cut-off frequency ω_c the gain of the feedback block (compensator) is close to zero, therefore, the integrator output is essentially composed of only the feedward components. At low frequency, the compensator will play an important role in eliminating dc- Drift and initial value problems, also it reduces errors in magnitude and phase as well. Moreover, to get better performances, it is found that the limiter level (saturation block) should be set to the reference value of stator flux, then the estimator reaches steady state as soon as after a half cycle of flux waveform even with incorrect initial value.

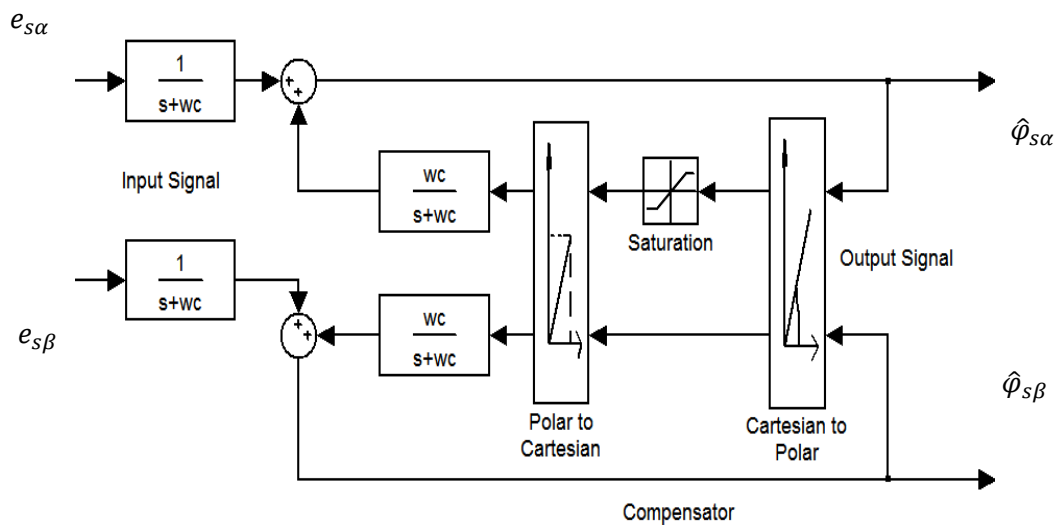


Fig 5. Block diagram of flux estimation of the six-phase motor drive (IM1).

4. Results and discussion

The DTC control scheme adopted for two series connected six-phase and three- phase induction motor drive is shown in (Fig 6).

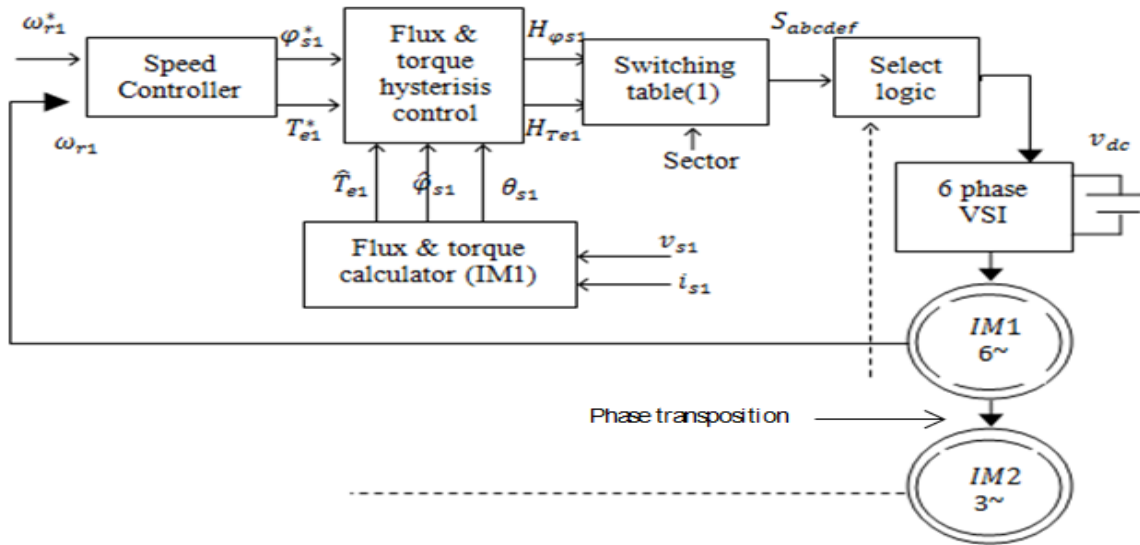


Fig 6. DTC diagram of two series connected six-phase and three phase motors.

Table 4. Induction motors parameters

Parameters	IM ₁	IM ₂
Stator resistance	$R_{s1}=10\Omega$	$R_{s2}=10\Omega$
Rotor resistance	$R_{r1}=6.3\ \Omega$	$R_{r2}=6.3\ \Omega$
Stator inductance	$L_{s1}=460\text{mH}$	$L_{s2}=460\text{mH}$
Rotor inductance	$L_{r1}=460\text{mH}$	$L_{r2}=460\text{mH}$
Mutual inductance	$L_{m1}=420\text{mH}$	$L_{m2}=420\text{mH}$
Number of pole	$P_1=4$	$P_2=4$
Moment of inertia	$J_1=0.04\ \text{kg.m}^2$	$J_2=0.04\ \text{kg.m}^2$
Friction coefficient	$B_1=0.001\ \text{N.m.s/rd}$	$B_2=0.001\ \text{N.m.s/rd}$

Induction motors parameters are shown in Table 4. These results are obtained for an exponential reference rotor speed from zero to 50 rad/s for IM1 and from zero to 100 rad/s for IM2. Stator flux references for IM1 and IM2 are set respectively to 1Wb and the dc-link voltage v_{dc} is 800V (2 Pu). Stator flux locus, torque and speed responses are shown respectively in (Fig 7), (Fig 8), and (Fig 9). As we can see, decoupling torque and flux for each motor and independent control for all the system drive are achieved as imposed in references values even under reversal speed

transient with mechanical load (4 N.m) applied to IM1 and (2 N.m) to IM2 at 0.02s. Currents waveform of “phase (a)” for each motor, are shown in (Fig 10). In (Fig 11) and (Fig 12), spectrum analyses are shown for “phase (a)” current for each motor. One can observe the presence of two different frequencies 16 Hz and 8 Hz controlling two-motors in (Fig 11.a), while in (Fig 11.b) only the proper frequency of three-phase motor is present.

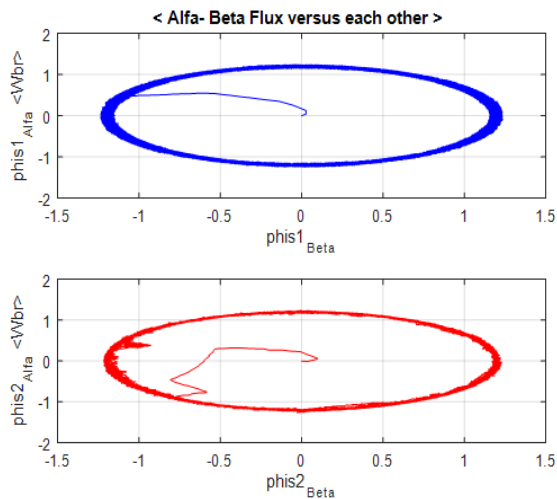


Fig7. Stator flux response of six-phase motor (top) and three phase motor(bottom)

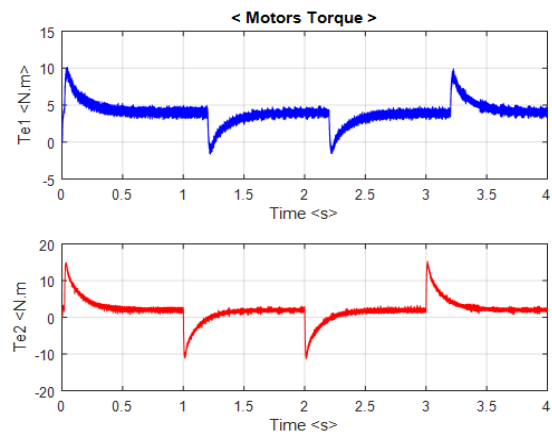


Fig8. Torque response of six-phase motor (top) and three phase motor(bottom)

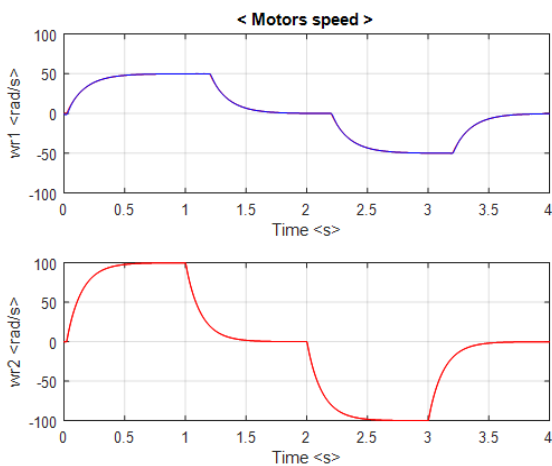


Fig9. Speed response of six-phase motor (top) and three phase motor (bottom)

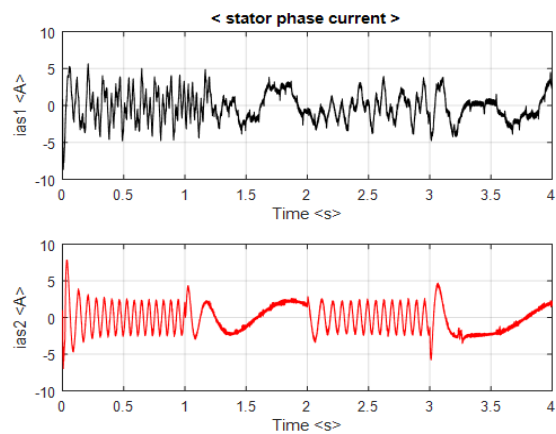


Fig10. Stator phase current response of six-phase (top) and three phase motor(bottom)

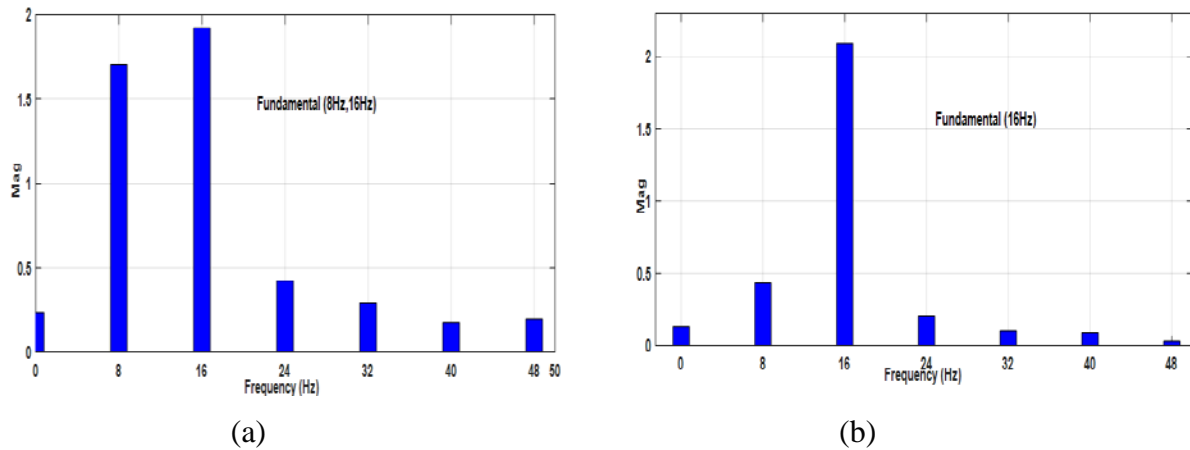


Fig11. Spectrum analysis of “phase (a)” current: six phases motor (a) three phase motor (b).

5. Conclusions

In this paper direct torque control (DTC) for two induction motors drive connected in series with an appropriate phase transposition and fed by single six-phase inverter has been developed. The method avoids firstly, the use of appropriate vectors providing flexible torque and flux control for each motor in the group by eliminating low frequencies harmonic currents and simplify the controller design. Secondly, a simple technique has been proposed allowing independent control of the two motors drive. The effectiveness and capability of the proposed method are shown by computer simulation.

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