Analysis of a Novel Stator Winding Structure Minimizing Harmonic Current and Torque Ripple for Dual Six-Step Converter-Fed High Power AC Machines

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Abstract: Many attempts have been made to expand the application of AC drives to high power levels. One way to use AC drives at high power levels is to use multiple power converters together to supply power to a large machine. For a multiple converter combination scheme, the six-step converter is competitive due to its robust structure and simplicity of control. In our previous study, an AC drive with dual stator windings fed by dual six-step converters was proposed. Two sets of electrically isolated windings are placed in the stator slots, and one set is shifted from the other by 30° in space. Two converters are used to power the dual windings, and the phase voltages from the two converters are also shifted 30° from each other in time. The 5th and 7th harmonics of the airgap flux and rotor currents are reduced dramatically, and the output torque from the drive is superior to that of the drive which is singly fed from a six-step converter. However, for each individual six-step converter, the 5th and 7th harmonic currents are found to be substantial and the functioning of the power converter is evidently deteriorated. In this paper, we propose a novel stator winding structure and control strategy to solve the converter problem. Principles associated with the new stator winding are discussed and a practical implementation presented.

I. Introduction

The advantages of using variable speed AC drives to replace variable speed DC drives in the low and medium power ranges have been widely recognized. However, at high power levels, the application of AC drives is limited. This limitation occurs mainly because 1) for high power drive applications, reliability is very critical, demanding a complicated and expensive system structure; 2) high power semiconductor devices are expensive; and 3) high power semiconductor devices with fast switching capability are not readily available so that high switching frequency, high power rating PWM may not be possible[5];this directly affects the performance of the drive. Many attempts have been made to expand the application of AC drives to high power levels [1,2]. One feasible configuration is to use multiple power converters, where the individual converters are small and simple in structure, to power a large machine. Compared to a single, full rating converter with large capacity, the multiple, small rating converter combination displays potential of low cost and high reliability. In addition, multiple operational modes and flexible control of the constructed systems are also very attractive [1].

For the multiple converter combination scheme, the six-step or quasi-six-step converter is very competitive because of its robust structure and ease of control. In addition, the switching frequency of a six-step converter is so low that the GTO devices of large capacity are readily available [3,4].

In our previous study, an AC drive, as shown in Fig. 1, with dual stator windings fed from dual six-step converters was proposed [1]. Two sets of electrically isolated windings are placed in the stator slots, and one set is shifted from the other by 30° in space. Two converters are used to power the dual windings. The phase voltages from the two converters are also shifted 30° from each other in time. Computer simulation shows that the airgap flux created by the 5th and 7th harmonic currents, and the harmonic rotor currents, are reduced dramatically in the proposed machine. In terms of torque ripple, the output torque from the proposed drive is superior to that of the drive which is singly fed from one six-step converter. However, we also found that for each individual converter, the 5th and 7th harmonic currents are substantial, reaching 110% and 60% of the fundamental current respectively. The peak value of the converter current is almost three times that of the fundamental component. In such a situation, the functioning of the power converters is evidently deteriorated [1].

In this paper, the causes of the degraded converter current are studied. Then, we propose a novel structure of dual stator windings and corresponding control strategy to solve the converter current problem. Principles associated with the new stator winding are discussed in detail and a practical implementation is presented. Furthermore, the significance and potential of the proposed winding structure for high power, AC drive application is fully addressed. The content of the paper is organized as follows. In Section II, the features and governing equations of the doubly-fed dual winding AC drive system in [1] are briefly reviewed. In Section III, we discuss the principles related to torque improvement and converter current deterioration for the doubly-fed dual winding drive system. The possible solution to the converter current problem by mutual inductance is included in this section. A novel, yet practical, implementation of the mutual inductance is presented and calculated. Computer simulation results for various operational conditions are presented in Section IV.

II. System Structure and Operational Principle

The schematic description of the system under discussion in this paper is shown in Figure 1. The fundamental feature of the system is that two sets of windings are equipped in the stator of the electric machine and two simple 6-step identical power modules are used in the power converter. The stator core of the electric machine is standard for an induction or synchronous machine. The two sets of three phase stator windings are identical in connection and electrically isolated from each other. Also, the two sets of windings are displaced by a phase angle, θ_s, along the stator inner circumference. The rotor is a typical cage style for induction machine operation.

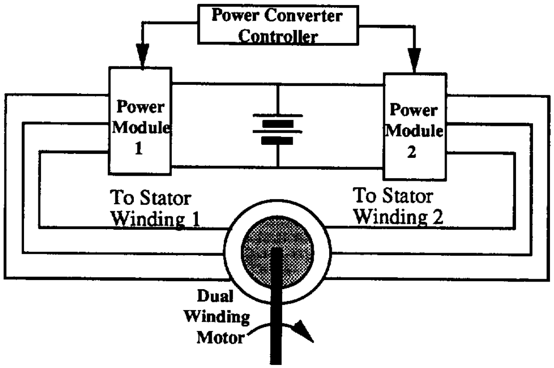

Fig. 1 Schematic description of the proposed drive system

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Under the well-known *d-q-n* transformation, the equations describing the machine dynamics are of the standard form:

$$\underline{v}_{dq1} = r_1 \underline{i}_{dq1} + \frac{d\underline{\lambda}_{dq1}}{dt} + \underline{\omega} \times \underline{\lambda}_{dq1} \tag{1}$$

$$\underline{v}_{dq2} = r_2 \underline{i}_{dq2} + \frac{d\underline{\lambda}_{dq2}}{dt} + \underline{\omega} \times \underline{\lambda}_{dq2} \tag{2}$$

$$\underline{v}_{dqr} = r_r \underline{i}_{dqr} + \frac{d\underline{\lambda}_{dqr}}{dt} + (\underline{\omega}-\underline{\omega}_r) \times \underline{\lambda}_{dqr} \tag{3}$$

where $$\underline{v}_{dq1}=\begin{pmatrix} v_{d1} \\ v_{q1} \\ v_{n1} \end{pmatrix}, \qquad \underline{i}_{dq1}=\begin{pmatrix} i_{d1} \\ i_{q1} \\ i_{n1} \end{pmatrix},$$

$$\underline{\lambda}_{dq1} = \begin{pmatrix} l_{d1} \\ l_{q1} \\ l_{n1} \end{pmatrix}, \qquad \underline{\omega} = \begin{pmatrix} 0 & -\omega & 0 \\ \omega & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix},$$

$$\underline{v}_{dq2}=\begin{pmatrix} v_{d2} \\ v_{q2} \\ v_{n2} \end{pmatrix}, \quad \underline{i}_{dq2}=\begin{pmatrix} i_{d2} \\ i_{q2} \\ i_{n2} \end{pmatrix}, \quad \underline{\lambda}_{dq2} = \begin{pmatrix} \lambda_{d2} \\ \lambda_{q2} \\ \lambda_{n2} \end{pmatrix}$$

$$\underline{v}_{dqr}=\begin{pmatrix} v_{dr} \\ v_{qr} \\ v_{nr} \end{pmatrix}, \qquad \underline{i}_{dqr}=\begin{pmatrix} i_{dr} \\ i_{qr} \\ i_{nr} \end{pmatrix},$$

$$\underline{\lambda}_{dqr} = \begin{pmatrix} \lambda_{dr} \\ \lambda_{qr} \\ \lambda_{nr} \end{pmatrix}, \quad \underline{\omega} - \underline{\omega}_r = \begin{pmatrix} 0 & \omega-\omega_r & 0 \\ -\omega+\omega_r & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix},$$

and "x" represents the vector cross product of $\underline{\omega}$ and $\underline{\lambda}_{dqns}$. Also, the flux linkages are related to the currents, in matrix form,

$$\underline{\lambda}_{dq1} = \underline{L}_{dq1} \underline{i}_{dq1} + \underline{L}_{dq12} \underline{i}_{dq2} + \underline{L}_{dq1r} \underline{i}_{dqr}$$

$$\underline{\lambda}_{dq2} = \underline{L}_{dq2} \underline{i}_{dq2} + \underline{L}_{dq12} \underline{i}_{dq1} + \underline{L}_{dq2r} \underline{i}_{dqr}$$

$$\underline{\lambda}_{dqr} = \underline{L}_{dqr} \underline{i}_{dqr} + \underline{L}_{dq1r} \underline{i}_{dq1} + \underline{L}_{dq2r} \underline{i}_{dqr}$$

wherein $$\underline{L}_{dq1}=\begin{pmatrix} L_{d1} & 0 & 0 \\ 0 & L_{q1} & 0 \\ 0 & 0 & L_{l1} \end{pmatrix}, \quad \underline{L}_{dq2}=\begin{pmatrix} L_{d2} & 0 & 0 \\ 0 & L_{q2} & 0 \\ 0 & 0 & L_{l2} \end{pmatrix},$$

$$\underline{L}_{dqr}=\begin{pmatrix} L_{dr} & 0 & 0 \\ 0 & L_{qr} & 0 \\ 0 & 0 & L_{lr} \end{pmatrix}, \quad \underline{L}_{dq12}=\begin{pmatrix} L_{d12} & 0 & 0 \\ 0 & L_{q12} & 0 \\ 0 & 0 & 0 \end{pmatrix},$$

$$\underline{L}_{dq1r}=\begin{pmatrix} L_{d1r} & 0 & 0 \\ 0 & L_{q1r} & 0 \\ 0 & 0 & 0 \end{pmatrix}, \underline{L}_{dq2r}=\begin{pmatrix} L_{d2r} & 0 & 0 \\ 0 & L_{q2r} & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

The torque equation of the machine under the transformation becomes

$$T_e = \frac{3}{2}\frac{p}{2} \left[\lambda_{dr}(i_{q1}+i_{q2}) - \lambda_{qr}(i_{d1}+i_{d2}) \right] \tag{4}$$

According to Eqs. (1) through (4), the single phase equivalent circuit of the dual stator winding induction machine in Fig. 2 can be derived for steady state operation [1].

Several very important points can be extracted from observation of the equivalent circuit:

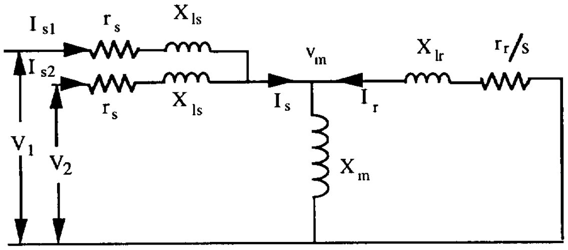

Fig. 2 Steady state equivalent circuit of the dual winding machine

1) If singly fed, the machine is a conventional induction machine, and all of the harmonic voltages generated by the power converter will tend to produce harmonic currents going through the magnetizing branch as well as the rotor circuit. As a result, both airgap flux and rotor current will contain substantial harmonics. Since the electromagnetic torque is the cross product of airgap flux by rotor current, torque ripple produced by the singly fed induction machine from the six-step converter is inevitable;

2) In the singly fed operation mode, the harmonic currents are driven by the harmonic voltages. These harmonic currents are limited by the leakage impedance of the stator and rotor windings;

3) If the machine is doubly fed by two identical voltage sources, the two voltage sources will input equal amounts of current to the stator windings and make equal contributions to the production of airgap flux;

4) If the machine is doubly fed by two voltages, equal in magnitude but out of phase by 180°, the two voltages will not be able to generate magnetizing current. This is equivalent to saying that the airgap flux generated by one voltage source will be canceled by the other. The currents will not be able to reach the rotor circuit either;

5) If the machine is doubly fed by two voltages out of phase by 180°, the current is driven by the two voltages jointly and limited only by stator leakage impedance and winding resistance. It can be expected that the magnitude of the current will be substantial although the current does not impact torque production.

In Section III, items 1) through 5) summarized above will be used as the guidelines to study the torque ripple reduction and converter current deterioration in the doubly fed dual winding induction machine drive system.

III. Converter Current Improvement

A. Torque Improvement and Converter Current Deterioration

In Fig. 1, two power converters are connected to a common DC bus to power the dual winding induction machine. In the six-step operation mode, voltage waveforms from each converter are shown in Fig. 3. Note that only the following characteristic harmonic voltages are present and of primary concern:

$$V_h = \frac{2E}{\pi}\frac{1}{6p\pm1}, \qquad p = 1, 2, 3, \ldots, \infty \tag{5},$$

where V_h is the magnitude of the 6p±1th harmonics and E is the DC bus voltage. It is clear that if the switching patterns are the same for both converters, the corresponding harmonics are of equal magnitude. It is also clear that for the machine under consideration, the most influential harmonic voltages will be in lower order, 5th and 7th for, for their relatively large magnitudes.

According to items 3) and 4) in the last section, we would like to have the fundamental voltages be in phase and the 5th and 7th harmonics out of phase by 180° in the equivalent circuit. In doing so, we can equally divide the required power between the two converters. On the other hand, the effects of the 5th and 7th harmonics are minimized to reduce torque ripple. Hence, the machine's performance will be close to that of a machine fed by sinusoidal voltages.

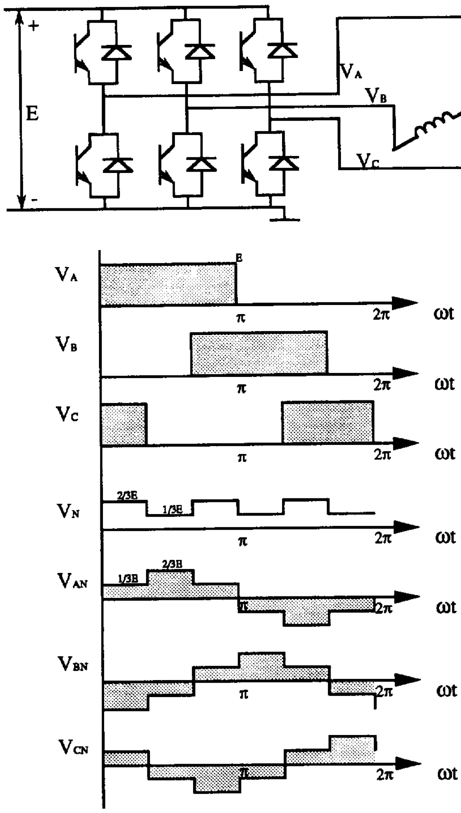

Fig. 3 Voltage waveforms for a six-step converter

Note that since the two sets of stator windings are placed 30° apart electrically in space, the phase angle between the two output voltages from the dual converters is also shifted by 30° in time. By *d-q-n* transformation, it is not difficult to prove that the two fundamental voltages in the equivalent circuit are in phase while the 5th and 7th harmonics are out of phase by 150° and 210° respectively. Therefore, the airgap flux produced by the fundamental voltages of the dual windings is enhanced while that produced by 5th and 7th harmonics are almost canceled. It is seen that we have achieved the desirable result described in item 3) and 4).

According to item 5) in the last section, although the 5th and 7th harmonic currents almost can not enter the magnetizing branch and the rotor circuit to produce airgap flux and torque, they can still circulate along an easy loop consisting of the two voltages and the two stator impedances. Along this loop the 5th and 7th harmonic currents are driven jointly by the respective harmonic voltages from both converters and limited only by the stator leakage reactance and winding resistance. Hence, the 5th and 7th harmonic currents become substantially large, compared with those in the singly fed case where the harmonic current is driven by one voltage and limited by both rotor and stator impedance.

B. Mutual Inductance for Converter Current Improvement

Increasing stator leakage inductance or winding resistance is an intuitive approach to suppress the converter harmonic currents. However, this approach will also unfavorably reduce the fundamental current and increase machine copper losses. In addition, the starting and pull-out torque of the machine will be decreased.

It is evident that we need to introduce another mechanism to improve the deteriorated converter current, and meanwhile, to maintain the fundamental current unchanged. An ideal solution would be to create an impedance in the equivalent circuit so that it is seen to be transparent by fundamental voltage and maximum by other major harmonics. Based on this consideration, a mutual inductor as shown in Fig. 4 is conceived and inserted into each phase of the stator windings. Expressing the h-th harmonic components of the two converter voltages as V_{1h} and V_{2h}, we can create the mutual coupling in such a way that the impedance is maximum if the voltages, V_{1h} and V_{2h} are out of phase completely (180°). When the phase angle between V_{1h} and V_{2h} decreases, the impedance decreases proportionally as well. Eventually, the impedance reaches zero and is seen to be transparent by V_{1h} and V_{2h} when they are in phase. To obtain the impedance as described above, the two coils of the mutual inductor should be polarized as shown in Fig. 4 and the coupling coefficient be unity ($L_1=L_2=M$). The principle of this mutual inductor is similar to that of an interphase inductor which is frequently used to combine power converters in parallel.

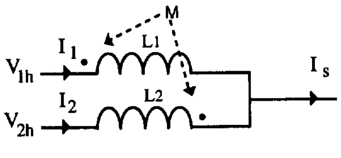

Fig. 4 Mutual inductor

Note that for the system shown in Fig. 1, the 5th and 7th harmonics of V_1 and V_2 have been shifted by 150° and 210° respectively from those of I_1. Therefore, the mutual inductors will be very effective in limiting the 5th and 7th harmonic currents for each individual converter when connected into the dual stator windings as suggested. The equivalent circuit in Fig. 2 can be modified to the form as shown in Fig. 5 to include the mutual inductor.

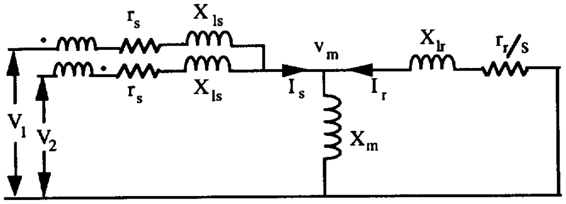

Fig. 5 Equivalent circuit of the proposed machine in steady state

If the coupling coefficient is unity, the equivalent circuit can be further modified to the form shown in Fig. 6. It is apparent that the mutual inductor has zero impedance to the in-phase voltages.

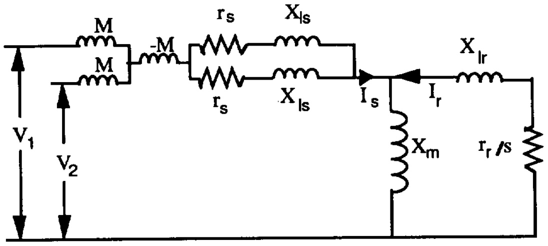

Fig. 6 Equivalent circuit of the proposed machine with ideal mutual inductance coupling

However, when the voltages are out of phase by 180°, the mutual inductor will build up a major flux and, thus, induce a large counter EMF to limit the current. Expressing the counter EMF as a voltage drop across a reactance, we can obtain the value of the reactance as

$$X_h = 2h\,\omega_e M \qquad (6)$$

where X_h is the reactance limiting h-th harmonic current (Ω),
M is the mutual inductance of two coils windings (H),
and ω_e is the fundamental angular frequency (rad/s).

The principle discussed in this section constitutes the core of the solution to minimizing 5th and 7th harmonics of the individual converter current.

C. Implementation of the Mutual Inductance

At first glimpse one may think that the addition of mutual inductors to the drive system would require additional components, and, thus, increase the cost substantially. However, our close study shows that the realization of the mutual inductance can be integrated into the machine design by modifying the end winding structure. As illustrated in Fig. 7, in the dual winding stator of the machine, the two sides of a coil are located in the slots which are approximately one pole pitch apart. The top and bottom conductors belong to Phase "A1" and the middle two conductors to Phase "A2". In such an arrangement, a magnetic ring can be used to couple the end part of the coils to create a mutual coupling. To control the degree of mutual coupling, the number of magnetic rings can be selected from one to as many as two times the slot number. As indicated in the figure, the fundamental currents I_{A1} and I_{A2} will not see the impedance created by this mutual coupling. For the 5th and 7th harmonics of I_{A1} and I_{A2}, the impedance is maximized.

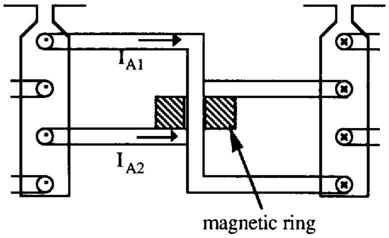

Fig. 7 Mutual inductance realized in the machine

To illustrate the effectiveness of the new end winding structure for mutual inductance purposes, a case calculation is presented in the following example. The machine specifications are given in Table 1.

Table 1

Power rating	100 hp	r_s	0.17	ohms
Rotor speed	3500 rpm	X_{ls}	0.6	ohms
Rated torque	200 n.m	X_{lr}	0.3	ohms
J 3.67	kg.m^2	X_m	13.08	ohms
		r_r	0.23	ohms

For each magnetic ring, the inductance can be expressed as

$$L = n^2 \frac{\mu_0 \mu_r A}{\ell}; \qquad (7)$$

where L is the self inductance of one coil created by one magnetic ring,
n is the number of turns in each coil,
μ_r is the relative permeability,
A is the cross section of the magnetic ring,
ℓ is the effective circumference length of the magnetic ring.

Ideally, the mutual inductance M for each magnetic ring is equal to the self inductance L. That is,

$$M = L = n^2 \frac{\mu_0 \mu_r A}{\ell}; \qquad (8)$$

If we choose the practical values below in the sample calculation

$n = 4$
$A = 100$ mm^2
$\ell = 65$ mm
$\mu_r = 1500$

Then we have

$$M = 44 \quad \mu H \qquad (9)$$

The maximum mutual inductance for one phase winding is

$$M_{max} = \frac{2s\,M}{\#\text{ of phases}} = 1.06 \text{ mH} \qquad (10)$$

where "s" is 36, the number of the stator slots. The maximum reactance to limit the 5th and 7th harmonic current can be found by Eq. (6)

$$X_5 = 10\omega_e M = 4 \text{ ohms} \qquad (11)$$
$$X_7 = 14\omega_e M = 5.6 \text{ ohms} \qquad (12)$$

Comparing the results from Eqs. (11) and (12) to the magnetizing reactance of this machine, 13.08 ohms, it is very clear that the desired mutual inductance is achieved effectively. Furthermore, we can always control the value of mutual inductance between M_{max} and zero by selecting the right number and/or dimensions of the magnetic rings.

IV. Computer Simulation Results

The principles and implementation of using mutual inductance to improve converter current presented above have been examined by computer simulation for several cases. In the computer simulation, the dual winding machine as described in Table 1 and its dynamic model derived in [1] are used. Different values of mutual inductance have been used in the computer simulation.

In case 1, the dual winding induction machine is singly powered by dual converters in order to examine the power sharing capability of the converters and the performance of the machine. The switching of the dual power converters is synchronized. Fig. 8 shows the output current through the converters and the rotor winding. The RMS and the peak values of the converter current are also calculated and shown in the same figure. The spectrum analysis of the current is shown in Fig. 8, and higher harmonics beyond 15th are neglected due to their small magnitudes and impact on the torque production. The electromagnetic torque, a critical performance characteristics of the machine, is included in this figure. It is clear that the machine has a very large torque ripple due to the existence of the 5th and 7th harmonic currents through the rotor winding and the magnetizing branch. Inspecting the peak and the RMS values of the currents in each individual converter, we can

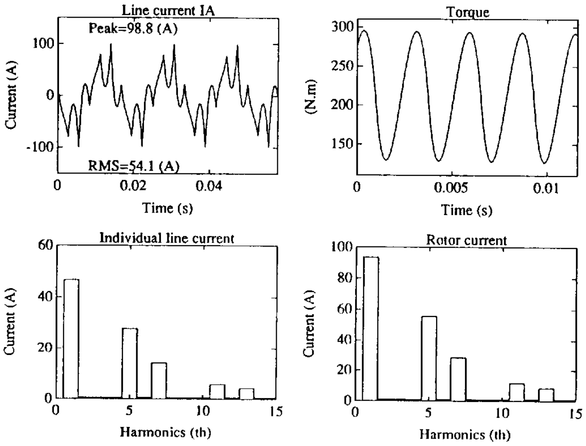

Fig. 8 Simulation result of case 1

see that the rating of each converter must be greater than half the rating of the machine to accommodate the highly distorted current. Large rating power devices in each converter must be utilized because of the large peak current through them. The machine performance is not satisfactory because of the torque ripple and iron losses associated with the 5th and 7th harmonic current generated airgap flux.

In case 2, two sets of electrically separated windings are fed from two six-step converters. The currents, the current spectrum and the torque are plotted in Fig. 9. In this case, two windings are shifted by 30 degrees in space and the voltages from each converter are shifted by 30 degrees in time. It is noticeable that the torque ripple is very small, and the 5th and 7th harmonic currents through the rotor windings are much smaller compared to those in case 1. However, for each individual converter, the 5th and 7th current harmonics increase dramatically, resulting in very large RMS and peak values. The results actually verified the important points obtained in Section II. In effect, the torque performance is improved at the expense of deteriorated current in each converter. According to the simulation, each converter has to be rated, at least, at 0.78 rated power of the machine. The power devices in each converter must sustain a peak value of current at least three times that of the fundamental current. Obviously, under such an operational condition, the advantages of using multiple, small rating, low cost converters in place of a single full rating, expensive converter are questionable.

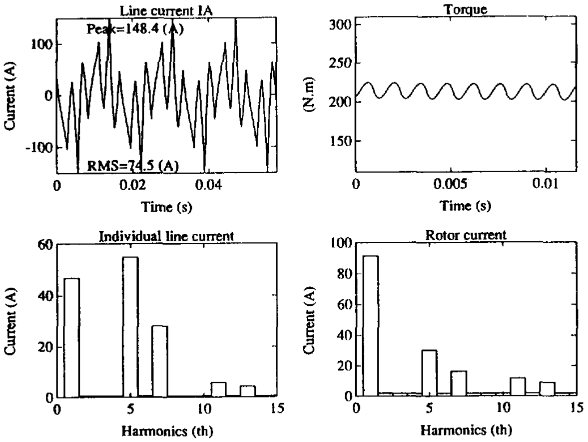

Fig. 9 Simulation result of case 2

In case 3, a small mutual inductor (0.03 p.u.) representing the mutual coupling of the end winding as shown in Fig. 7 is included in the machine. The simulation results are plotted in Fig. 10. The results from case 3 show that the operational condition of each converter is improved significantly. The 5th and 7th harmonics in each individual converter are reduced to almost half compared to that in case 2. The 5th and 7th harmonic currents through the rotor winding decrease at the same time. From the peak and the RMS value calculations, we can see that the required rating of each converter and its power devices are much smaller compared to those in case 2.

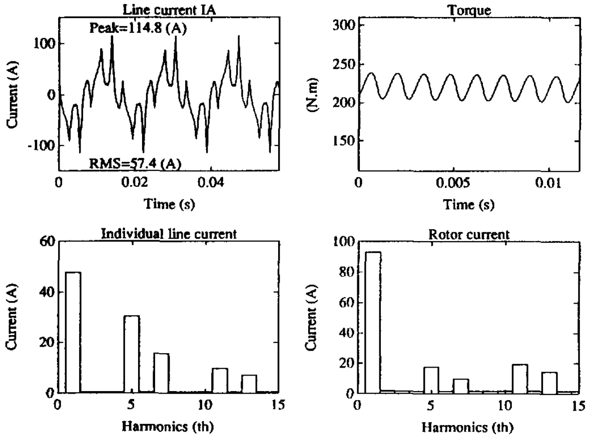

Fig. 10 Simulation result of case 3

For sake of comparison, in case 4 a larger value of mutual inductance (0.13 p.u.) is used and the simulation results are plotted in Fig. 11. Results from case 4 indicate that the operational conditions for converters and machine have been further improved. This result is achieved by selecting a proper number of magnetic rings to enhance the desired mutual coupling discussed in Section III.

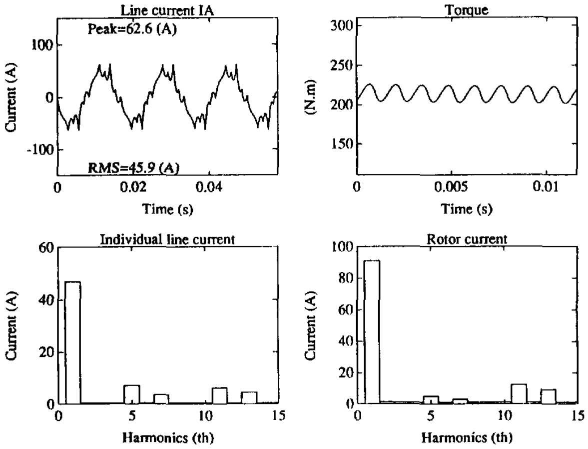

Fig. 11 Simulation result of case 4

V. Conclusions

In this paper, we have studied the causes of degraded converter current when dual six-step converters feed a dual winding induction machine drive in detail. Then, we proposed a novel end winding structure and corresponding control strategy to solve the converter current problem while retaining the advantages of the dual winding induction machine drive. Principles associated with the new stator winding are discussed, and a practical implementation is presented. Computer simulation is used to verify the theoretical analysis. The following conclusions have been reached:

1. High power, high performance AC machine drives can be achieved by using the dual winding, dual six-step converter configuration proposed in this paper.

2. The mutual inductance plays a critical role in improving the performance of the entire system, including the machine as well as the converters.

3. The mutual inductance is realized by the integrated machine design with novel winding structure proposed in this paper. Compared to the interphase inductance, the cost of the implementation is minimum and the performance is improved.

In effect, the induction machine discussed in this paper can be regarded as an induction machine with a built-in filter to minimize both converter harmonic current and machine torque ripple. Although we have only used dual six-step converters to illustrate the concepts, these concepts are not restricted to the six-step switching algorithm. For any low switching frequency, high rating PWM converter powered variable speed drives, the configuration studied in this paper is very attractive. Fabrication of a scale model of the analyzed system is in progress at The Ohio State University and results will be reported in the near future.

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