Dual-Three Phase Induction Machine Drives Control—A Survey

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Keywords: multi-phase drives, dual-three phase induction machine, control

1. Introduction

Multi-phase motor drives can be proposed for special custom applications to solve particular technical problems. Despite the higher complexity of the drive, the interest on the multi-phase drives has grown in the last years, in particular on the five-phase and six-phase ones, with induction and synchronous motors.

The paper reviews the most relevant results and provides a comprehensive survey and analysis of the control issues on the VSI fed dual-three phase induction machine drives (two sets of windings shifted by 30 electrical degrees with isolated neutral points); the machine modeling and the modulation strategy aspects are discussed to introduce the different control schemes.

2. Advantages and Applications

The paper discusses the potential advantages of the dual-three phase induction motor drives that can be exploited in specific applications (mainly high power/high current applications):

- Mitigation of torque pulsation problems.
- Reduction of the rotor harmonic losses.
- Reduction of the rated current of the components.
- The possibility to increase the torque per ampere ratio.
- Improvement of the reliability at system level.
- Reduction of the current harmonics in the DC link capacitor.
- The possible to modify the pole-pairs number using the inverter.
- The possibility to supply more machines from a single inverter.

3. Machine Model

The paper present two different modeling approaches that can be used for machine analysis and drive control:

(1) Vector Space Decomposition (VSD) theory.
(2) Dual Three-Phase (DTP) modeling approach.

The VSD approach decomposes the original six-dimensional vector space of the machine into three orthogonal subspaces; only one is involved in the electro-mechanical energy conversion. The DTP approach is based on the classical theory used for the analysis of three-phase electrical machines.

4. PWM Strategies for Six-Phase VSI

The inverter contains a network of 12 power switches arranged in 6 legs, so $2^6 = 64$ configurations can be obtained; this increases the number the possible PWM strategies. The paper focuses on advantages and drawbacks of the most important PWM techniques: Conventional Space Vector Modulation.

1. Multilevel Conventional Space Vector Modulation.
2. Vector Space Decomposition Modulation strategy.
3. Double three-phase Space Vector Modulation.
4. Double zero-sequence injection) technique.

5. Control of Dual-Three Phase Drives

The research work concerning the control aspects of the dual-three phase induction motor drives is mainly dedicated on the field oriented and direct torque control techniques.

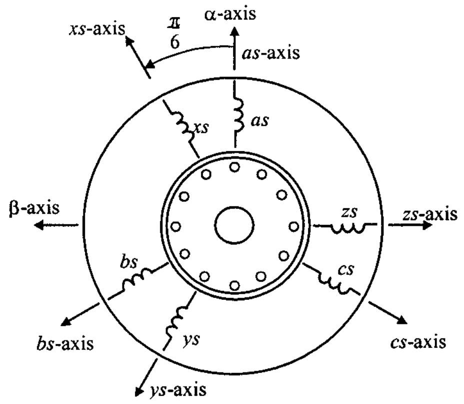

Fig. 1. Dual-three phase induction machine

5.1 Field Oriented Control A decoupled control of the dual-three induction machine flux and torque can be obtained by a direct extension of the three-phase case. On the contrary, the current control extension from the three-phase to the dual-three phase drive must consider some specific aspects such as the unbalance current sharing between the two stator winding sets and the multiple coupling terms. The paper presents different current control implementation, either in stationary frame or in synchronous reference frame, able to cope with these problems.

5.2 Direct Torque Control The paper presents two main groups of Direct Torque Control solutions:

- Variable switching frequency solutions; Direct Self Control and Switching-Table based techniques.
- Constant switching frequency solutions; Pulse Width Modulation based techniques.

A common aspect is the lack of current control that imposes a dedicated design of the drive power units in order to avoid unbalanced current sharing between the three-phase stator sets. Other aspects concern the phase current waveforms, the control robustness against the parameters detuning and the flux/torque estimation.

6. Conclusions

Dedicated control schemes solutions for the dual-three phase induction motor drives have been developed and experimentally demonstrated. Some solutions could be of immediate relevance to industry. Novel concepts, related to the exploitation of specific properties of dual-three phase machines in particular applications, such as single-inverter multi-motor drives or dual-source motor drives are in early research stage.

Paper

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The paper aims to perform an overview on the state-of-the-art in the control of multi-phase drives employing dual-three phase induction machines. In particular, the paper is focused on modeling aspects, Pulse-Width Modulation (PWM) techniques for Voltage Source Inverters (VSI), Field Oriented Control (FOC) and Direct Torque Control (DTC) strategies for dual-three phase induction machines. Furthermore, the paper briefly presents the advantages of dual-three phase induction motor drives over the conventional three-phase drives and the different applications reported in the literature.

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1. Introduction

In the past the three-phase distribution grid has imposed the same number of phases for AC machines since they have been directly connected to the grid for industrial applications. In adjustable speed AC drives, the machine is usually supplied by a DC-AC converter, so the number of phases is not limited any more by the utility grid. Hence, from the advent of the power electronic devices, multi-phase motor drives have been studied to solve particular technical problems. For example, in high power/high current applications, the multi-phase solution allows to divide the controlled power on more inverter legs, reducing the rated current of the power electronic switches and offering a high reliability at system level due to the redundant structure. These aspects can justify the higher complexity of the multi-phase drive in special custom applications, such as electrical ship propulsion, traction drives, electric/hybrid vehicles, high power pumps and aerospace applications (1).

In the last five years, the interest on the multi-phase drives has considerably grown and an important increase of the quantity in published work has been noticed. As a direct consequence, some international conferences have hosted sessions dedicated to multi-phase motor drives (2). The literature reports different multi-phase solutions from the point of view of the phase number and the machine type; the more interesting and addressed ones are the five-phase and six-phase ones, employing induction and synchronous permanent magnet or synchronous reluctance motors (3).

The paper deals with a review on the most relevant research results published in the literature (1)–(51), regarding the VSI fed dual-three phase induction motor drives. The machine has two sets of windings spatially shifted by 30 electrical degrees with isolated neutral points (Fig. 1).

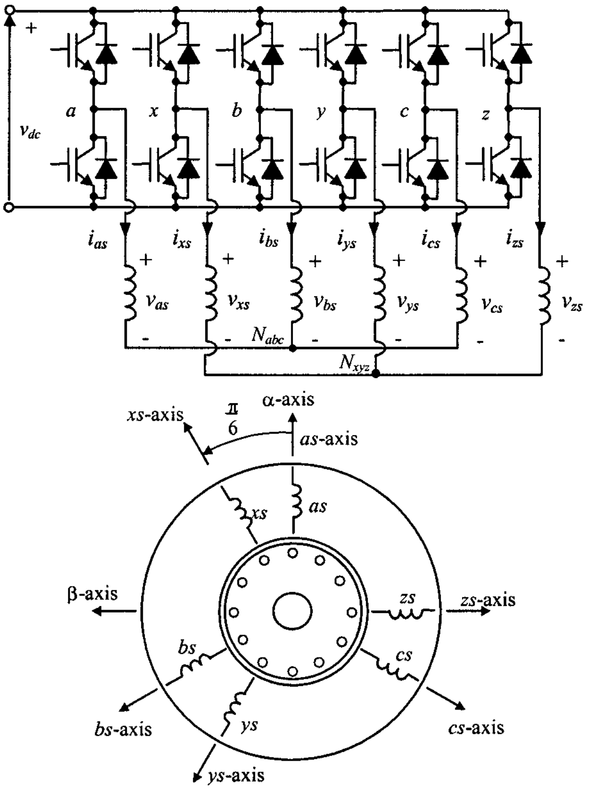

Fig. 1. Dual-three phase induction machine

This machine is reported in the literature with different names, such as: six-phase (28), split phase (33), dual three-phase (20), dual-star (11) or quasi six-phase (3) induction machine. Furthermore, the same name is sometimes used for different phase displacement between the two three-phase stator sets.

To have an unique nomenclature, the term dual-three phase machine will be used in this paper specifying, when necessary, the phase displacement between the stator sets for

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values different from 30 electrical degrees.

Since the paper attempts to provide a comprehensive survey and analysis of the dual-three phase induction machine drives control, the machine modeling and the modulation strategy aspects are discussed before the presentation of the different control schemes.

2. Advantages and Applications

The dual-three phase induction motor drives have several advantages over their three-phase counterparts; some of these advantages are common to multi-phase drives.

(1) Reduction of the amplitude with a simultaneous increase of the frequency of torque pulsations; that reduces the mechanical stress for the mechanical load.

(2) Reduction of the rotor harmonic losses due to the absence of some rotor harmonic currents.

These are two of the advantages that started years ago the interest towards the multi-phase machine due to the limited switching frequency capability of the power electronic components available at that time. These aspects are still valid for very high power applications.

When supplied by a square-wave VSI or Current Source Inverter (CSI), a three-phase induction machine develops an electromagnetic torque having a dominant time harmonic of frequency six times the supply fundamental frequency. This torque harmonic leads to important mechanical stress for the mechanical system in high power drives. The situation is significantly improved for the dual-three phase induction machine (Fig. 1) whose particular winding configuration results in the elimination of all air-gap flux time harmonics and induced rotor current harmonics of order $k = 6 \cdot n \pm 1$, $(n = 1, 3, 5, \cdots)$. As consequence, all torque harmonics of order $k = 6 \cdot n$, $(n = 1, 3, 5, \cdots)$ are eliminated, reducing significantly the torque ripple and the rotor losses, as demonstrated in the simulation carried out in (4) and experimentally confirmed in (5)(6).

A comparison between two high power traction drives employing three-phase and dual-three phase induction machines, respectively, is performed in (7), showing a reduction of the torque ripple by one half for dual-three phase drive in contrast to the three-phase counterpart.

(3) The rated current of the power electronic switches is halved respect to the three-phase inverter of the same power. The introduction of PWM controlled inverters in low and medium power range, due to the development of power electronics technology, has eliminated the need to use multi-phase machines to reduce the torque pulsations (3). However, high current devices with high switching frequencies are not available yet. In this case, the sharing of the controlled power on more inverter legs is an alternative solution to the component paralleling to reduce the rated current of the power switches.

As illustrated in (8), a vector-controlled 850 kW dual-three phase induction machine drive (with zero displacement between the machine stator winding sets) is used to drive a melt pump in a polyethylene plant. The machine is fed by a GTO inverter having a switching frequency of 500 Hz.

Electrical Vehicles (EV) represent another possible application that can benefit from current splitting, because in many cases the low inverter DC link voltage (provided by a battery) imposes high phase currents; the multi-phase solution allows reducing the current per phase without increasing the voltage per phase (1).

(4) The possibility to increase the torque per ampere ratio for the same machine volume. This is possible in multi-phase drives using spatial mmf forces other than the fundamental component. This aspect has been investigated in (9) for a dual-three phase machine drive, where up to almost 40% of torque density improvement can be obtained (compared to a three-phase machine with the same flux peak value) by injecting third harmonic zero sequence components in the phase currents; that is possible by connecting the machine winding neutral points to the midpoint of the inverter DC link.

(5) Improved reliability at system level. An important issue in favor of the multi-phase drives is the reliability; the multi-phase machines, due their phase redundancy, can start and run with one or more phase open. The higher reliability of multi-phase drives is fully exploited if each machine phase is supplied by an independent, four-quadrant converter (10).

A high power application is presented in (11)(12) for a locomotive where two independent three-phase inverters supply four dual-three phase induction motors in parallel; in case of failure on one inverter, the drive operates with the other valid inverter supplying the remaining three-phase stator winding sets.

(6) Reduction of the current harmonics drawn by the DC link filter capacitor for VSI, especially for inverter square-wave operation. In the multi-phase drives, it is possible to lower the DC link current harmonics flowing in the DC link capacitor filter, reducing significantly both capacitor size and cost, especially for the inverter square-wave operation (13)(14). In case of PWM operation, the dual-three phase solution, either with zero degrees (15) or 30 degrees (16) displacement between the machine stator winding sets, allows a reduction of the DC link current harmonics.

(7) When the supply frequency must be kept constant, it is possible to obtain a speed variation by modifying the number of the machine pole-pairs. Another benefit of using multi-phase machines is the possibility to extend the constant power operation range by changing the machine number of poles. That can be done by controlling the frequency and phase of the machine currents without mechanical switches, as illustrated in (17)(18) for a dual-three phase induction machine having 60 degrees displacement between the stator sets (true six-phase machine). This advantage can be useful in applications with limited value of supply voltage, such as in EV. Other advantages coming from pole changing, such as the reduction of the acoustic noise and the current ripple, are addressed in (18).

(8) The possibility to supply more than one machine from a single inverter to get a multi-motor, multi-phase drive.

For applications requiring multi-motor drives, like paper mills, textile manufacturing, etc., the three-phase drives solution leads to a system where each machine is fed by an inverter sharing with the other inverters a common DC link. In case of high-power two-motor induction drives, it is possible to use two different dual-three phase induction machines supplied by a single VSI with appropriate series connection of the stator windings of these two machines, as described in (19).

In conclusion, the dual-three phase induction motor drives are suitable in high power/high current applications. In particular, the transport applications (ship propulsion, locomotive, EV) are frequently addressed in the literature.

3. Machine Model

The construction of the dual-three phase induction motor is rather similar to the three-phase one, having the same rotor, the same stator magnetic core but the stator windings are split into two three-phase sets. As consequence, also the mathematical modeling approach of dual-three phase induction machines is similar to the three-phase ones and usually it is obtained under the same simplifying assumptions: sinusoidally winding distributions, unity stator and rotor turns ratio, constant air-gap, the magnetic saturation and the core losses are neglected.

When necessary, the mmf spatial harmonics ought to be also considered, as for pole-changing control(17)(18). Hereinafter, the machine modeling will consider only the fundamental spatial mmf in the air-gap.

The literature reports two different modeling approaches:

(1) Vector Space Decomposition (VSD) theory.

(2) Dual Three-Phase (DTP) modeling approach.

Both machine models can be used for machine operation analysis and drive control, depending on the application.

3.1 Vector Space Decomposition (VSD) Theory The VSD theory has been introduced in(20) to transform the original six-dimensional space of the machine into three two-dimensional orthogonal subspaces (α,β), (μ_1,μ_2) and (z_1,z_2) by using a proper 6×6 transformation matrix $[T_6]$ either in power invariant(20)(21) or non-power invariant (amplitude invariant) forms(22) (see Appendix).

The rotor cage is considered to be equivalent with a dual-three phase wound rotor. In addition(20), neglects the stator mutual leakage inductance for short-pitch machines. As demonstrated in(20), the $[T_6]$ matrix has these properties:

- The fundamental components of the machine variables and the harmonics of the order $k = 12\cdot n \pm 1$, $(n = 1,2,3,\cdots)$ are mapped in the (α,β) subspace. These components contribute to the air-gap flux.
- The harmonics of the order $k = 6\cdot n \pm 1$, $(n = 1,3,5,\cdots)$ are transformed in the (μ_1,μ_2) subspace. These harmonics (the 5th, 7th, …) do not contribute to the air-gap flux since the (α,β) and (μ_1,μ_2) subspaces are orthogonal.
- The zero-sequence components (of order $k = 3\cdot n$, $n = 0,1,2,3\cdots$) are mapped in the (z_1,z_2) subspace.

Hence, from the point of view of the flux and torque production, the analysis and control of the machine using the VSD theory is greatly simplified, since the machine model in the (α,β) subspace is identical to the model of a three-phase machine (Fig. 2). If the two stator sets have isolated neutral points, no current components flow in the (z_1,z_2) subspace(20); consequently, the machine model referred to the stationary reference frame can be reduced to two sets of decoupled equations corresponding to the machine (α,β) and (μ_1,μ_2) subspaces(20).

Using complex vector notation, the machine model in the (α,β) subspace is(20)–(22)

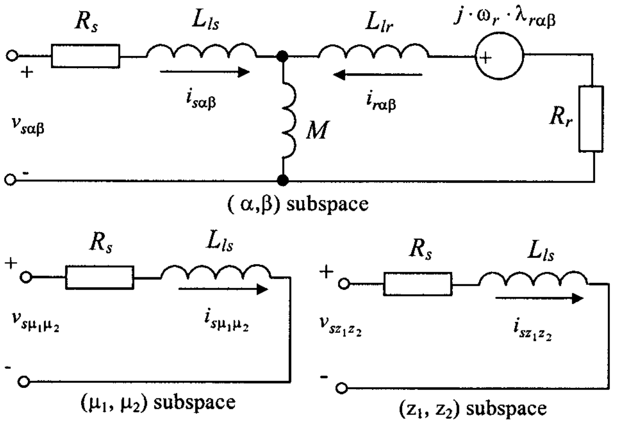

Fig. 2. Machine single phase circuits according to VSD theory

$$\begin{cases} \bar{v}_s = R_s\cdot\bar{i}_s + p\cdot\bar{\lambda}_s \\ 0 = R_r\cdot\bar{i}_r + p\cdot\bar{\lambda}_r - j\cdot\omega_r\cdot\bar{\lambda}_r \\ \bar{\lambda}_s = L_s\cdot\bar{i}_s + M\cdot\bar{i}_r \\ \bar{\lambda}_r = M\cdot\bar{i}_s + L_r\cdot\bar{i}_r \\ T_e = k_T\cdot\dfrac{P}{2}\cdot\dfrac{M}{L_r}\cdot\left(\lambda_{r\alpha}\cdot i_{s\beta} - \lambda_{r\beta}\cdot i_{s\alpha}\right) \end{cases}, \quad \begin{cases} \bar{v}_s = v_{s\alpha} + j\cdot v_{s\beta} \\ \bar{i}_s = i_{s\alpha} + j\cdot i_{s\beta} \\ \bar{i}_r = i_{r\alpha} + j\cdot i_{r\beta} \\ \bar{\lambda}_s = \lambda_{s\alpha} + j\cdot\lambda_{s\beta} \\ \bar{\lambda}_r = \lambda_{r\alpha} + j\cdot\lambda_{r\beta} \end{cases}$$

$$\left.\begin{array}{l} k_T = 1 \text{ for power invariant form of } [T_6] \\ k_T = 3 \text{ for non-power invariant form of } [T_6] \end{array}\right\}\cdots\cdots (1)$$

where ω_r is the rotor speed, P is the number of poles and p is the derivative operator. The machine parameters are reported in Appendix.

As shown by (1), the torque production involves only quantities in the (α,β) subspace and consequently the machine control is simplified since it needs to act only on a two-dimensional subspace.

In practice, the combined effects of the two stator sets in the air-gap flux and torque production are represented by a "mean" bi-phase machine in the (α,β) subspace (Fig. 2). The (d,q) synchronous reference frame, oriented either on the machine rotor flux, stator flux or air-gap flux is obtained as for a three-phase machine(23).

The machine model in the (μ_1,μ_2) subspace describes two independent passive R-L circuits as

$$\begin{bmatrix} v_{s\mu_1} \\ v_{s\mu_2} \end{bmatrix} = \begin{bmatrix} R_s + L_{ls}\cdot p & 0 \\ 0 & R_s + L_{ls}\cdot p \end{bmatrix}\cdot\begin{bmatrix} i_{s\mu_1} \\ i_{s\mu_2} \end{bmatrix}\cdots\cdots (2)$$

For ideal sinusoidal supply, the voltage components in the (μ_1,μ_2) subspace are zero. In case of non-sinusoidal supply, such as power electronic converters, the voltage excitation in the (μ_1,μ_2) subspace will produce current components in this subspace; these components are limited only by a low value of the equivalent impedance, i.e. the stator resistance and the stator leakage inductance.

A modified VSD model of a short-pitch machine, taking into account the mutual leakage inductance, is presented in(24). Here, it has been demonstrated that the leakage inductance values for the (α,β), (μ_1,μ_2) and (z_1,z_2) circuits are different; full-pitch coils maximize the impedance in the (μ_1,μ_2) and (z_1,z_2) subspaces, being the better choice for inverter fed operation(24); test measuring procedures for the machine leakage inductances are also given in(24).

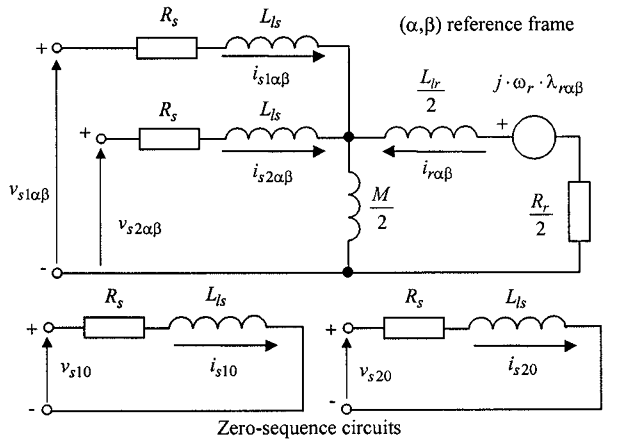

Fig. 3. Single-phase equivalent circuits for the DTP approach

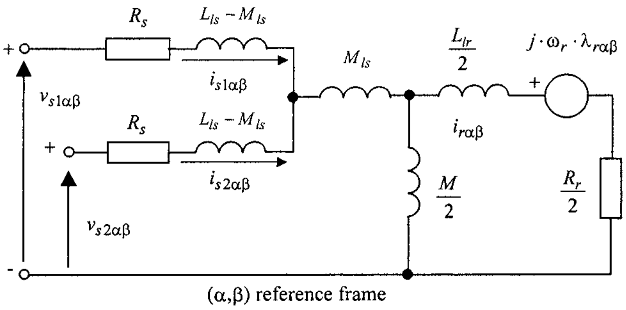

Fig. 4. Stationary frame circuit for the DTP approach considering the mutual leakage inductance for short-pitch machines

3.2 Dual Three-Phase (DTP) Modeling Approach

This approach has been introduced in (4). The machine has multiple three-phase stator sets and the rotor cage is equivalent with a three-phase wound rotor; the machine single-phase equivalent circuits in stationary reference frame are depicted in Fig. 3.

To have a complete equivalence between the DTP and the VSD modeling approaches, the magnetizing inductance and the rotor parameters of Fig. 3 are one half respect to those employed by the VSD theory (Fig. 2).

Using complex vector notation, the machine model in the stationary reference frame is

$$\begin{cases} \bar{v}_{s1} = R_s\cdot\bar{i}_{s1} + p\cdot\bar{\lambda}_{s1} \\ \bar{v}_{s2} = R_s\cdot\bar{i}_{s2} + p\cdot\bar{\lambda}_{s2} \\ 0 = R_r\cdot\bar{i}_r + p\cdot\bar{\lambda}_r - j\cdot\omega_r\cdot\bar{\lambda}_r \end{cases} \quad\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (3)$$

$$\begin{cases} \bar{\lambda}_{s1} = L_s\cdot\bar{i}_{s1} + M\cdot\bar{i}_{s2} + M\cdot\bar{i}_r \\ \bar{\lambda}_{s2} = M\cdot\bar{i}_{s1} + L_s\cdot\bar{i}_{s2} + M\cdot\bar{i}_r \\ \bar{\lambda}_r = M\cdot\bar{i}_{s1} + M\cdot\bar{i}_{s2} + L_r\cdot\bar{i}_r \end{cases} \quad\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (4)$$

$$\begin{aligned} T_e &= \frac{3}{2}\cdot\frac{P}{2}\cdot\frac{M}{L_r}\cdot\bar{\lambda}_r\times\left(\bar{i}_{s1}+\bar{i}_{s2}\right) \\ &= \frac{3}{2}\cdot\frac{P}{2}\cdot\frac{M}{L_r}\cdot\left[\lambda_{r\alpha}\cdot\left(i_{s1\beta}+i_{s2\beta}\right) - \lambda_{r\beta}\cdot\left(i_{s1\alpha}+i_{s2\alpha}\right)\right] \end{aligned}$$

$$\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (5)$$

A complete description of the DTP machine state-space model in (d, q) synchronous reference frame aligned on the machine rotor flux is given in (8)(25).

The model for the zero sequence circuits is

$$\begin{bmatrix} v_{s10} \\ v_{s20} \end{bmatrix} = \begin{bmatrix} R_s & 0 \\ 0 & R_s \end{bmatrix}\cdot\begin{bmatrix} i_{s10} \\ i_{s20} \end{bmatrix} + \frac{d}{dt}\left\{\begin{bmatrix} L_{ls} & 0 \\ 0 & L_{ls} \end{bmatrix}\cdot\begin{bmatrix} i_{s10} \\ i_{s20} \end{bmatrix}\right\}$$

$$\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (6)$$

However, if the star connection is used and the neutral points of the two stator sets are not connected, the zero-sequence currents will be automatically zero even when the two sets of supply voltages have zero-sequence components.

The single-phase circuit in stationary reference frame of Fig. 3 and described by (3–6) is valid only for full-pitch machines or when neglecting the mutual leakage inductance in case of short-pitch machines. If the mutual leakage inductance has to be considered (27), the single phase machine equivalent circuit must be modified (Fig. 4).

The modified DTP machine model in arbitrary (d, q) rotating reference frame, taking into account the mutual leakage inductance, is given in (1)(28).

4. PWM Strategies for Six-Phase VSI

The quality of the phase current waveforms, as well as the drive dynamic performance, is greatly influenced by the power electronic converter. When supplied by a square-wave VSI (5), the dual-three phase induction machine draws large current harmonics of order $k = 6\cdot n\pm 1$, $(n = 1, 3, 5, \cdots)$ which do not contribute to the air-gap flux and do not influence the torque pulsations. These harmonics (5th, 7th, ...) are limited only by the stator resistancce and the stator leakage inductance; they will produce additional losses in the machine resulting in the increase of size and cost of both machine and inverter.

A possible approach to solve the problem is to use external filters, as shown in (29). Another solution concerns the machine structure, as shown in (30), where an end winding structure using magnetic rings has been used. That increases the stator leakage reactance only for the current harmonics, acting as a machine built-in selective filter.

Besides simultaneous regulation of voltage amplitude and frequency, the PWM operation for VSI can improve the quality of the delivered current waveforms for multi-phase drives. In this way, acting on the power converter, the problem of the low frequency current harmonics is solved, without modifying the machine design and construction. For high power drives the PWM operation is not possible and multilevel voltage synthesis can be used (31), by means of multi-converter topologies.

The suitable approach for the analysis of the six-phase inverter PWM operation is the VSD (20) theory, since it provides an unified method to demonstrate the generation of the loss-producing current components.

The inverter contains a switching network of 12 power switches arranged to form 6 legs; each leg supplies one motor phase (Fig. 1). Only one of the power switches of the same leg can operate in the on state to avoid the shortcircuit of the DC link, so $2^6 = 64$ possible configurations can be obtained. The machine phase voltages can be computed using the switching function associated to one inverter leg; that is defined as

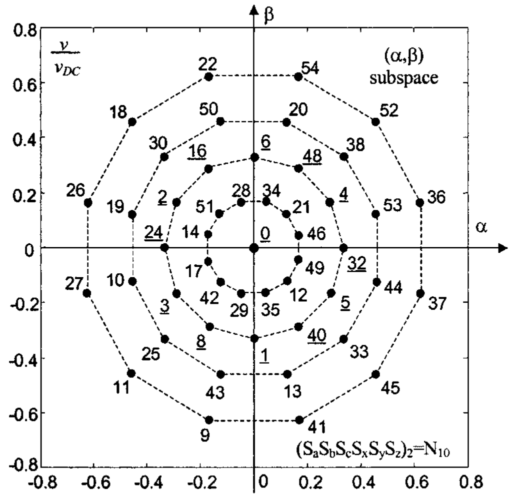

Fig. 5. Inverter voltage vectors in the (α,β) subspace

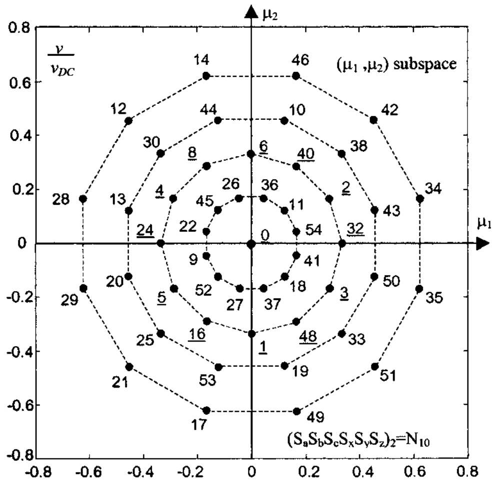

Fig. 6. Inverter voltage vectors in the (μ_1,μ_2) subspace

$$\begin{cases} S_j = 1, & \text{if the upper switch is on (lower switch is off)} \\ S_j = 0, & \text{if the upper switch is off (lower switch is on)} \end{cases} \quad \cdots\cdots (7)$$

where $j = a, b, c, x, y, z$.

For the machine having isolated neutral points, the machine phase voltages are separately computed for each three-phase set as

$$\left.\begin{array}{l} v_{is} = \left(S_i - \frac{1}{3}\cdot \sum_{k=a,b,c} S_k\right)\cdot v_{DC} \quad i = a,b,c \\ v_{js} = \left(S_j - \frac{1}{3}\cdot \sum_{k=x,y,z} S_k\right)\cdot v_{DC} \quad j = x,y,z \end{array}\right\} \cdots\cdots (8)$$

where v_{DC} is the inverter DC link voltage.

Using the VSD matrix transformation $[T_6]$ and the matrix form of (8), the voltage components in the machine subspaces (α,β), (μ_1,μ_2) and (z_1,z_2) are computed as

$$\begin{bmatrix} v_{s\alpha} \\ v_{s\beta} \\ v_{s\mu_1} \\ v_{s\mu_2} \\ v_{sz_1} \\ v_{sz_2} \end{bmatrix} = \frac{v_{DC}}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} & 0 \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} & \frac{1}{2} & \frac{1}{2} & -1 \\ 1 & -\frac{1}{2} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} & 0 \\ 0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} & \frac{1}{2} & \frac{1}{2} & -1 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} S_a \\ S_b \\ S_c \\ S_x \\ S_y \\ S_z \end{bmatrix} \quad \cdots\cdots (9)$$

As shown in (9), no voltage components are generated in the (z_1, z_2) subspace; for this reason, the machine topology with two separate neutral points is usually preferred.

Considering all the 64 inverter switching configurations, the projections of the normalized voltage vectors (respect to the DC link voltage v_{DC}) in the remaining orthogonal subspaces (α,β) and (μ_1,μ_2), are depicted in Figs. 5, 6.

The decimal numbers in Figs. 5, 6 show the inverter switching state N, i.e. its binary equivalent number gives the values of the switching functions for the inverter legs (considered in the order *abcxyz*). The inverter provides only 48 independent non-zero vectors and one zero vector to form a 12-sided, 4-layer polygon in each machine subspace.

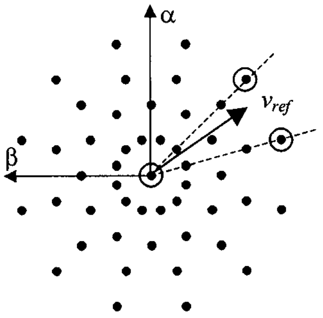

Fig. 7. Conventional SVM

The vectors with underlined switching configuration number N are obtained for different switching configurations of the inverter.

According to the VSD theory, the main goals of the PWM converter control are:

- To generate the reference voltage vector $\bar{v}_s^*$ in the (α,β) subspace, according to the desired flux and torque.
- To have zero average voltage vector in the (μ_1,μ_2) subspace to minimize the loss-producing harmonics.

4.1 Conventional Space Vector Modulation (CSVM)

This strategy has been proposed for dual three-phase drives in (32). For this strategy, similar to the one widely used for the three-phase inverters (33), two adjacent external vectors and the zero vector are used during a switching period to achieve the reference vector (Fig. 7) in the (α,β) subspace. Since only the (α,β) plane is controlled, harmonic voltage components will be generated in the (μ_1,μ_2) subspace. As a result, large loss-producing current harmonic components will flow in the motor phases (32).

4.2 Multilevel CSVM (ML-CSVM) This approach is based on a similar concept used by the PWM techniques for the multilevel inverters to reduce the voltage distortion in the (α,β) subspace. Thus, only non-zero vectors are used; their choice depends on the reference voltage magnitude (Fig. 8). Even with reduced voltage distortion in the (α,β) subspace,

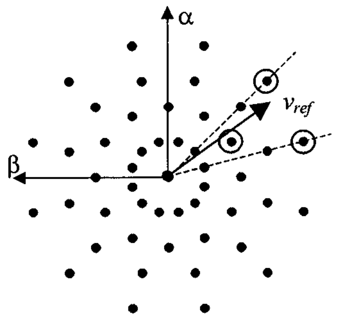

Fig. 8. Multilevel CSVM

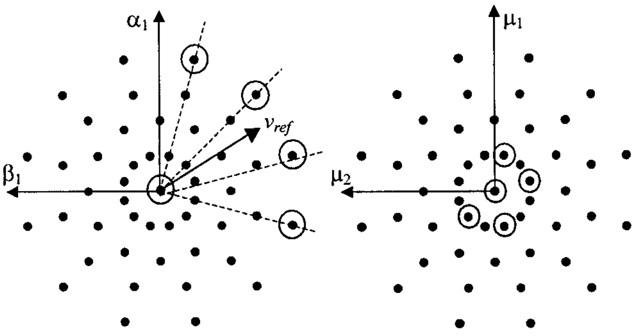

Fig. 9. VSD modulation strategy

the average voltage in the (μ_1,μ_2) plane is not zero and will produce even higher current harmonics compared with the CSVM(34).

4.3 Vector Space Decomposition Modulation (VSDM) Strategy This strategy, derived in(20) from machine modeling, controls both (α,β) and (μ_1,μ_2) subspaces using 4 adjacent non-zero vectors and one zero vector during one switching period, as shown in Fig. 9. Due to the minimization of the mean voltage in the (μ_1,μ_2) subspace, this modulation strategy offers great advantages concerning the reduction of the loss-producing current harmonics. This aspect is extremely important for short-pitch machines, where the equivalent impedance in the (μ_1,μ_2) subspace is reduced in contrast with full-pitch machines(24). Implementation problems of the VSDM strategy have been reported in(20), due to its complexity. However, by performing intensive off-line computations and appropriate choosing of zero-voltage vectors during one sampling period, a low cost DSP implementation has been proposed in(35) for a short-pitch machine.

4.4 Double Three-Phase SVM (DSVM) For this approach, introduced in(36), the six-phase inverter consists of two independent three-phase inverters sharing the same DC link. From the machine point of view, the voltage vector projections provided by both inverters form two 6-side polygons phase-shifted by 30 electrical degrees. Each three-phase inverter is independently controlled using the three-phase SVM(33).

The reference voltage vectors for the two identical SV modulators have the same amplitude, but the reference voltage vector for the (xyz) inverter lags the reference voltage vector of the (abc) inverter by 30 electrical degrees, as shown in Fig. 10 for positive speed. Another approach is to use the same reference voltage vector applied to two different SVM modulators, as described in(37). Despite the fact that only the (α,β) subspace is controlled, the current harmonics are considerably reduced compared with the CSVM method(34)(36)(37).

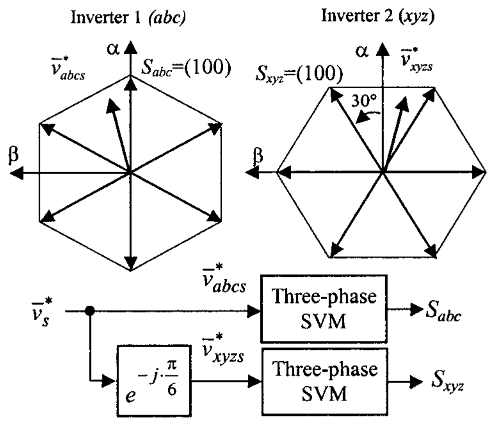

Fig. 10. Double SVM strategy

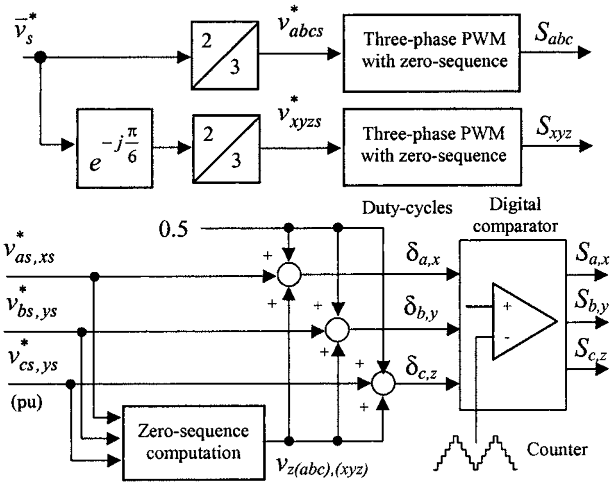

Fig. 11. Double zero-sequence injection technique

4.5 Double Zero-Sequence Injection (DZSI) Technique The main goal of this strategy(34) is the implementation with low cost DSP controllers having digital modulators based on ramp comparison PWM. Thus, the three-phase zero sequence injection(38) has been extended to the dual-three phase case, as shown in Fig. 11. This method gives results similar to those obtained with the DSVM strategy(34) and represents a good solution, especially for full-pitch machines.

5. Control of Dual-Three Phase Drives

In the literature, the papers dedicated to the control aspects of the dual-three phase induction motor drives are mainly dedicated to the vector control techniques (field oriented and direct torque control) while less interest is devoted toward scalar control.

As already stated about the machine model and the modulation strategy, also the vector control schemes for three-phase machines can be extended to the dual-three phase drives. In fact, the VSD theory(20) demonstrates how the machine model can be transformed into a system of decoupled equations in orthogonal reference frames (Fig. 2), being the (α,β) equation system identical to that obtained for a three-phase machine, while the (μ_1,μ_2) current components do not

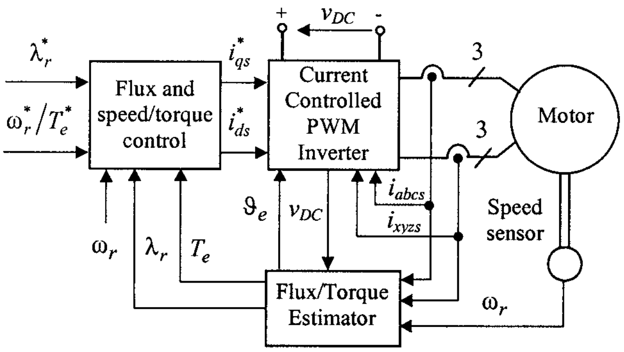

Fig. 12. DRFOC scheme for dual-three phase induction machine drives

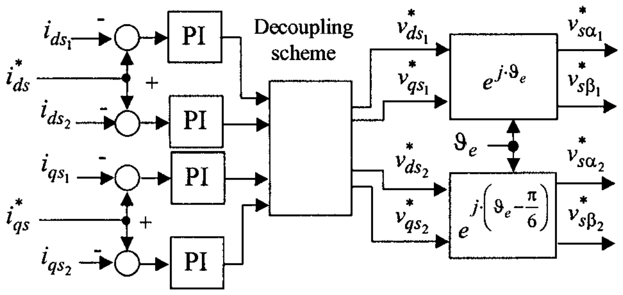

Fig. 13. Double (d, q) synchronous frame current control

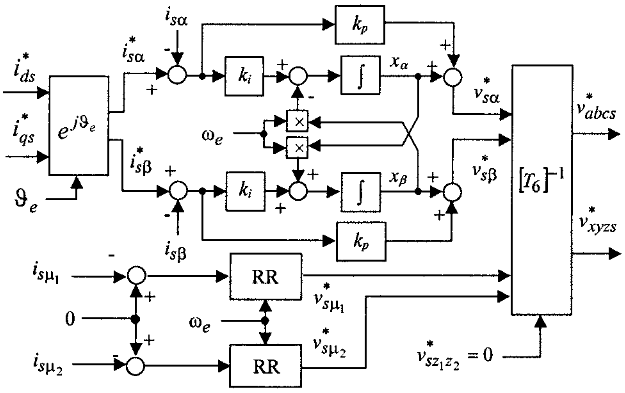

Fig. 14. Stationary frame current control scheme

contribute to the machine flux and torque production.

5.1 Field Oriented Control (FOC)

The FOC theory aims to obtain a decoupled control of the machine flux and torque. That is possible for the dual-three induction machine by referring the (α,β) machine model (obtained either with VSD or the DTP) to a rotating (d, q) reference frame aligned on the one of the machine flux linkages: rotor flux, stator flux or air-gap flux.

The d-axis component of the stator current vector controls the flux, meanwhile the q-axis current component controls the torque. For this reason, the FOC requires current control on the inverter. The current control forms an inner loop of the overall control system, receiving the reference currents from the outer loops (flux loop and torque/speed loops)(39).

The literature reports papers mainly dedicated on Direct Rotor Field Oriented Control (DRFOC) for dual-three phase induction motor drives. In this case, the rotating (d, q) reference frame is aligned on the rotor flux vector whose magnitude and position are provided by a flux estimator, as shown in Fig. 12.

The flux estimation needed for field orientation can be performed using either the VSD (Fig. 2) or DTP (Fig. 3) machine models; for example, a rotor flux estimation using the DTP machine model for a dual-three phase Direct Rotor FOC (DRFOC) scheme is presented in(40), where the stator windings are connected in series and supplied by a three-phase inverter with hysteresis current control. When VSD machine model is used, the dual-three phase drives adopt flux estimators normally employed for the three-phase induction machines.

On the contrary, the current control extension from the three-phase to the dual-three phase drive must consider some specific aspects; in particular, the small inherent asymmetries between the two three-phase power sections can lead to unbalance current sharing between the two stator winding sets(9)(41).

This phenomenon can arise when the machine is supplied from two completely independent three-phase voltage source converters.

The current control can be implemented either in stationary frame or in synchronous reference frame, depending on the required current control performance for the considered specific application.

A Direct Rotor FOC (DRFOC) scheme based on DTP machine modeling is discussed in(8) for a GTO inverter-fed high-power machine. The current control uses a double (d, q) synchronous reference frame approach to simultaneously control the flux-producing components (i_{ds1}, i_{ds2}) and the torque-producing components (i_{qs1}, i_{qs2}) corresponding to the two stator winding sets. A decoupling scheme for current regulation, based on the machine state-space model, has been also proposed. Another DRFOC scheme, based on the VSD theory (which gives a simpler rotor flux estimation) and also using the double (d, q) current control, is discussed in (22), meanwhile a comparison of different (d, q) synchronous frame current regulation schemes is given in(43).

The basic double (d, q) current control scheme(8)(22)(42) is illustrated in Fig. 13. When the neutral points of the two three-phase stator sets are connected, the control scheme must be completed with other two PI regulators, as described in(9).

The double (d, q) synchronous reference frame current control for dual-three phase drives has the disadvantage of the multiple speed-dependent coupling terms to be compensated(8)(42). For this reason, a straightforward current control scheme in stationary (α,β) reference frame has been proposed in(43); this scheme does not need decoupling schemes and it is able to deal with the unbalance current sharing between the two stator winding sets (Fig. 14).

The (α,β) current components, are regulated by means of a regulator being equivalent to a PI regulator in (d, q) reference frame. The fundamental current components which appear in the (μ_1, μ_2) subspace in case of unbalance current sharing, are forced towards zero by two Resonant Regulators (RR) tuned on the fundamental frequency(43), as shown in Fig. 14.

5.2 Direct Torque Control (DTC)

The main goal of DTC is to obtain a fast, decoupled control of the stator flux and the electromagnetic torque without inner current control loops(44). From the literature, the DTC solutions for the

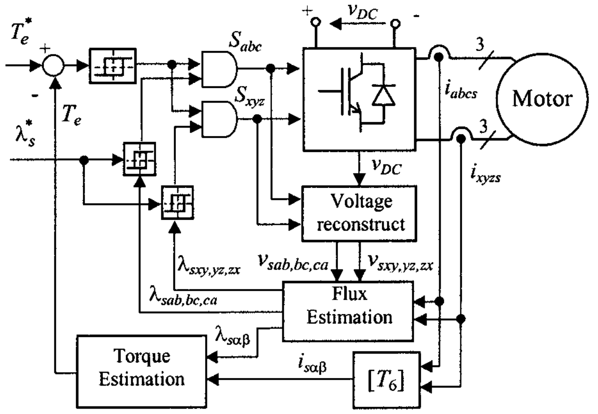

Fig. 15. DSC for dual-three phase induction motor drive

three-phase machines can be divided into two main groups:

- Direct Self Control (DSC) and Switching-Table based DTC (ST-DTC) techniques; these solutions give variable switching frequency.
- Pulsewidth Modulation based DTC (PWM-DTC) techniques; these solutions impose constant inverter switching frequency.

The DSC and the ST-DTC schemes can be extended for dual-three phase drives (44)-(46), considering the larger number of non-zero voltage vectors that can be provided by the six-phase inverter.

Furthermore, a general consideration is that the lack of current control imposes a dedicated design of the drive power units in order to avoid unbalanced current sharing between the two three-phase stator sets (26).

The basic DSC scheme for dual-three phase induction motor drives is shown in Fig. 15. By using the voltage vectors corresponding to the external layer of the 12-side polygon in the (α,β) subspace (Fig. 5), the DSC imposes a 12-side polygonal trajectory of the stator flux.

However, that is achieved by generating 5th and 7th voltage harmonics; these voltages will produce large current harmonics in the (μ_1,μ_2) subspace, as shown by the simulation results of a DSC scheme described in (47).

That will result in the increase of size and cost of both machine and inverter. However, the DSC strategy can be used in high power, low switching frequency applications, such as traction drives (48).

The ST-DTC basic scheme for dual three-phase induction motor drives is shown in Fig. 16. Based on the estimated stator flux position, a torque three-level hysteresis regulator and a flux two-level regulator are used to generate the inverter switching functions through an optimal Switching Table (ST). The key issue for ST-DTC is the ST design in order to get sinusoidal machine phase currents, by minimizing the current components in the (μ_1,μ_2) subspace. Different ST design solutions are discussed and experimented in (49) with good torque and flux regulation performance but with some problems regarding the phase currents distortion. Other ST-DTC strategies, involving voltage vectors from internal layers of the 12-side polygon in the (α,β) subspace (Fig. 5) have been simulated in (50).

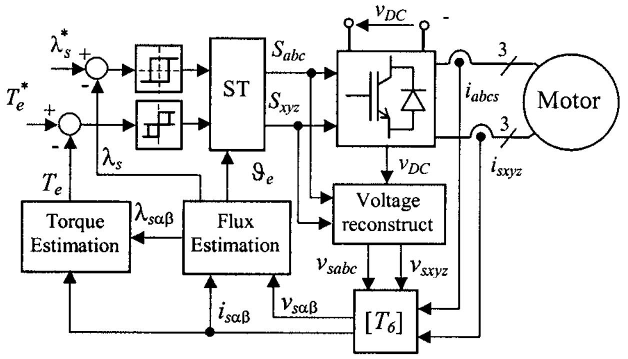

Fig. 16. ST-DTC for dual-three phase induction motor drive

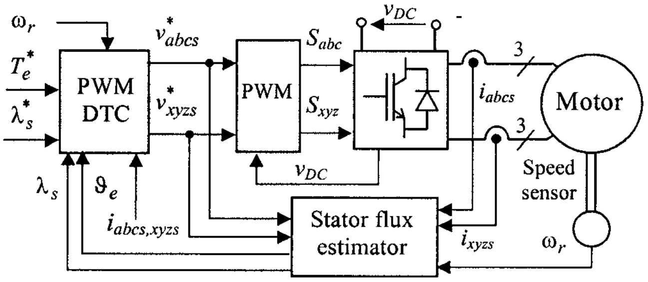

Fig. 17. PWM-DTC dor dual-three phase induction motor drive

In several applications, such as EV, it is preferred to have a constant switching frequency to obtain quasi sinusoidal phase currents using PWM operation.

In this case, an average stator voltage command vector over a sampling period must be computed, to get the required stator flux and electromagnetic torque. The basic PWM-DTC scheme is shown in Fig. 17.

A predictive PWM-DTC scheme, using the VSD theory for machine modeling, has been proposed in (48) to get sinusoidal machine currents; the algorithm has been implemented in stator flux synchronous reference frame.

To get a robust control scheme against motor parameters detuning, a PWM-DTC scheme, based on the VSD theory, is presented in (51). The reference voltage vector is obtained through simple PI regulators implemented in stator flux synchronous reference frame. The stator flux is estimated by means of a full-order observer, which provides also stator current estimation; the estimated currents are used to compensate the inverter dead-time effects (51).

6. Conclusions

The available literature about the dual-three phase induction motor drives is mainly dedicated to high power/high current and high reliability applications, such as traction drives, ship propulsion, EV, pumps, compressors, etc. These applications can better exploit the advantages of the multi-phase solution over the conventional three-phase counterpart.

The major part of the published papers dealt with the development of control schemes for dual-three phase induction motor drives starting from well-known three-phase solutions. The transition from the three-phase to the dual-three phase machine control requires dedicated solutions. In particular, to avoid possible stator current distortion and unbalance current sharing between the two stator winding sets, specific approaches in terms of machine modeling, modulation techniques and current control schemes have been developed and experimentally demonstrated. Some of these solutions could be of immediate relevance to industry.

Novel concepts, which are in early research stage, are related to the employment of specific properties of dual-three phase machines in particular applications, such as single-inverter multi-motor drives or dual-source motor drives.

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Appendix

The transformation matrix $[T_6]$ used for the VSD theory is

$$[T_6] = k \cdot \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} & 0 \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} & \frac{1}{2} & \frac{1}{2} & -1 \\ 1 & -\frac{1}{2} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} & 0 \\ 0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} & \frac{1}{2} & \frac{1}{2} & -1 \\ 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 \end{bmatrix}$$

$$\begin{cases} k = \dfrac{1}{\sqrt{3}} \text{ for the power invariant form} \\ k_T = \dfrac{1}{3} \text{ for the non - power invariant form} \end{cases}$$

app. Table 1. List of machine parameters and symbols

R_s, R_r	Stator and rotor resistances
L_{ls}	***Stator self leakage inductance***
L_{lr}	Rotor leakage inductance
M	Magnetizing inductance
M_{ls}	Stator mutual leakage inductance
L_s, L_r	Stator and rotor inductances
P	Number of poles
λ_s, λ_r	Stator and rotor flux linkages
ϑ_e	Flux vector position
ω_r	Rotor electrical speed
ω_e	Synchronous speed
j	Imaginary operator

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