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Efficiency Analysis of PWM Inverter Fed Three-Phase and Dual Three-Phase High Frequency Induction Machines for Low/Medium Power Applications

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Abstract—A performance analysis of three-phase and dual three-phase (DTP) induction pulsewidth modulation (PWM) inverter-fed motor drives is conducted in this paper. The focus is on the efficiency performance of high-frequency DTP machines compared to their three-phase counterparts in low/medium power applications. For this purpose, a DTP machine, having two sets of stator three-phase windings spatially shifted by 30 electrical degrees (asymmetrical six-phase winding configuration), was tested for both six-phase and three-phase winding configurations under the same magnetic conditions. Simulation and experimental results are presented to evaluate the efficiency performance of three-phase and dual-three induction motor drives employing PWM voltage source inverters.

Index Terms—Efficiency, multiphase induction machines, pulsewidth modulation (PWM) inverter fed operation, three-phase induction machines.

I. INTRODUCTION

THE THREE-PHASE distribution grid has imposed the same number of phases for ac machines since they were first directly connected to the grid for industrial applications. In adjustable speed ac drives, since a dc–ac converter usually supplies the machine, the utility grid no longer limits the number of phases. Hence, since the introduction of power electronic devices, multiphase motor drives have been studied to solve particular technical problems in custom applications. For example, in high power/high current applications, the multiphase solution allows the division of controlled power on more inverter legs, reducing the rated current of the power electronic switches and offering high reliability at system level due to the redundant structure. Other potential advantages of multiphase drives over the three-phase ones are [1]–[3]: 1) lower torque pulsations at high frequency; 2) reduced rotor harmonic currents for induction motor drives; 3) higher power per rms ampere ratio for the same machine volume; and 4) reduced harmonic content of the dc link current in the case of voltage source inverter (VSI)-fed drives. These aspects can justify the higher complexity

of the multiphase drive in special custom applications, such as electrical ship propulsion, traction drives, electric/hybrid vehicles, high power pumps and aerospace [1]–[3].

In the last five years, the interest in multiphase drives has grown considerably and some international conferences and journals have hosted sessions dedicated to multiphase motor drives [4]. The literature reports different multiphase solutions from the point of view of the phase number and the machine type; the more interesting ones drawing attention are the five-phase and six-phase models that employ induction, synchronous permanent magnet or synchronous reluctance motors [2].

A widely discussed six-phase solution is the dual three-phase (DTP) induction machine having two sets of three-phase windings spatially shifted by 30 electrical degrees with isolated neutral points (Fig. 1). This machine is reported in the literature with different names, including six-phase, split-phase, DTP, dual-star or asymmetrical six-phase induction machine.

To have a clear nomenclature, the term DTP is adopted for the machine and the drive to indicate the two separate sets of three-phase windings shifted by 30 electrical degrees. Meanwhile, the term six-phase is applied to the converter whose structure is not affected by the winding configuration.

During the last three decades, literature related to dual-three phase induction motor drives has covered an entire path: from machine modeling and design [5], [6], through the steady-state analysis of the six-step operation using voltage source or current source inverters [7], [8], to vector control [9], [19] using suitable pulsewidth modulation (PWM) techniques [10]–[12]. In [13] the potentially higher torque density of a dual-three phase machine (compared to a three-phase solution) is demonstrated, exploiting 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. Using this winding configuration, up to 40% of torque density improvement is reported [13], compared to a three-phase machine having the same flux peak value.

Another relevant issue in multiphase drive application is that of the machine and drive efficiencies. Recently, some papers have discussed the comparison between three-phase and six-phase induction motor drives for a six-pulse voltage source inverter supply [14], [15]; in these papers, the multiphase system shows higher efficiency. The first theoretical approach

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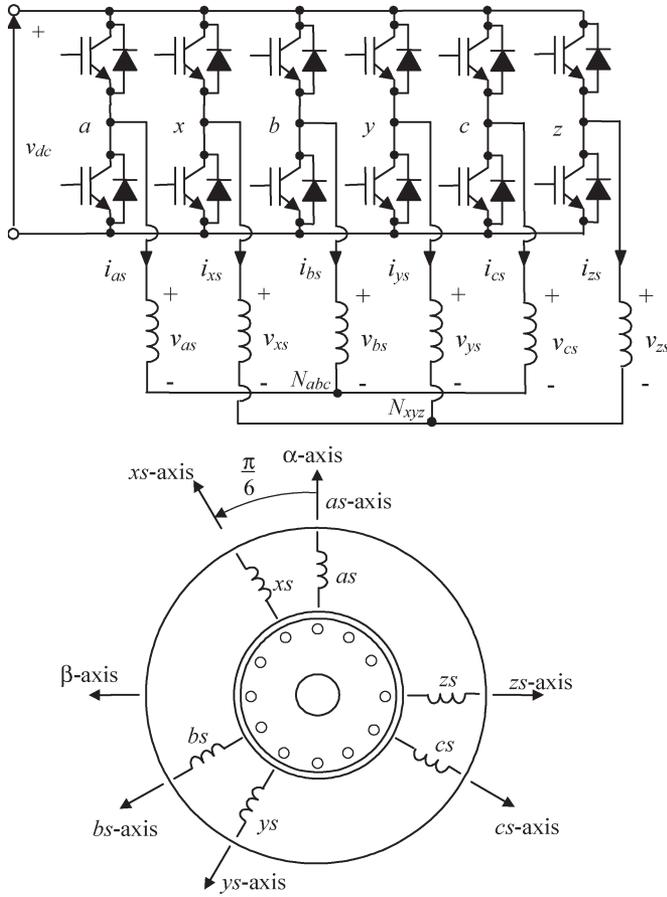


Fig. 1. DTP induction machine.

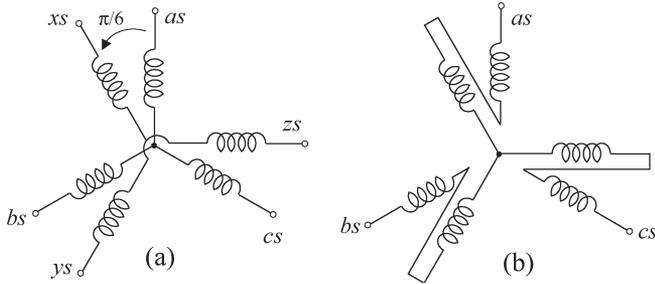


Fig. 2. (a) DTP and (b) three-phase winding configurations.

regarding multiphase induction machines fed by PWM inverters is presented in [18], where the authors show a reduction of 4 ÷ 8% in stator copper loss. To the best of the authors' knowledge, a dedicated efficiency analysis, based on the comparison of experimental results obtained using three-phase and DTP induction motor drives supplied from PWM VSIs, has never been reported in the literature.

The aim of this paper is to perform the efficiency analysis and comparison of three-phase and DTP drives fed by PWM VSIs using an induction machine operating either with a DTP winding configuration with isolated neutral points (one slot per pole per phase) or a three-phase winding configuration (two slots per pole per phase), as shown in Fig. 2.

The prototype was developed for an integrated starter-alternator in mild-hybrid vehicles. The geometry constraints

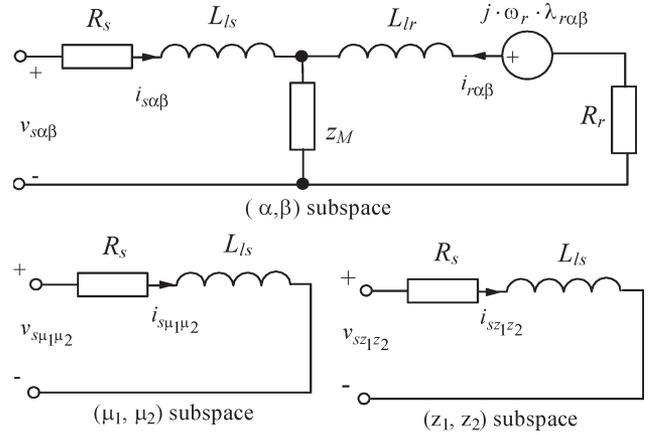


Fig. 3. Machine equivalent circuits for VSD approach.

of the application imposed a flat shape for the motor to be integrated into the gearbox; a large rotor inner diameter was also necessary to host the required clutches inside the rotor. For these reasons, the machine has several poles (12), hence it must be supplied by a “high” fundamental frequency (up to 650 Hz).

The most interesting efficiency analysis considers the overall drive efficiency. As a first step, the machine and the converter are considered separately both in simulation and in experimental analysis. Then the complete system analysis can be developed for the drive efficiency evaluation.

II. MACHINE MODELING AND ANALYSIS

Compared with a three-phase solution, the DTP machine has the same rotor and the same magnetic core, but the stator windings are split into two three-phase sets phase shifted by 30 electrical degrees (Fig. 1). As a consequence, the mathematical modeling approach of dual-three phase induction machines is also similar to its three-phase counterpart.

DTP machine modeling can follow one of two different paths. According to the DTP approach [5], the machine can be represented with two pairs of (α, β) windings that correspond to the two three-phase windings in a stationary reference frame. According to the second approach, based on vector space decomposition (VSD) [10], the machine can be represented with two stator-rotor pairs of windings in two mutually orthogonal stationary subspaces, where the first stator-rotor (α, β) pair leads to electromechanical energy conversion while the second stator-rotor (μ_1, μ_2) pair does not. It can be shown that the supply harmonics of the order $12n \pm 1$ ($n = 1, 2, 3, \dots$) map into the (α, β) subspace, while the harmonics of the order $6n \pm 1$ ($n = 1, 3, 5, \dots$) map into (μ_1, μ_2) subspace [10]. For ideal sinusoidal supply, the (μ_1, μ_2) currents are zero. The equivalent circuits obtained with the VSD and DTP approaches are shown in Figs. 3 and 4, respectively.

In both modeling approaches, the two zero sequence components [the third subspace $(z_1 - z_2)$ obtained using VSD] can be omitted from consideration, since the neutral points of the two three-phase windings are isolated. This paper uses a VSD modeling approach, since the equivalent circuit in the (α, β) subspace is identical (with different parameter values) with the equivalent circuit of the three-phase machine (Fig. 3).

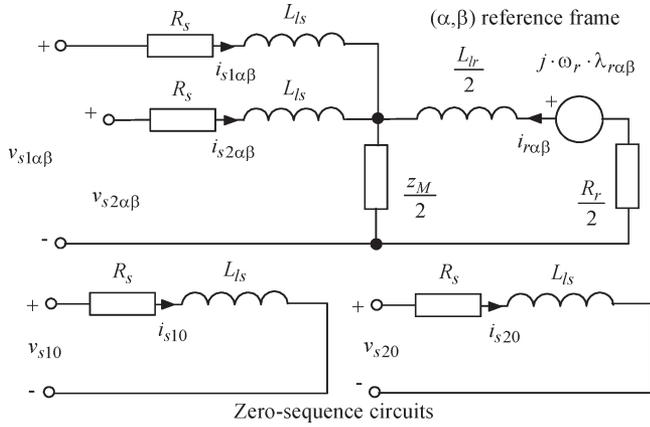


Fig. 4. Machine equivalent circuits for DTP approach.

The machine parameters for the VSD modeling approach are given in the Appendix, together with the machine parameters for three-phase configuration and the motor rated values.

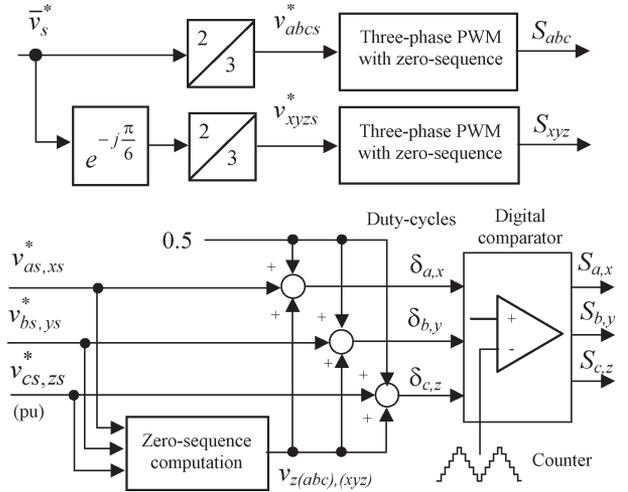
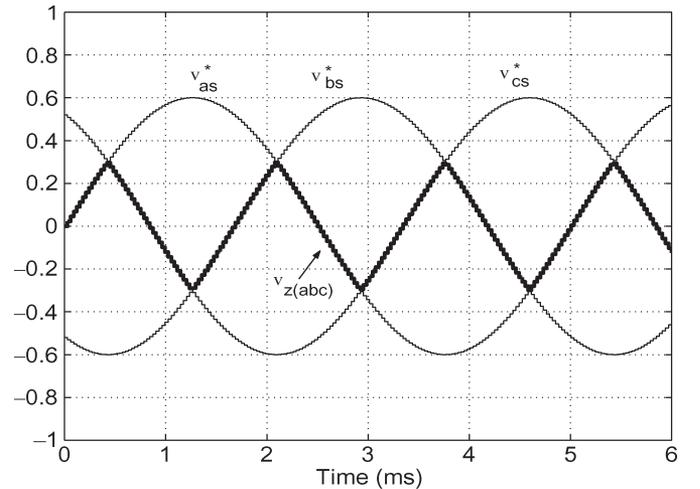
The design equations and criteria are thus substantially the same for three-phase and DTP machines, as they are usually obtained under the same simplifying assumptions: sinusoidal winding distributions and constant air-gap. Under these assumptions, it can be shown that, considering sinusoidal voltage/current waveforms and given the same operating conditions, the two solutions should exhibit similar efficiency. However, it is expected that the slightly better MMF spatial waveform of a DTP machine should lead to some reduction of the losses compared to the three-phase solution.

III. CONVERTER ANALYSIS

When supplied by a square-wave VSI [7], the DTP induction machine draws large current harmonics of the order $k = 6 \cdot n \pm 1$, ($n = 1, 3, 5, \dots$), which do not contribute to the air-gap flux and do not influence the torque pulsations. These harmonics (5th, 7th, ...) are mapped in the machine (μ_1, μ_2) subspace (being thus limited only by the stator resistance and the stator leakage inductance) and drastically reduce machine efficiency [10].

Besides simultaneous regulation of voltage amplitude and frequency, the PWM operation for VSI can improve the quality of the delivered machine current waveforms. The six-phase inverters, having a higher number of switching configurations, allow the implementation of a larger number of modulation techniques compared to the three-phase inverters [3]. The suitable approach for the analysis of the six-phase inverter operation is the VSD theory [10], since it provides a unified method to demonstrate the generation of the low-order, loss-producing current components in the (μ_1, μ_2) subspace. According to the VSD theory, the main goals of any PWM technique are: 1) to generate a reference voltage vector \bar{v}_s^* in the (α, β) subspace (according to the desired flux and torque); and 2) to have a zero average voltage vector in the (μ_1, μ_2) subspace to minimize the loss-producing harmonics.

The PWM technique used for this paper is the double zero-sequence injection (DZSI) scheme, shown in Fig. 5. The DSZI approach is the extension to the six-phase case of the three-phase zero-sequence injection technique [16]. Thus, the six-

Fig. 5. DZSI modulation scheme; S_χ ($\chi = a, b, c, x, y, z$) are the inverter switching functions.Fig. 6. Zero sequence computation for abc voltage command set (p.u.).

phase inverter consists of two independent three-phase inverters sharing the same dc link.

From the machine point of view, the voltage vector projections in the (α, β) subspace form two six-sided polygons, which are phase-shifted by 30 electrical degrees. Each three-phase inverter unit is independently controlled; the two three-phase units receive two reference voltage vectors phase-shifted by 30 electrical degrees (Fig. 5). Since the harmonics generated in the (μ_1, μ_2) subspace [11] by the DSZI modulation scheme are very small, the machine efficiency is only slightly lowered.

The zero sequence components corresponding to each stator set are phase-shifted by 30 electrical degrees; they are separately computed with a simple logic algorithm. This algorithm reconstructs the zero sequence component of one three-phase set [20] as the voltage command which has an intermediate value, as shown in Fig. 6 for the abc set.

The DZSI has the advantage of being easily implemented without any computational effort. It obtains inverter duty-cycle commands very similar to those obtained for the conventional space vector modulation of three-phase inverters, thus yielding a linearity extension of PWM by 15% for each three-phase set.

IV. EFFICIENCY ANALYSIS AND COMPARISON

The efficiency comparison between the three-phase and the DTP drive should be performed at the same dc bus voltage and delivering the same power (same speed and same torque) at the same thermal conditions (same cooling and temperature). Hence, the rms value of the phase currents in the three-phase drive is twice that of the DTP case. For this reason, a fair comparison based on experimental results would require two dedicated designs and prototype realizations for the two solutions. Since only the DTP drive is available, the results required for a valid analysis and comparison have been obtained as follows:

- 1) Motor analysis: The windings of the machine prototype can be connected both in three-phase and DTP configuration, as described in Fig. 2. Supplying the machine with two proper sets of symmetric voltages yields the same magnetic conditions. In both cases, the efficiency tests can be performed at the same torque, speed and machine fundamental flux.

Nevertheless, some differences are expected particularly for the copper losses. In fact, the DTP machine requires less current to produce the same airgap fundamental MMF and produces lower-magnitude higher order MMF harmonics [2]; as a consequence, the stator and rotor joule losses should be lower for the DTP machine. In [18], it has been shown that a theoretical reduction of stator joule losses equal to 6.7% can be obtained for DTP machines when compared to the equivalent three-phase machine (same output with the same magnetic condition), while the reduction of joule rotor losses is not relevant.

- 2) Converter analysis: The comparison requires two converters using power electronic components having the same characteristics and technology but with different rated currents. The efficiency results for the two configurations were obtained by a commercial simulation tool that does not require further validation. Furthermore, the eventual imprecision in determining the absolute value of the converter losses (for example, the power required by the auxiliary analog and digital electronic circuitry are neglected) has reduced importance in a comparison.

Merging the data measured on the machine and the simulation data computed under the same working conditions of the experimental test, the efficiency of the three-phase and DTP drives can be correctly compared.

A. Motor Efficiency Comparison

The machine efficiency comparison for the DTP and the three-phase winding configurations is based on experimental results. The switching frequency of the insulated-gate bipolar transistor (IGBT) inverter has been set at 10 kHz (the inverter has six legs; during the three-phase tests only three legs are used). Both three-phase and DTP drives were controlled using an open loop V/f control strategy. The motor load is a dc machine (having a built-in torque sensor) fed by a four-quadrant thyristor converter. The experimental test schemes are shown in Fig. 7, while the general view of the test rig is shown in Fig. 8.

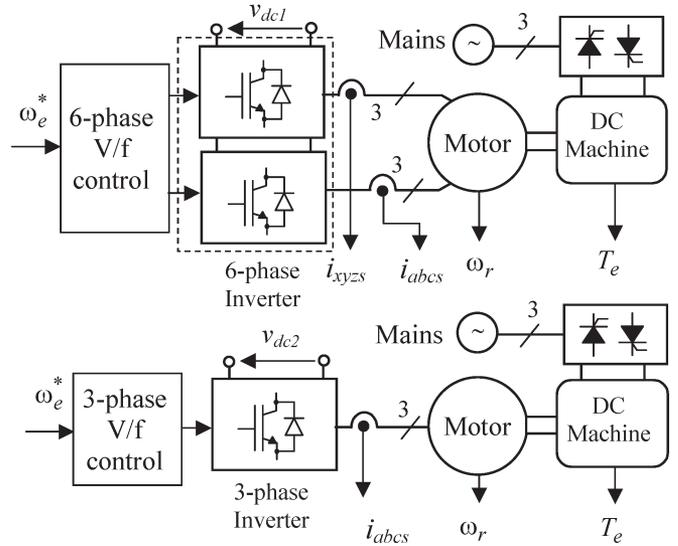


Fig. 7. Experimental test schemes for six-phase and three-phase configurations.

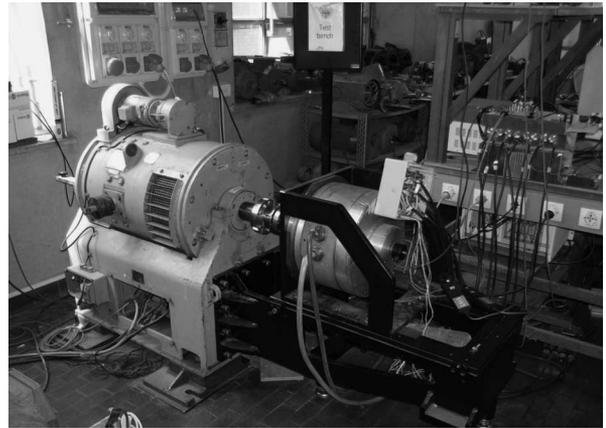


Fig. 8. General view of the test rig.

Different efficiency tests were carried out at three different fundamental frequency values (75, 150, and 300 Hz corresponding to a synchronous motor speed equal to 750, 1500, and 3000 r/min) with different load torque levels. For each frequency, the motor results are measured in thermal steady state conditions. It is important to remark that the magnetic conditions of the motor core should be the same in each test. To guarantee this condition, a different phase voltage is required in accordance with the three-phase or DTP machine winding connection. Taking into account the 30° shift between the two three-phase winding systems of the machine, the voltages imposed for the three-phase connection must be slightly less than twice the voltages imposed for the DTP connection ($V_{3\phi} \cong 1.95V_{6\phi}$). In any case, the adopted open loop V/f control strategy does not compensate for the supply voltage drop at the machine leads when the load torque changes. This means that a slight variation of the motor core magnetic condition is inevitably passing from no-load to load operations for a constant supply frequency.

To have a fair comparison in terms of the effects of the PWM supply on the iron losses [17], the same modulation index was used in the corresponding three-phase and DTP tests. Hence,

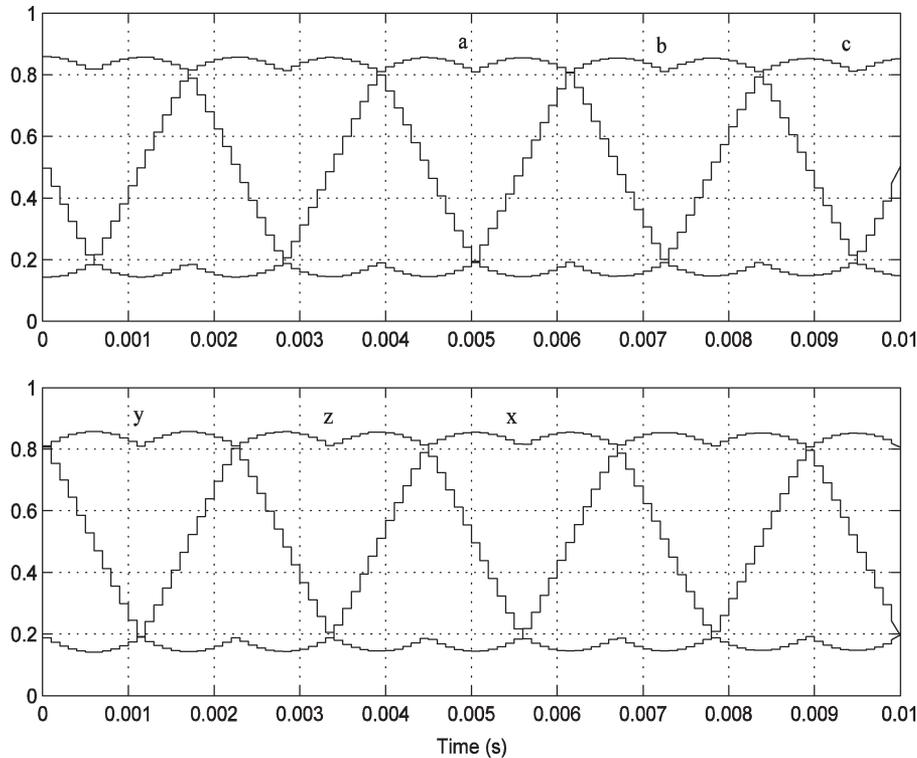


Fig. 9. Inverter duty-cycle commands for six-phase operation at 150 Hz of fundamental frequency and 45 N · m load torque.

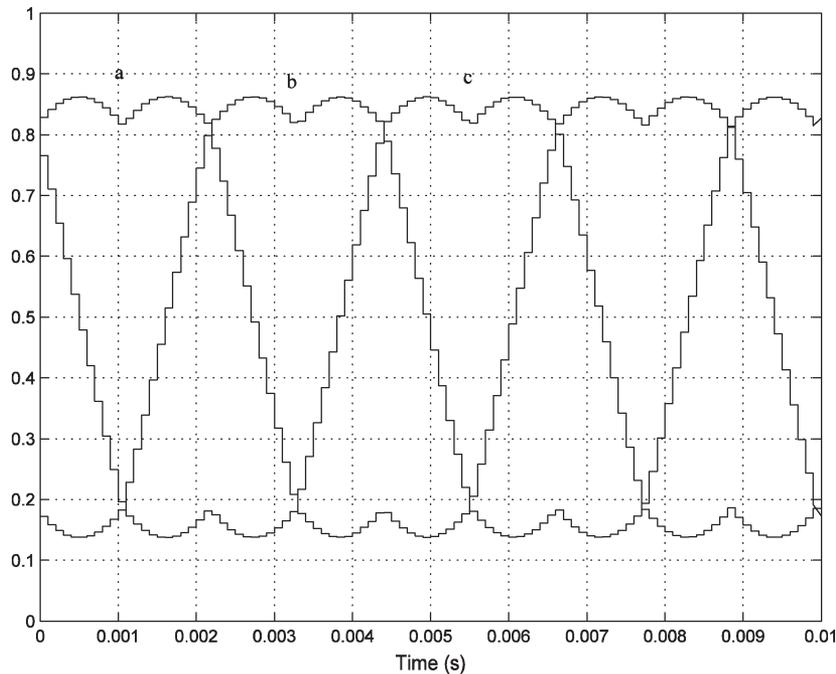


Fig. 10. Inverter duty-cycle commands for three-phase operation at 150 Hz of fundamental frequency and 45 N · m load torque.

the inverter dc link voltage during the three-phase tests must be almost double compared to that used for the DTP operation; this ensures that duty-cycles of inverter commands in the corresponding cases are almost identical, as shown in Figs. 9 and 10. As a consequence, the influence of the PWM operation on the machine iron losses is the same for the two cases.

The phase currents exhibit sinusoidal waveforms (Figs. 11 and 12) with a slight influence of the inverter dead-time effect

for both cases. The current amplitudes are practically the same in the corresponding three-phase and DTP tests.

Fig. 13 summarizes the performed efficiency tests: the figure shows the electric (active) and the mechanical power in each of the measured points at the three different frequencies. The mechanical power is exactly the same in the corresponding three-phase and DTP tests; the electric (active) power values in the corresponding three-phase and DTP tests are quite close and the

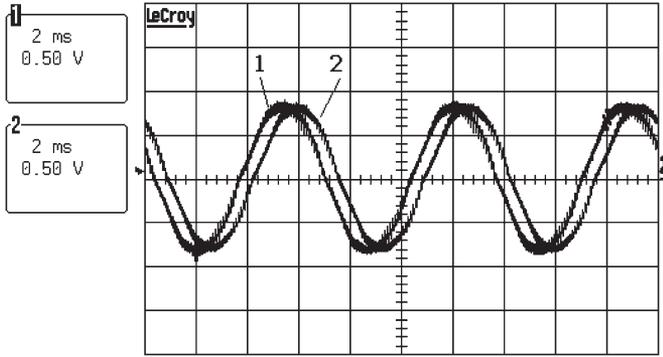


Fig. 11. Phase currents for six-phase test at 150 Hz of fundamental frequency with 45 N · m load torque (10 mV/A): (1) i_{as} ; (2) i_{xs} .

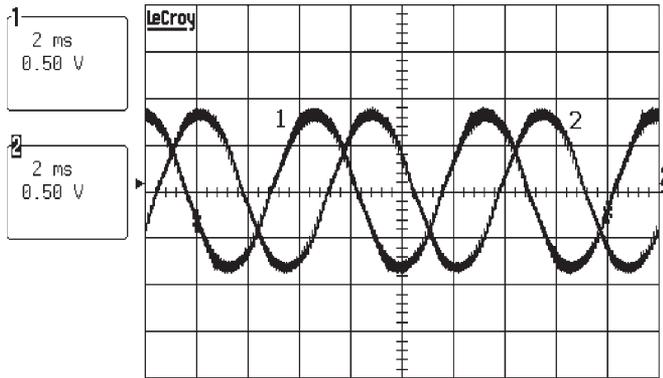


Fig. 12. Phase currents for three-phase test at 150 Hz of fundamental frequency with 45 N · m load torque (10 mV/A): (1) i_{as} ; (2) i_{bs} .

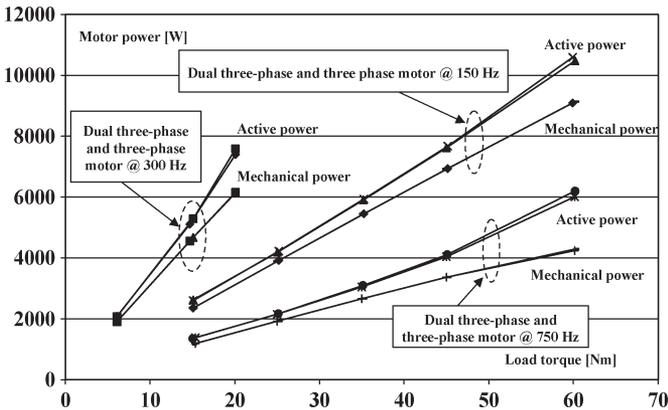


Fig. 13. Active and mechanical power versus the load torque, for the considered frequencies.

differences cannot be appreciated in the figure. The power factor is also practically the same in the corresponding three-phase and DTP tests due to the very similar magnetic conditions.

Table I compares measurement results under the same steady state thermal conditions for the DTP phase and three-phase machine at the rated torque (45 N · m) and frequency (150 Hz).

Figs. 14–16 show the motor efficiencies for the DTP and three-phase winding connections measured during the variable load tests at the supply frequencies 75, 150, and 300 Hz, respectively. Since the highest considered frequency belongs to the constant power speed range, the machine flux in these tests has been weakened at 50% of the rated value.

TABLE I
COMPARISON BETWEEN SIX-PHASE AND THREE-PHASE MACHINE OPERATION UNDER THE SAME STEADY-STATE THERMAL CONDITIONS

	Dual three-phase PWM operation	Three-Phase PWM operation
DC link voltage, (V)	107	200
DC link current, (A)	82.2	42.3
Phase voltage, (V)	37.1	71.6
Phase current, (A)	57.4	59.5
Fundamental frequency, (Hz)	150	150
Fundamental phase voltage, (V)	26.1	50.8
Fundamental phase current, (A)	57.1	59.4
Active power, P (W)	7620	7670
Fundamental active power, (W)	7550	7590
Displacement power factor	0.846	0.840
Load torque, (Nm)	45.0	45.2
Motor speed, (rpm)	1470	1470
Output mechanical power, (W)	6920	6940
Motor efficiency	0.908	0.907

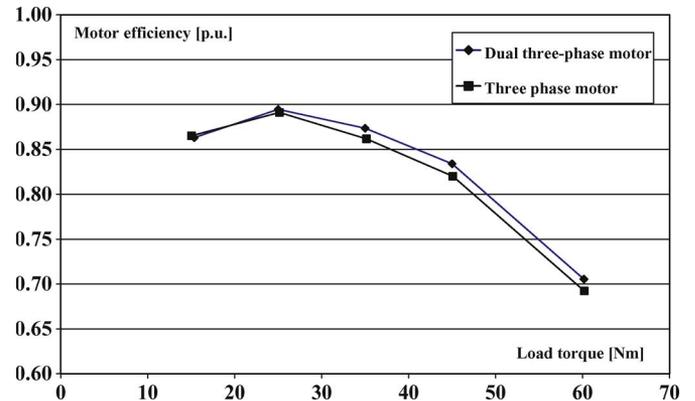


Fig. 14. DTP and three-phase efficiency versus torque at 75 Hz.

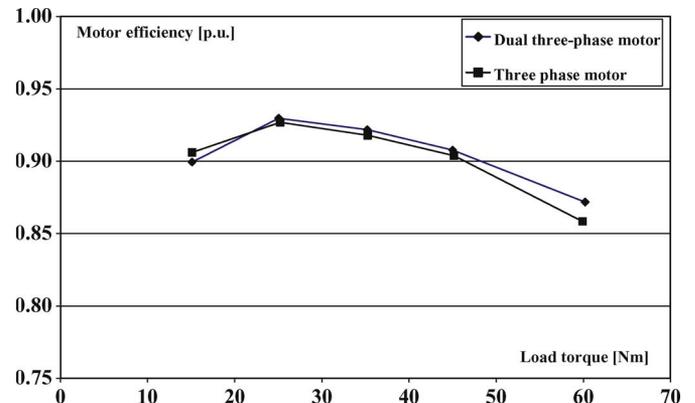


Fig. 15. DTP and three-phase efficiency versus torque at 150 Hz.

The experimental results show that there are no significant differences in the efficiency performance between the DTP and the three-phase machines working under the same electrical, magnetic and mechanical conditions.

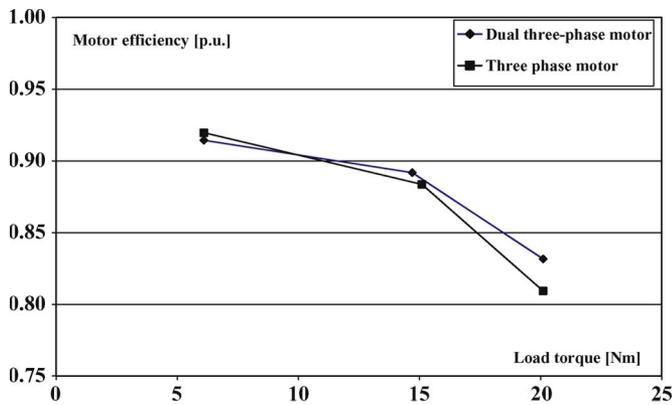


Fig. 16. DTP and three-phase efficiency versus torque at 300 Hz.

TABLE II
STATOR LOSS PERCENTAGE REDUCTION FOR THE DTP MACHINE WITH RESPECT TO THE EQUIVALENT THREE-PHASE MACHINE (AIRGAP FLUX RATED CONDITION)

Load torque [Nm]	75 Hz fundamental frequency test	150 Hz fundamental frequency test
60	4.2 %	5.9 %
45	6.9 %	7.2 %
35	6.9 %	6.4 %
25	5.3 %	6.4 %

As stated in [18], considering that the magnitude of the fundamental field, slot-passing effects and high-frequency inverter switching are basically the same for both machines, the iron losses should be the same. On the contrary, the copper losses are expected to be different because the DTP machine requires less current to produce the same fundamental MMF, and it produces lower-magnitude higher pole-number MMF harmonics.

With reference to the stator joule losses, at rated conditions the stator winding loss is 531 W for the three-phase operation, while a value of 494 W was found for the six-phase operation. These experimental results confirm the theoretical percentage reduction (equal to 6.7%) of the stator joule loss reported in [18] for this type of machine. Table II reports the percentage stator copper loss reduction for different loads and supply frequencies at the rated machine airgap flux. In this case, the obtained values of the stator joule loss percentage reductions also confirm the theoretical results reported in [18].

B. Converter Efficiency Comparison

A realistic comparison between a six-phase converter and a three-phase counterpart must be performed for the case when the converters supply two induction machines of the same rated power and the same rated voltage under the same power factor and fundamental frequency conditions.

In this case, the phase output current for the three-phase converter is doubled compared to the six-phase converter. Thus, the comparison requires two dedicated converters using power electronic components having the same rated voltage but with different rated currents. Due to the difficulties in performing the experimental test with two different dedicated converters, the efficiency results for the two configurations were obtained by

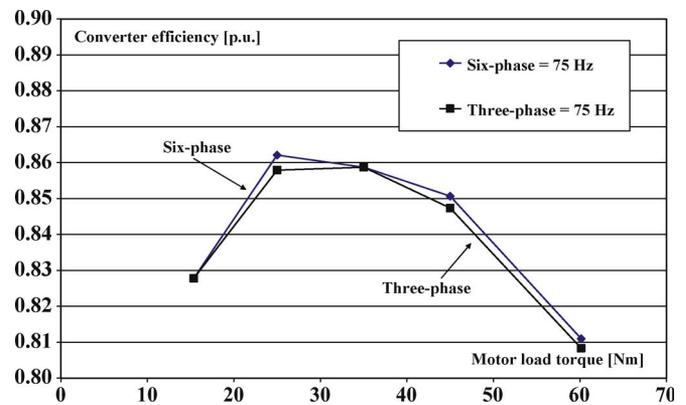


Fig. 17. Six-phase and three-phase converter efficiencies versus torque at 75 Hz.

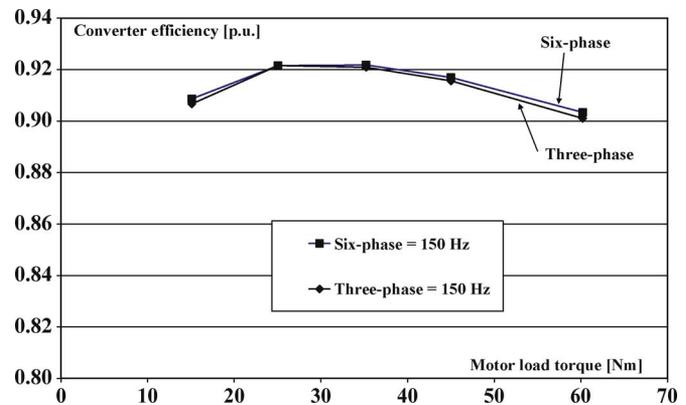


Fig. 18. Six-phase and three-phase converter efficiencies versus torque at 150 Hz.

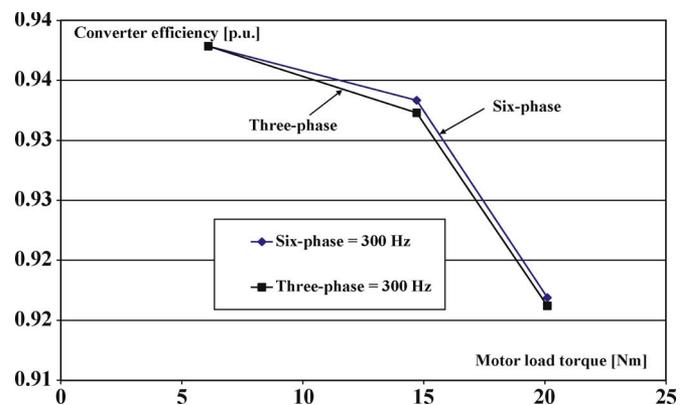


Fig. 19. Six-phase and three-phase converter efficiencies versus torque at 300 Hz.

means of the commercial design tool SEMISEL by Semikron GmbH.

This design tool can be used to estimate the converter losses for a given load operating point (fundamental frequency, output current and voltage), a given dc link voltage and a specified Semikron power electronic component chosen for the converter design. The losses due to auxiliary circuitry are neglected.

The efficiency comparison was performed with measurement values (fundamental voltage, current and power factor) obtained for the DTP motor and assuming doubled phase

TABLE III
DTP MACHINE PARAMETERS (AT 75 °C)

Stator resistance	R_s	0.022 Ω
Rotor resistance	R_r	0.009 Ω
Short-circuit inductance	L_{cc}	118 μH
Stator leakage inductance (*)	L_{ls}	82 μH
Rotor leakage inductance (*)	L_{lr}	36 μH
Magnetizing inductance	M	0.955 mH
Iron losses equivalent resistance	R_{fe}	30.5 Ω
Inertia	J	0.25 kgm^2

current for the three-phase converter as reference. The converter efficiencies for the six-phase and three-phase power electronic topologies at the supply frequencies 75, 150, and 300 Hz and variable motor loads are shown in Figs. 17–19. The simulation results show that there are no significant differences in the efficiency performance between the six-phase and three-phase converters.

V. CONCLUSION

This paper presents the efficiency analysis and comparison of three-phase and DTP induction motor drives fed by PWM VSI. The proposed comparison uses a high frequency, DTP induction motor prototype developed for low/medium power applications. The comparison should be performed at the same dc bus voltage and deliver the same power (three-phase currents about two times the DTP ones). To avoid the design and realization of two dedicated prototypes, the comparison was carried out using an induction machine operating either with a three-phase or DTP winding configuration, under the same magnetic and mechanical conditions.

The efficiency results for the three-phase and the six-phase converter were obtained by means of a commercial simulation tool. The converter efficiencies were computed under the same working conditions of the motor in the experimental tests. Thus, the motor experimental results and the converter simulation results can be merged to obtain the drive efficiencies in different operating conditions for the three-phase and DTP cases. For the PWM drive under analysis, the motor and the converter efficiencies in both the three-phase and DTP drives are similar; the difference is in the range of 1%, which is the range of the measured/simulated data uncertainties.

In spite of a meaningful reduction of the stator copper loss, the total efficiency of the two machines is quite close; this fact depends on the balance between the iron loss and the joule loss. Since the iron losses should be the same for both machines, the impact of the iron losses makes the stator copper loss reduction in a “high” frequency machine such as the prototype under test less evident.

In conclusion, for drives similar to those presented in this paper, the efficiency is not a discriminatory parameter in evaluating the performances and the advantage/disadvantages of three-phase and DTP induction motor drives fed by PWM VSI. Advantages could be expected with the dual machine in situations where the joule losses are much larger than the iron losses, such as in 50/60 Hz applications.

TABLE IV
THREE-PHASE MACHINE PARAMETERS (AT 75 °C)

Stator resistance	R_s	0.045 Ω
Rotor resistance	R_r	0.017 Ω
Short-circuit inductance	L_{cc}	232 μH
Stator leakage inductance (*)	L_{ls}	160 μH
Rotor leakage inductance (*)	L_{lr}	72 μH
Magnetizing inductance	M	1.7 mH
Iron losses equivalent resistance	R_{fe}	57.4 Ω
Inertia	J	0.25 kgm^2

(*)The split between stator and rotor leakage inductances is computed on the basis of the design data.

TABLE V
MACHINE DESIGN DATA

Stator outer diameter	D_{so}	330 mm
Stator inner diameter	D_{si}	273 mm
Rotor outer diameter	D_{ro}	272 mm
Rotor inner diameter	D_{ri}	230 mm
Magnetic core length	L_{mc}	55 mm
Stator slots (trapezoidal - open)	N_s	72
Rotor slots (trapezoidal - open)	N_r	90
Rotor cage		Copper
Stator windings		Full pitch
Cooling		water

APPENDIX

The prototype is a 10-kW 40-V 200-Hz 12-poles full-pitch DTP induction machine. The measured parameters for six-phase and three-phase configurations are given in Tables III and IV, respectively, for a temperature of 75 °C. The motor design data are given in Table V.

The power electronic devices chosen for the DTP and three-phase dedicated inverter design solutions used for converters efficiency comparison are:

- 1) Six-phase inverter: SKM100GBO63D—IGBT power module, 100 A, 600 V.
- 2) Three-phase inverter: SKM200GBO63D, IGBT power module 200 A, 600 V.

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