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 pulsedwidth 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, pulsedwidth 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 pulsedwidth 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...
Fig. 1. DTP induction machine.

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

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 \((\alpha, \beta)\) 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 \((\alpha, \beta)\) pair leads to electromechanical energy conversion while the second stator-rotor \((\mu_1, \mu_2)\) pair does not. It can be shown that the supply harmonics of the order \(12n \pm 1\) \((n = 1, 2, 3, \ldots)\) map into the \((\alpha, \beta)\) subspace, while the harmonics of the order \(6n \pm 1\) \((n = 1, 3, 5, \ldots)\) map into \((\mu_1, \mu_2)\) subspace [10]. For ideal sinusoidal supply, the \((\mu_1, \mu_2)\) 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 \((\alpha, \beta)\) subspace is identical (with different parameter values) with the equivalent circuit of the three-phase machine (Fig. 3).
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 $k = 6 \cdot n \pm 1$, ($n = 1, 3, 5, \ldots$), 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 ($\mu_1$, $\mu_2$) 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 ($\mu_1$, $\mu_2$) 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 ($\alpha$, $\beta$) subspace (according to the desired flux and torque); and 2) to have a zero average voltage vector in the ($\mu_1$, $\mu_2$) 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 DZSI approach is the extension to the six-phase case of the three-phase zero-sequence injection technique [16]. Thus, 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 in the ($\alpha$, $\beta$) 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 ($\mu_1$, $\mu_2$) 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 configurations, 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.

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 ($V_{3Φ} \approx 1.95V_{6Φ}$). 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,
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.

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.
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].

### TABLE II

<table>
<thead>
<tr>
<th>Load torque [Nm]</th>
<th>75 Hz fundamental frequency test</th>
<th>150 Hz fundamental frequency test</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>4.2 %</td>
<td>5.9 %</td>
</tr>
<tr>
<td>45</td>
<td>6.9 %</td>
<td>7.2 %</td>
</tr>
<tr>
<td>35</td>
<td>6.9 %</td>
<td>6.4 %</td>
</tr>
<tr>
<td>25</td>
<td>5.3 %</td>
<td>6.4 %</td>
</tr>
</tbody>
</table>

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 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 ºC)  
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator resistance Rs</td>
<td>0.045 Ω</td>
</tr>
<tr>
<td>Rotor resistance Rs</td>
<td>0.017 Ω</td>
</tr>
<tr>
<td>Short-circuit inductance Lsc</td>
<td>232 μH</td>
</tr>
<tr>
<td>Stator leakage inductance (θ) Lθ</td>
<td>160 μH</td>
</tr>
<tr>
<td>Rotor leakage inductance (θ) Lθ</td>
<td>72 μH</td>
</tr>
<tr>
<td>Magnetizing inductance M</td>
<td>1.7 mH</td>
</tr>
<tr>
<td>Iron losses equivalent resistance Rs</td>
<td>57.4 Ω</td>
</tr>
<tr>
<td>Inertia J</td>
<td>0.25 kgm²</td>
</tr>
</tbody>
</table>

TABLE IV  
THREE-PHASE MACHINE PARAMETERS (AT 75 ºC)  
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator outer diameter Dso</td>
<td>330 mm</td>
</tr>
<tr>
<td>Rotor outer diameter Dso</td>
<td>273 mm</td>
</tr>
<tr>
<td>Rotor inner diameter Dsi</td>
<td>272 mm</td>
</tr>
<tr>
<td>Rotor inner diameter Dsi</td>
<td>230 mm</td>
</tr>
<tr>
<td>Magnetic core length Lmnc</td>
<td>55 mm</td>
</tr>
<tr>
<td>Stator slots (trapezoidal - open) Ns</td>
<td>72</td>
</tr>
<tr>
<td>Rotor slots (trapezoidal - open) Ns</td>
<td>90</td>
</tr>
<tr>
<td>Rotor cage</td>
<td>Copper</td>
</tr>
<tr>
<td>Stator windings</td>
<td>Full pitch</td>
</tr>
<tr>
<td>Cooling</td>
<td>Water</td>
</tr>
</tbody>
</table>

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.

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