A New Breed of Electric Machines - Basic Analysis and Applications of Dual Mechanical Port Electric Machines

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Abstract - Conceptually, mechanical port of an electric machine can be doubled and the concept of dual-mechanical-port (DMP) will then give birth to a new breed of electric machines. In this paper, the various possible structures of DMP electric machine are discussed. Basic modeling and analysis issues related to the DMP electric machine are presented. An exemplary design of DMP machine is given and verified by FEM results. Potential applications and future research work are given to conclude the paper.

Keywords: electrical machines, dual rotors, doubly excited, dual mechanical port

1. Introduction

Any electric machine, DC or AC, is considered as a physical device to accomplish electromechanical energy conversion. In this regard, an electric machine is described as a coupled electromagnetic field with one electrical and one mechanical port [1]. As shown in Fig. 1, the electrical port of a conventional electric machine is characterized by its terminal voltages and currents while the mechanical port its shaft speed and torque. This is the traditional single-in and single-out port configuration.

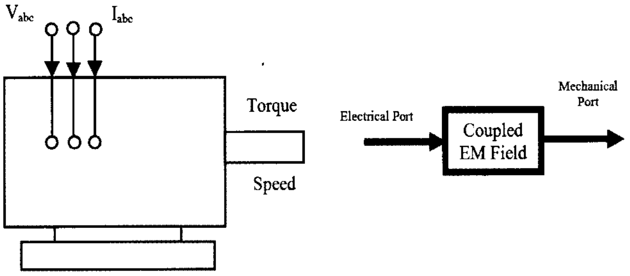

Fig. 1 Conventional Electric Machine

A single-in and -out port electric machine sometimes can be designed in a doubly excited configuration, resulting in a doubly-fed electric machines. The doubly fed electric machine is quite attractive for high-power variable-speed applications where special operation mode and high energy efficiency is needed, such as those used in wind power generation. A doubly fed electric machine is illustrated in Fig. 2 (a). Conceptually, the mechanical port of an electric machine can also be doubled and the concept of dual-mechanical-port (DMP) will then give birth to a family of new electric machines. The concept of electric machine with dual mechanical ports is illustrated in Fig. 2 (b).

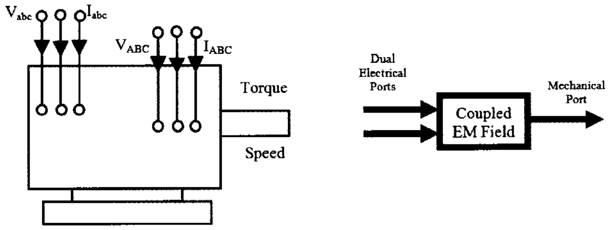

Fig. 2 (a) Doubly Excited Electric Machine

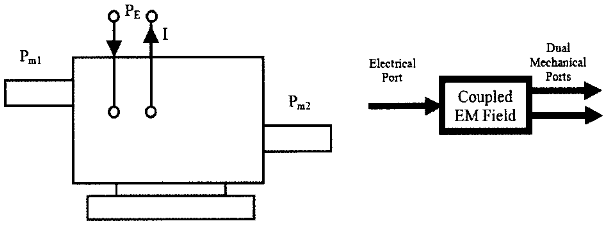

Fig. 2 (b) Conceptual Electric Machine with Dual Mechanical Shafts

In this paper, various possible structures of a DMP electric machine will be explored and operation features discussed. Further, the modeling and analysis issues related to the DMP electric machine are to be investigated. To fully illustrate operational features, explore design and analysis principles, and discuss application potentials, an exemplary design of DMP machine is given and verified by FEM results.

2. Structure and Operational Principles

A basic structure of a DMP electric machine can be illustrated by its cross-section as shown in Fig. 3. As shown, a DMP electric machine typically has three basic

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parts, separated by two air-gaps and magnetically coupled. In general but not necessarily, the three parts can all equipped with windings mutually coupled through magnetic flux lines. For example, Parts #1 and #2 share the same magnetic flux lines with the same pole numbers and, when in operation, the 2 magnetic fields from Parts #1 and #2 are synchronized. Similar magnetic coupling between Parts #2 and #3 is also required. In addition, the following important features can be identified in a DMP machine:

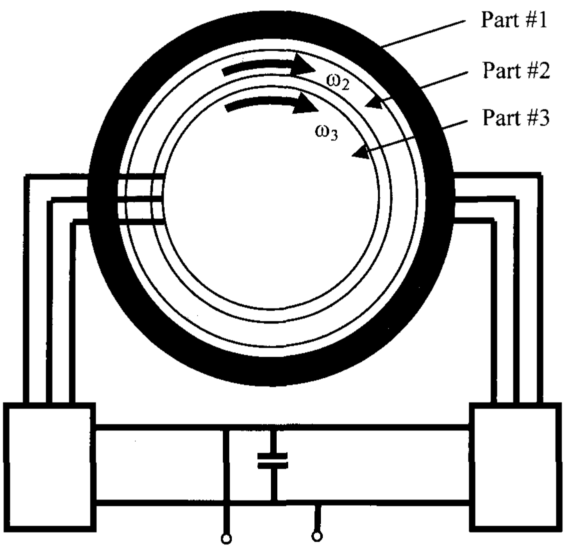


Fig. 3 Basic structure of DMP electric machine

a) Among the three parts, at least two will be allowed to move mechanically, constituting the two mechanical ports, characterized by none-zero mechanical torque and speeds at the port.
b) The two mechanical movable parts or mechanical ports can be assigned arbitrary among the three.
c) The stationary part of the three will have to have electrical terminals as the electrical port.
d) The middle part is sandwiched by the inner and outer air-gaps, both contributing electromagnetic torque to the piece; hence, the overall electromagnetic torque of the center part is the sum from both inner and outer air-gap.
e) As the dual mechanical ports the two moving parts are linked to and have external independent mechanical speeds and torque that are determined by the external loads or engine connected.
f) Depending on the speed of a moving part relative to the rotating field, electrical terminals may be also needed on the moving part so that the energy flow is balanced not only for the overall machine but also for each individual part.

In Table 1, various possible moving part assignments are listed and their speeds are specified. In all cases, the machine is a DMP, or a so-called dual-rotor electric machine.

Table 1 Possible moving part assignment of DMP

	Case 1		Case 2		Case 3	
Part #1	$\omega_1=0$	stator	$\omega_1>0$	rotor	$\omega_1>0$	rotor
Part #2	$\omega_2>0$	rotor	$\omega_2=0$	stator	$\omega_2>0$	rotor
Part #3	$\omega_3>0$	rotor	$\omega_3>0$	rotor	$\omega_3=0$	stator

Let us examine Case 1 where Part #1 is stationary (stator), and the other two rotating (rotors). It is especially interesting to investigate the operation modes with relative speeds between the 2 rotors. Three operating conditions discussed below:

i) If $\omega_2=\omega_3$, the two rotors are of the same speed and no relative speed between the 2 rotors and, thus, no relative speed EMF induced in the windings on the 2 rotors. In this condition, no electromechanical energy flow involved between the 2 rotors and equivalently we can treat the 2 rotors sticking together as one and the machine essentially is simply a conventional single-rotor machine with 2 shafts.
ii) If $\omega_2>\omega_3$ or $\omega_2<\omega_3$, in either condition, there is a slip between the two rotors. To have meaningful torque interactions between the 2 rotors, one of the rotors has to be excited with the slip frequency so that the 2 magnetic fields of the rotors are synchronized. If we decide to compensate Part #3 (inner rotor), then the inner rotor will need excitation windings with a slip electric frequency (relative to outer rotor) plus the frequency of the outer rotor. The energy flow through the winding is proportional to the slip between the two rotors.
iii) The energy flows through the excited rotor due to slip may be negative or positive depending on whether the slip is positive or negative.
iv) The excitation of slip frequency can also be done through excitation control over the outer rotor with the inner rotor as the reference base. In such a case, the slip frequency excitation will be applied to the winding terminals on the outer rotor.
v) In either slip compensation conditions, additional control can be given to the stator through the stator terminals to affect the overall electromechanical energy flow of the machine.
vi) In addition to the electric port, the external mechanical energy flow are always allowed to be input/output independently to the 2 mechanical ports (shafts) and the only law to observe for the DMP machine is energy conservation.

We can observe that in terms of electromechanical energy flow, Condition i) is identical to that of a conventional electric machine with a single-in and -out ports; that is, the energy flow-in or -out from the single electrical port always equals to that of the single mechanical port (neglecting losses). However, for other conditions discussed in ii), the analysis becomes much complicated since we have three ports involving in energy flow in the DMP machine. Overall, the energy flow is balanced. However, depending on the energy flow directions among the dual mechanical ports and electric port, the operation modes are very versatile.

For only Case 1 in Table 1, we have presented many possibilities of operation modes. For Cases 2 and 3, another array of operation modes can be obtained, using similar methods in analysis. Though all possible structures and operation modes are equally interesting in theory, it is the specific application objectives that dictate the choice of one over the rest.

3. An Exemplary Design and Analysis

3.1 DMP machine structure

Fig. 4 shows an exemplary design of a DMP machine of 4 poles. The outmost cylinder is chosen as the stator with 3 phases of windings installed, acting as the pure electrical port, and the dual rotors the other 2 cylinders inside.

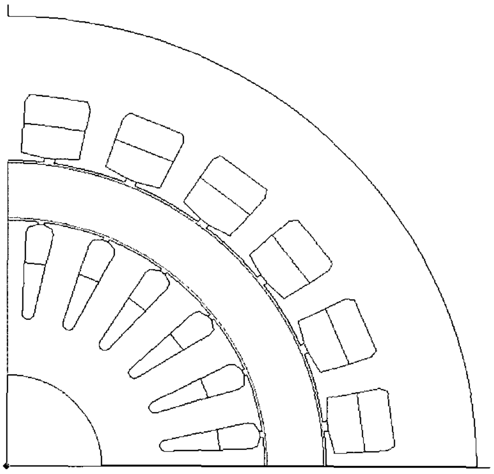


Fig. 4 Exemplary design of DMP machine

We anticipate the 2 rotors with different speeds in operation in general and choose the inner rotor as the slip power compensation port. So, the inner rotor will not only be one of the two mechanical ports but also part of the electrical port. The two electrical ports, one on the stator and the other the inner rotor, can share a common DC bus to form the single electrical port for the overall machine (as shown in Fig. 3). Since the outer rotor is the reference base for controlling slip power compensation, it does not need to have active excitation control, becoming a pure mechanical port. For that reason, we have used permanent magnets to build the outer rotor. The main dimensions and the winding specifications of the DMP are listed in Table 2.

Table 2 Main dimensions (in mm) and winding of DMP

	stator	outer rotor	inner rotor
OD	170	120	98
ID	121	99	35
# of turns	68	PM	68

3.2 Dynamic modeling and equivalent circuit

Because of several similarities between the DMP and a wound rotor doubly fed induction machine, we will present the DMP equivalent circuit based on that of a conventional doubly fed wound rotor induction machine. First, a brief review is in order of the steady state equivalent circuit of a wound rotor induction machine as shown in Fig. 5.

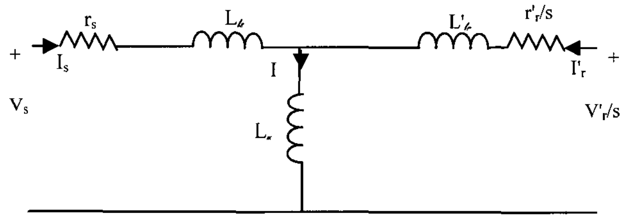


Fig. 5 Equivalent Circuit for Wound Rotor Induction Machine

In this equivalent circuit, the joint currents of the stator and rotor winding produce the air gap flux mutually coupling to both stator and rotor windings. Note that the conventional doubly fed induction machine has dual electric ports that are represented by the stator and rotor voltage terminals. The single mechanical port of the machine is represented by te element, r'_2/s, meaning that the power going through this virtual resistor is the converted power from electrical to mechanical, or vice versa. To be mentioned in the equivalent circuit is the factor of "1/s" on the rotor voltage. Here, "v_r" is the actually applied voltage (with stator-rotor turn ratio considered) to the rotor windings and the factor "1/s" accounts for the rotor speed difference referred to the synchronous rotating field. If the rotor is synchronized with the rotating field, "s" equals to zero, or else if the rotor standstill, "s" unity. For the new breed of DMP machine, we propose the equivalent circuit by adding a parallel connected current source I_{pm} to the magnetizing branch as shown in Fig. 6.

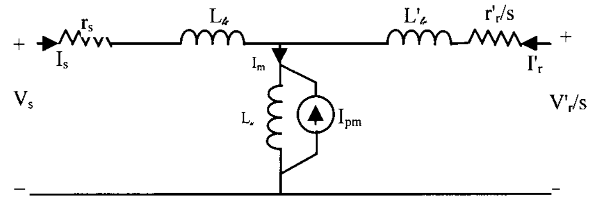


Fig. 6 Equivalent Circuit for DMP with PM Outer Rotor

To explain the modification of the equivalent circuit, we need to compare the electromagnetic structure of the DMP to that of the wound rotor doubly fed induction machine. If the DMP outer rotor were removed, or replaced by a piece of slid iron ring, the DMP essentially would have degenerated to a wound rotor induction machine. In other word, if the outer rotor were removed, the DMP machine would have become identically a wound rotor induction machine with a huge air gap. Not surprising, the equivalent circuit of a wound rotor induction machine applies to the DMP in this case except that the magnetizing inductance becomes very small because of the vastly enlarged air gap. Alternatively, if the polarized permanent magnet outer rotor of the DMP were replaced by a piece of none-polarized, none-salient, solid iron ring, the DMP also would have become a wound rotor induction machine since the solid iron ring is neither polarized nor salient - its mechanical rotation is not electromechanical energy related. Compared to the removal of the PM outer rotor to its replacement by a solid iron ring, the later makes the DMP air gap much smaller and therefore, much larger magnetizing inductance. As discussed in both cases where the DMP outer rotor were either removed or replaced, the equivalent circuit would have become that of a wound rotor induction machine.

However, if the PM outer rotor is placed in the air gap and rotating synchronously with the main field, the DMP magnetic structure changes very differently. First of all, the total magnetic field of the air gap is now contributed and driven by three MMFs, one from the stator excitation, another the inner rotor excitation, and the third the outer rotor permanent magnets. We can regard the above circuit an intermediate equivalent circuit to account for MMF contribution by the permanent magnets. In this intermediate circuit we have defined a current source I_{pm} to represent the function of the permanent magnets. Here the permanent magnets are described by a magnetizing current source, in parallel connection to the magnetizing branch of the wound rotor induction machine equivalent circuit. To qualify the permanent magnets in such a description we need to ensure that the permanent magnets are rotating synchronously with the main field and create magnetic flux linking to both the stator and rotor windings. Examining the magnetic structure of the DMP, it is clear the permanent magnet outer rotor satisfies the conditions. The magnitude of I_{pm} is directly proportional the magnetizing strength of the magnets.

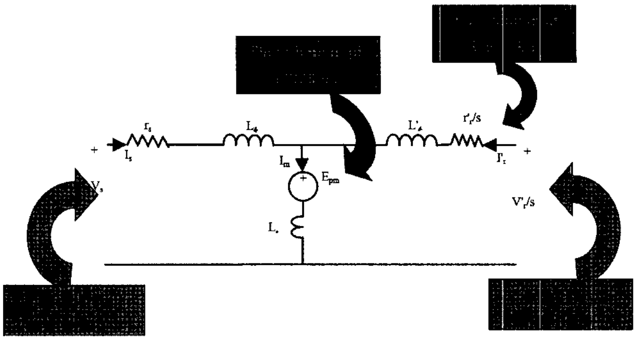


Fig. 7 Equivalent Circuit for DMP for Steady State

As we discussed in previous section, the outer PM rotor not only contributes to the main magnetic flux generation, but also acts as one of the dual mechanical ports of the DMP machine. To explicitly exhibit the role of the outer rotor in electromechanical energy conversion, we transform its current source representation into the voltage source counterpart by Thevine equivalent. Finally, the equivalent circuit of the DMP in Fig. 7 arrives with two electrical ports and two mechanical ports. Note that the voltage source embedded in the magnetic branch drives magnetic flux in the magnetizing branch. The joint currents from both the stator and rotor interact with the voltage source, resulting in the electromagnetic torque and power. The power represents the electromechanical power conversion through the outer rotor, the second mechanical port of the DMP machine once the equivalent circuit of the DMP machine is established, we can find the physical meaning and the relative size of each parameter as listed in Table 3.

Table 3 Parameters of DMP

R_1	0.27 ohms	I_{pm}	243 A
R_2	0.49 ohms	λ_m	0.374 wb
$L_1 = L_2 \approx L_m$	15.4×10^{-4} H	E_m	$\omega\lambda_m$

The transient model of the DMP is derived briefly and presented in [2]. The following are the major equations:

$$V^e_{qs} = i^e_{qs} r_s + \frac{d\lambda^e_{qs}}{dt} + \omega\lambda^e_{ds} \tag{1}$$

$$V^e_{ds} = i^e_{ds} r_s + \frac{d\lambda^e_{ds}}{dt} - \omega\lambda^e_{qs} \tag{2}$$

$$V^e_{qr} = i^e_{qr} r_r + \frac{d\lambda^e_{qr}}{dt} + (\omega - \omega_r)\lambda^e_{dr} \tag{3}$$

$$V^e_{dr} = i^e_{dr} r_r + \frac{d\lambda^e_{dr}}{dt} - (\omega - \omega_r)\lambda^e_{qr} \tag{4}$$

where

$$\lambda^e_{qs} = L_s i^e_{qs} + L_m i^e_{qr} \tag{5}$$

$$\lambda^e_{ds} = \lambda^e_m + L_s i^e_{ds} + L_m i^e_{dr} \tag{6}$$

$$\lambda^e_{qr} = L_r i^e_{qr} + L_m i^e_{qs} \tag{7}$$

$$\lambda^e_{dr} = \lambda^e_m + L_r i^e_{dr} + L_m i^e_{ds} \tag{8}$$

For the DMP, there are three torque equations

$$T_{e,stator} = \frac{3}{2}\frac{P}{2}(\lambda_m i_{qs} + \lambda_{dr} i_{qs} - \lambda_{qr} i_{ds}) \tag{9}$$

for the stator,

$$T_{e,pm-rotor} = \frac{3}{2}\frac{P}{2}\lambda_m (i_{qs} + i_{qr}), \tag{10}$$

for the PM rotor, and

$$T_{e,wd-rotor} = \frac{3}{2}\frac{P}{2}(\lambda_m i_{qr} + \lambda_{ds} i_{qr} - \lambda_{qs} i_{dr}) \tag{11}$$

for the wound rotor.

Note that the dynamic Eqs. (1) through (11) are all referred to the PM rotor reference frame, that is, the d-axis of the reference frame is aligned with that of the permanent magnet rotor.

3.3 Modes of operation

Utilizing the derived equivalent circuit and dynamic model, we can investigate the power flow and operation modes achievable by the DMP. Let us start to investigate the power flow through the stator windings. The power input or output through the stator terminals is purely electrical since the stator is stationary. Once the electrical power reaches to the stator terminal and continues across the air gap between the stator and PM rotor, it becomes electromechanical power to be handled by the outer rotor. Similarly, at the inner wound rotor, the electrical and mechanical power is combined and net amount goes across the air gap between the inner wound and outer PM rotors. The net power arrives on the outer PM rotor from the stator and inner rotor finally determines the net power in or out of the mechanical port of the outer PM rotor. The equation to illustrate the overall power balance of the DMP machine is (losses neglected):

$$\pm P_{e,\,\text{stator}} \pm P_{m,\,\text{pm-rotor}} \pm P_{e,\,\text{wd-rotor}} \pm P_{m,\,\text{wd-rotor}} = 0 \tag{12}$$

In the equation, the "±" indicate the power flow in or out. The first subscript "m" or "e" represents mechanical or electrical power related. The second subscript specifies if the power is related to the stator, outer PM rotor or inner wound rotor. As can be observed, this single equation is multi-variable based and theoretically, has infinite sets of mathematic solutions and each corresponds to one operation mode. In practice, of course, many physical constraints apply. Nevertheless, the appropriate solutions, each corresponding one operation mode, are much more than those of a single-in single-out conventional electrical machine. We will show several of the solutions to the equation and attempt to interpret application situations corresponding to them.

a. $+ P_{e,\,\text{stator}} - P_{m,\,\text{out-rotor}} - P_{m,\,\text{in-rotor}} \pm P_{e,\,\text{in-rotor}} = 0$

In this case, we input electrical power to the stator, and output mechanical power to both the inner and outer rotors. The inner wound rotor may a have lower or higher mechanical speed than that of the main field, and hence $\pm P_{e,\,\text{in-rotor}}$ will take care of the balance due to the slip of the inner wound rotor. In this case, we call the DMP machine as a power splitter because the input electrical power is splitted into and output from the 2 mechanical power ports. This is basically a motoring operation mode.

b. $- P_{e,\,\text{stator}} + P_{m,\,\text{out-rotor}} + P_{m,\,\text{in-rotor}} \pm P_{e,\,\text{in-rotor}} = 0$

Opposite to (a) we can change the signs of power related to the stator and rotors. That is, we input mechanical power from both rotors, and output electric power to the stator. The inner rotor is allowed to have a lower or higher speed than that of the main field, the $\pm P_{e,\,\text{in-rotor}}$ will take care of the balance due to the slip of the inner rotor. In this case, we can call the DMP machine as a power combiner because mechanical power is combined and converted into electrical power, mainly in the generating operation mode.

c. $- P_{m,\,\text{out-rotor}} + P_{m,\,\text{in-rotor}} = \mp P_{e,\,\text{stator}} \pm P_{e,\,\text{in-rotor}} = 0$

In this mode, additional constrain is imposed, that is, not only is (11) satisfied but also are the electrical and mechanical subset of the equations balanced and equal to zero. This is a so-call variable ratio gearbox operation mode in which we want the mechanical power balanced from both rotors but allow them to have different speeds. Since the two rotor speeds are different with the power equals to each other, the torques of the two rotors will be inversely proportional to the speeds. According to the equation, we need to involve in the stator and inner rotor electrical power in the process in such a way that they are also balanced. We may call the DMP machine functioning as a variable E-gearbox because we use electromechanical device to achieve variable gearbox results.

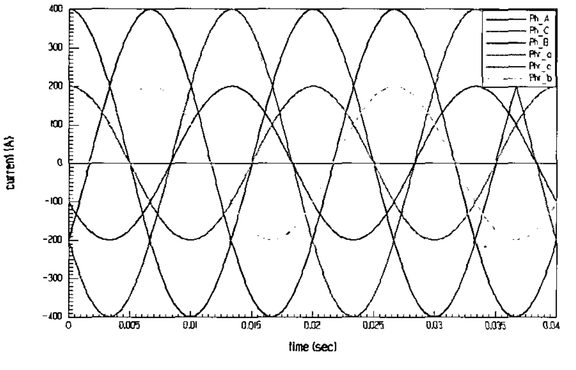
d. $-P_{m,\,\text{out-rotor}} + P_{m,\,\text{in-rotor}} = \mp P_{e,\,\text{stator}} \pm P_{e,\,\text{in-rotor}} = C$

Case (c) can be extended slightly from "0" to a constant "C", implying that the mechanical power of the two rotors is not completely balanced and the remaining can be absorbed by the electrical terminals and sent to the common DC bus, for example a battery bank, for energy storage or draining. This operation mode is very similar to a hybrid traction system for electrical vehicles.

We can derive many other modes of operation. In addition, if the rotating parts are assigned differently, we can derive another family of operation modes and versatility and flexibility of DMP machine is truly extraordinary.

3.4 Finite Element Analysis

In evaluating the electromagnetic design, Finite Element Analysis (FEM) is used to compute magnetic flux distribution, torque production, and controllability of the designed DMP machine. Shown in Fig. 8 (a) are the current waveforms in the stator and rotor windings. In order to focus on the DMP machine torque production, the windings of the stator are excited with 3 phase currents with a peak value of 10A and the windings of the inner rotor 5A. As expected and shown in Fig. 5 (b), when the 2 rotors are stationary and the 2 windings of the DMP are excited with sine currents, the torque production is also in sine function in time. The FEM result indicates that if the MMFs of both rotors are controlled in synchronization, a maximum and constant torque of 49 Nm will be achieved. Compared to AC machines of similar size, a DMP machine seems to be very impressive in torque production in addition to its highly flexible operational modes.



(a) Stator and inner rotor current

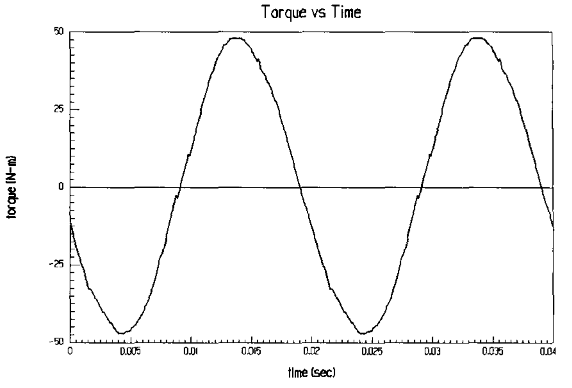


Fig. 8 (b) Torque production

Fig. 9 shows the magnetic flux distribution at the moment of maximum torque production.

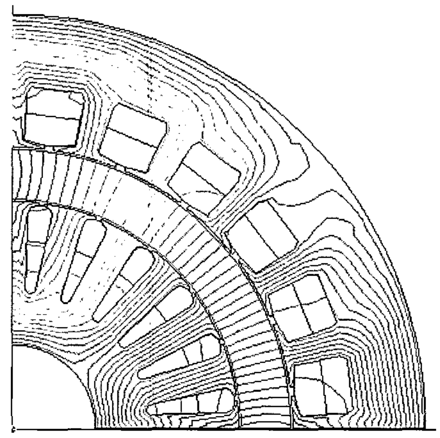


Fig. 9 Magnetic flux distribution

As indicated in the figure, the magnetic fields of the machine separated by the two air-gaps are unified; that is, the continuous flux lines go through both air-gaps and link all three parts, the cores of one stator and two rotors. The flux lines are driven by three sources, the stator MMF, the outer rotor permanent magnets, and the inner rotor MMF. In various conditions if the outer and inner rotors are of different speeds, the electrical frequencies and phase angle of the stator and inner of rotor windings have to be coordinated and controlled so that all MMFs are synchronized to produce a unified magnetic field.

3. Conclusions

Though AC electric machines have evolved for more than a century and arrived at very sophisticated level, a single electric machine with dual mechanical ports is a relatively new concept. When the mechanical ports of an electric machine are multiplied, a family of new electric machines can be achieved. Although this breed of new electric machines essentially follow the basic electromagnetic and electromechanical principles governing the conventional ones, the new breed electric machine still give electric machine design, control and especially application engineers enough new territory to explore, given the newly developed power electronics and digital control environment. The application potentials of the DMP machine are vast, from multi-source hybrid traction, integrated starter and generator, to variable gearboxes, just to list a few [3, 4]. The research work on DMP machine is in progress and more results are to be reported in future papers.

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