

d-q Analysis of a Variable Speed Doubly AC Excited Reluctance Motor

Feng Liang, Longya Xu and T.A. Lipo
 University of Wisconsin
 Department of Electrical and Computer Engineering
 1415 Johnson Drive
 Madison WI, 53706 USA

ABSTRACT

The paper describes a new type of variable speed doubly-fed reluctance machine and presents the model for the analysis of the machine. The stator of the machine is equipped with two sets of sinusoidally distributed windings having pole numbers P_1 and P_2 . The rotor consists of simple saliencies of pole number P_r , which is shown to be constrained to particular values by P_1 and P_2 . A d-q-n model and equivalent circuit is developed for this machine. Simulation results using the new model show that this machine can have the advantages of doubly-fed wound-rotor machine while eliminating the complicated wound rotor, brushes and slip rings normally associated with doubly fed machines.

INTRODUCTION

Developments in AC/AC converters with regenerating capability have led to a rapid increase of industrial applications utilizing AC adjustable speed drives (ASDs). However, the high cost of the ASDs compared to conventional speed-fixed motors remains one of the main obstacles towards an even broader number of applications. Since the cost of the converter tends to dominate the overall cost of existing ASD systems, reduction of the cost of the converters is of great significance. In practice, there are numerous situations, such as pump and compressor applications, where the speed does not need to change over a wide range. The fact that the power to be controlled in the speed adjusting process is only a small part of the machine rating in such applications implies that the converter rating can be reduced to a great extent for such drive systems. One of the means to reduce the converter rating is to use a solid state converter to control the slip power into or from the rotor terminals of a doubly-fed wound rotor induction motor. In such applications, a bidirectional power converter rated approximately 15 percent of the machine rating can provide ± 15 percent power transfer from the rotor to cover a 30 percent speed range at constant torque [1-3].

Although a doubly-fed wound rotor machine provides a means to reduce the converter rating, the complication of the rotor and the slip ring limit the application of such machines. To eliminate the complicated rotor and slip ring arrangement, the so-called self cascaded induction machine has been proposed [4-6]. A self cascaded machine normally consists of a specially wound rotor and a stator with two windings as shown in Fig. 1. The stator winding sets up a pole pair number of a multiple of three with respect to the main terminals A, B and C, and a nontriple pole pair number with respect to the star points a, b and c. One of the two windings is connected to the utility supply while the other is connected to a frequency converter for the purpose of speed control. Unfortunately, with an additional winding on the stator as well as special shorted windings on the rotor, this class of machine has suffered severely from the point of view of efficiency.

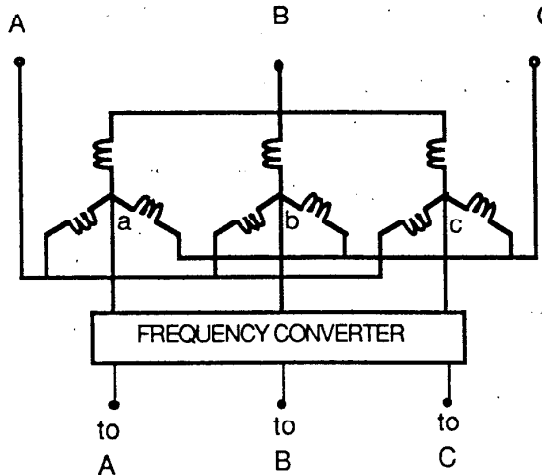


Fig. 1 Stator Connection of Doubly Excited Reluctance Motor.

The efficiency problem concerned with the doubly-fed induction machine can be substantially solved by using the doubly-excited reluctance machine (DERM) in which the stator is wound in the double three phase winding arrangement similar to the self cascaded induction machine and the rotor consists simple saliencies without an additional rotor winding. Such a machine was first proposed in a synchronous machine realization by Broadway [7-11] which was later constructed by Heyne and El-Antably [12] and analyzed by Xu, Liang and Lipo [13]. However, it appears that a doubly-excited three phase arrangement of such a machine, operating in a doubly fed, variable speed mode has never been previously proposed. In this machine the cage rotor of the normal self-cascaded machine is replaced by a low cost, readily manufactured salient rotor equipped without a cage winding. Hence, this type of machine has no rotor copper loss and consequently offers the possibility of high efficiency. The low machine manufacturing cost and maintenance cost due to the simple rotor structure, low converter cost due to the rating reduction and promise of high efficiency makes such a machine very attractive as a potential means of economical variable-speed generators, adjustable drives, and pump and compressor systems.

Because of the fact that the pole of the stator windings and the rotor saliency are different with each other, the magnetic field in DERM is not a rotating sine wave with constant magnitude, which unfortunately makes the understanding of the principle of operation of this kind of machine less than straight forward. Consequently, derivation of the motor equivalent circuits, which are applicable only for steady state, have thus far been

semi-intuitive with modification of the conventional induction and synchronous machine models made to incorporate the different pole numbers. To compute the interaction of the machine and converter, examine the stress on converter components and investigate the detailed design alternatives, it clearly is mandatory to develop a suitable model for transient analysis of such a machine. This paper clearly uncovers the operational principle of the machine by presenting the relationship between the pole numbers obtained by studying the coupling between the two sets of stator windings. With the inductances calculated by means of winding function, a d-q-n model and equivalent circuits have been developed by application of d-q transformation theory. It is shown that the machine speed can be adjusted by changing the frequency of one of the two stator winding current. Based on the model, the process of operating the machine with adjustable speed is investigated by means of simulation.

MACHINE MODEL IN PHASE VARIABLE COMPONENTS

The Stator and Rotor Structure

The stator configuration of the proposed DERM machine has conventional laminations with 36 uniformly distributed semi-open slots in much the same manner as the cascaded induction machine of Broadway [8]. The rotor, however, is constructed of laminations arranged to produce a large saliency between the direct and quadrature axes. No rotor cage is provided since induction motor starting torque is not required. A schematic of the connection diagram and a pictorial representation of basic stator and rotor geometry is shown in Figs. 2 and 3 respectively. When viewed from one set of leads (a, b, and c), the winding has a three phase, 6-pole construction. When viewed from the other terminals (A, B, and C), however, the winding is again three phase, but with two poles. When these two sets of leads are powered simultaneously from two independent sources, the terminal currents will not affect to each other due to the symmetric nature of the winding. Therefore, in this paper, superposition will be used and it will be assumed that the stator winding of the DERM can be replaced by two equivalent, physically separated windings while the currents remain unchanged. Hence, iron saturation effects are neglected in this analysis. The rotor of the machine can be either axially laminated rotor or conventional salient rotor. To focus on the development of the machine model, the simpler conventional salient rotor structure is considered in this paper.

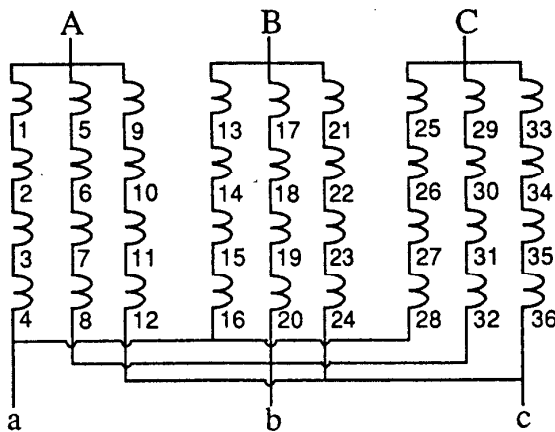


Fig.2 Winding Configuration for Stator of Doubly Excited Reluctance Motor

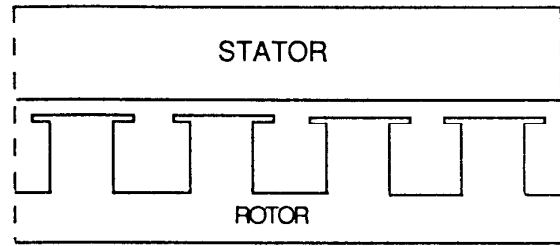


Fig. 3 Illustration of Basic Stator and Rotor Geometry

Machine Model and Calculation of Inductances
By inspection, the model describing the machine is defined by the set of differential equations,

$$v_{ABC} = r_1 i_{ABC} + \frac{d\lambda_{ABC}}{dt} \quad (1)$$

$$v_{abc} = r_2 i_{abc} + \frac{d\lambda_{abc}}{dt} \quad (2)$$

where $v_{ABC} = \begin{pmatrix} v_A \\ v_B \\ v_C \end{pmatrix}$, $i_{ABC} = \begin{pmatrix} i_A \\ i_B \\ i_C \end{pmatrix}$,

$$v_{abc} = \begin{pmatrix} v_a \\ v_b \\ v_c \end{pmatrix}, \quad i_{abc} = \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix},$$

$$\lambda_{ABC} = L_{ABC} i_{ABC} + L_{ABC,abc} i_{abc},$$

$$\lambda_{abc} = L_{abc,ABC} i_{ABC} + L_{abc} i_{abc},$$

with $L_{ABC} = \begin{pmatrix} L_{AA} & L_{AB} & L_{AC} \\ L_{BA} & L_{BB} & L_{BC} \\ L_{CA} & L_{CB} & L_{CC} \end{pmatrix}$,

$$L_{abc} = \begin{pmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{pmatrix},$$

$$L_{ABC,abc} = \begin{pmatrix} L_{Aa} & L_{Ab} & L_{Ac} \\ L_{Ba} & L_{Bb} & L_{Bc} \\ L_{Ca} & L_{Cb} & L_{Cc} \end{pmatrix},$$

and $L_{abc,ABC} = L_{ABC,abc}^T$. In these equations the quantity "T" denotes the transpose.

Additional equations for the torque and speed are

$$T_e = i^T \frac{\partial [L_{abc,ABC}]}{\partial \theta_{rm}} i \quad (3)$$

where $i = \begin{pmatrix} i_{abc} \\ i_{ABC} \end{pmatrix}$.

$$J \frac{d\omega_{rm}}{dt} = T_e - T_l \quad (4)$$

where J denotes the rotor inertia and T_l is the load torque.

Obviously, the computation and analysis of the machine inductances as defined by the four inductance matrices above is the key to the understanding of the principle of operation and to successful application of the model.

The machine inductances can be calculated by a variety of means including field theory, finite elements and various circuit

approaches. A particular convenient approach is called the method of winding functions [14-15] in which the inductances of the machine are calculated by an integral expression representing the placement of winding turns along the air gap periphery. The method is particularly convenient for the analysis of unusual machines since it assumes no symmetry in the placement of any motor coil in the slots. As is the case with most inductance calculations it is assumed that:

- 1). The iron of the rotor and stator has infinite permeability and saturation is not considered;
- 2). The stator surface is considered smooth and the effects of slots are corrected by the Carter coefficient.

According to winding function theory [13-15], the mutual inductance between any two windings "i" and "j" in any electric machine can be computed by the equation:

$$L_{i,j}(\theta_{rm}) = \mu_0 r l \int_0^{2\pi} g^{-1}(\theta_{rm}, \phi) N_i(\theta_{rm}, \phi) N_j(\theta_{rm}, \phi) d\phi \quad (5)$$

The term $g^{-1}(\theta_{rm}, \phi)$ is termed the inverse gap function which becomes a constant for the uniform air gap machine and is a constant in d-axis under the pole face and approximately zero in the q-axis for a salient-pole machine. The angle ϕ defines a particular angular position along the stator inner surface while θ_{rm} is the angular position of the rotor with respect to some stator reference. The term $N_i(\theta_{rm}, \phi)$ is called the winding function and represents, in effect, the MMF distribution along the air gap for a unit current in winding i . If this winding is located on the stator, the winding function is only a function of the stator peripheral angle ϕ while if the winding is located on the rotor the winding must be expressed as a function of both ϕ and the mechanical position of the rotor θ_{rm} .

Winding functions for two equivalent stator windings representing the six and two pole windings are drawn in Figs. 4(a) and (b). Note that a substantial space harmonic content is present in the winding function plots. Hence, the influence of the space harmonics is appreciable with this machine [15]. However, to present clearer picture of how the machine operates, this paper only considers the fundamental components of the winding functions as shown in Fig. 5(a). For the same reason, the inverse gap function in Eq. 5 is assumed to be zero in the region between two rotor poles. i.e.

$$g^{-1}(\theta_{rm}, \phi) = g^{-1} \quad \theta_{rm} + \frac{\pi}{2P_r}(2n-\alpha) \leq \phi \leq \theta_{rm} + \frac{\pi}{2P_r}(2n+\alpha)$$

$$g^{-1}(\theta_{rm}, \phi) = 0 \quad \theta_{rm} + \frac{\pi}{2P_r}(2n+\alpha) < \phi < \theta_{rm} + \frac{\pi}{2P_r}(2n+2-\alpha)$$

where P_r is the pole pair of the rotor and $n=0, 1, 2, 3, 4, \dots, 2P_r-1$.

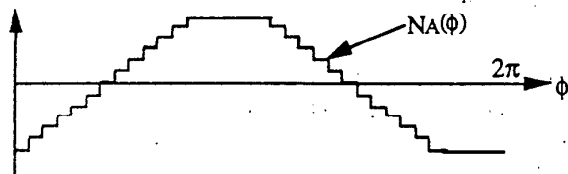


Fig. 4A Winding Function for 2-Pole Phase A

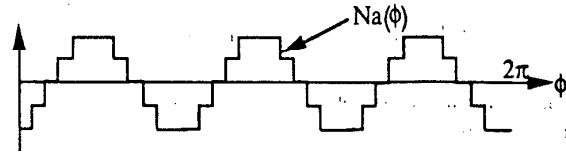


Fig. 4B Winding Function for 6-Pole Phase a

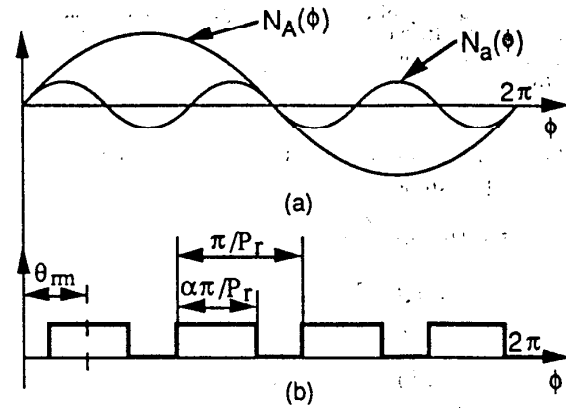


Fig 5 (a) Fundamental Components of the Winding Functions
(b) Typical Inverse Gap Function of Doubly Excited Reluctance Motor

With such simplification, the mutual inductance between phase A and phase a can be expressed as,

$$L_{Aa} = \mu_0 r l \int_0^{2\pi} g^{-1}(\theta_{rm}, \phi) N_A \sin(P_1 \phi) N_a \sin(P_2 \phi) d\phi$$

$$= \frac{\mu_0 r l N_A N_a}{g(P_2 - P_1)} \sin[(P_2 - P_1) \frac{\pi \alpha}{2P_r}] \sum_{n=0}^{2P_r-1} \cos[(P_2 - P_1) \theta_{rm} + \frac{\pi n(P_2 - P_1)}{P_r}]$$

$$- \frac{\mu_0 r l N_A N_a}{g(P_2 + P_1)} \sin[(P_2 + P_1) \frac{\pi \alpha}{2P_r}] \sum_{n=0}^{2P_r-1} \cos[(P_2 + P_1) \theta_{rm} + \frac{\pi n(P_2 + P_1)}{P_r}]$$

$$= K_1 \cos[(P_2 - P_1) \theta_{rm} + \delta] + K_2 \cos[(P_2 + P_1) \theta_{rm} + \beta] \quad (6)$$

where P_1 and P_2 is the pole pair of the two three-phase windings respectively,

$$K_1 = \frac{\mu_0 r l N_A N_a}{g(P_2 - P_1)} \sin[(P_2 - P_1) \frac{\pi \alpha}{2P_r}]$$

$$K_2 = - \frac{\mu_0 r l N_A N_a}{g(P_2 + P_1)} \sin[(P_2 + P_1) \frac{\pi \alpha}{2P_r}]$$

Similarly, L_{Ab} and L_{Ac} can be given by

$$L_{Ab} = K_1 \cos[(P_2 - P_1) \theta_{rm} + \delta + \frac{2\pi}{3}] + K_2 \cos[(P_2 + P_1) \theta_{rm} + \beta - \frac{2\pi}{3}] \quad (7)$$

$$L_{Ac} = K_1 \cos[(P_2 P_1) \theta_{rm} + \delta - \frac{2\pi}{3}] + K_2 \cos[(P_2 + P_1) \theta_{rm} + \beta + \frac{2\pi}{3}] \quad (8)$$

The mutual flux linking phase A produced by currents i_a , i_b and i_c is given by

$$\lambda_{A,abc} = L_{Aa} i_a + L_{Ab} i_b + L_{Ac} i_c \quad (9)$$

Obviously, electromechanical energy conversion will not occur if the frequency of the speed voltage in a given phase is different from the frequency of the current flowing in the same phase. This observation implies that $L_{A,abc}$ should have the same frequency as that of i_A . Based on this requirement, the constraints for pole pair number P_1 , P_2 , and P_r can be derived as follows.

If i_A is of frequency ω_1 and i_a , i_b , and i_c are given by

$$i_a = I_m \cos(\omega_2 t) \quad (10)$$

$$i_b = I_m \cos(\omega_2 t - \frac{2\pi}{3}) \quad (11)$$

$$i_c = I_m \cos(\omega_2 t + \frac{2\pi}{3}) \quad (12)$$

By substituting (6), (7), (8), (10), (11) and (12) into (9) and applying

$$2\cos(\alpha)\cos(\beta) = \cos(\alpha-\beta) + \cos(\alpha+\beta)$$

it can be shown that $\lambda_{A,abc}$ has two different frequencies:

$$(P_2 - P_1)\omega_{rm} + \omega_2$$

and $(P_2 + P_1)\omega_{rm} - \omega_2$

Since ω_{rm} can only have one unique value, the only means to make $\lambda_{A,abc}$ have the frequency ω_1 is to choose a proper rotor pole number to eliminate one of the components of the inductances L_{Aa} , L_{Ab} and L_{Ac} .

From (6), it can be determined that if

$$\frac{P_2 - P_1}{P_r} \neq \text{an even number}$$

then the sum $\sum_{n=0}^{2P_r-1} \cos[(P_2 - P_1)\theta_{rm} + \frac{\pi n(P_2 - P_1)}{P_r}]$ is zero.

It can also be shown that if P_1 , P_2 and P_r satisfy the constraint

$$\frac{P_2 + P_1}{P_r} = \text{an even number}$$

then L_{Aa} reaches its possible maximum value:

$$L_{Aa} = L_{m12} \cos[(P_2 + P_1)\theta_{rm}]$$

where $L_{m12} = 2P_r K_2$

Similarly, the other mutual inductances are given by

$$L_{Bc} = L_{Cb} = L_{Aa} = L_{m12} \cos[(P_2 + P_1)\theta_{rm}]$$

$$L_{Ab} = L_{Ba} = L_{Cc} = L_{m12} \cos[(P_2 + P_1)\theta_{rm} - \frac{2\pi}{3}]$$

$$L_{Ac} = L_{Ca} = L_{Bb} = L_{m12} \cos[(P_2 + P_1)\theta_{rm} + \frac{2\pi}{3}]$$

To reduce the pulsating torque, the self induced voltages must also have the same frequency as those of the currents. It can be shown that the only means to have that result is to choose P_1 , P_2 , and P_r in such a manner that the self inductances are constants.

By the same approach, it can be shown that if

$$\frac{2P_1}{P_r} \neq \text{an even number}$$

then

$$L_{AA} = L_{BB} = L_{CC} = L_{l1} + L_{m1}$$

and $L_{AB} = L_{BA} = L_{AC} = L_{CA} = L_{BC} = L_{CB} = -\frac{1}{2}L_{m1}$

$$\frac{\mu_0 r l N_a^2 \pi \alpha}{g}$$

where $L_{m1} = \frac{\mu_0 r l N_a^2 \pi \alpha}{g}$ and L_{l1} is the leakage inductance.

Similarly, with the constraint

$$\frac{2P_2}{P_r} \neq \text{an even number}$$

the inductance of the abc system are given by

$$L_{aa} = L_{bb} = L_{cc} = L_{l2} + L_{m2}$$

and

$$L_{ab} = L_{ba} = L_{ac} = L_{ca} = L_{bc} = L_{cb} = -\frac{1}{2}L_{m2}$$

$$\frac{\mu_0 r l N_a^2 \pi \alpha}{g}$$

where $L_{m2} = \frac{\mu_0 r l N_a^2 \pi \alpha}{g}$ and L_{l2} is the leakage inductance.

By examining the computed results of the self and mutual inductances of the DERM machine, the following conclusions are reached immediately:

(1) To have both windings involved in the process of electromechanical energy conversion, P_1 , P_2 and P_r have to be chosen in such a combination that the speed voltage in the windings have the same frequency as those of the currents.

(2) To reduce the pulsating torque, P_1 , P_2 and P_r have to satisfy some constraints so that the self inductances can be constants.

(3) The electromechanical energy conversion can occur only at a particular speed. In the case under consideration, this speed, is given by

$$\omega_{rm} = \frac{\omega_1 + \omega_2}{P_1 + P_2}$$

It can be shown that if the sequence of the currents i_a , i_b , and i_c is changed to be opposite to that of i_A , i_B and i_C , the rotor speed will be

$$\omega_{rm} = \frac{\omega_1 - \omega_2}{P_1 + P_2}$$

It is obvious that by changing ω_2 , the machine speed can be adjusted to either a higher or lower value than the speed of

$$\frac{\omega_1}{P_1 + P_2}$$

MACHINE MODEL IN D-Q-N SYSTEM

To predict the dynamic performance of the machine, Eqs. 1-4 containing time-varying parameters need to be solved simultaneously. To have a model with constant parameters for DERM, the theory of reference frame transformation is extended and applied to the analysis of the DERM. The complex variable notation is herein employed to simplify the transformation and development of equivalent circuits.

Defining

$$a = e^{j2\pi/3}$$

and

$$\begin{aligned} \dot{f}_{ABC} &= f_A + af_B + a^2f_C \\ \dot{f}_{abc} &= f_a + af_b + a^2f_c \end{aligned}$$

where the symbol "f" is used to represent any of the three phase variables such as voltage, current or flux linkage, (1) and (2) can be expressed in a compact form:

$$\dot{Y}_{ABC} = r_1 \dot{i}_{ABC} + p \dot{\lambda}_{ABC} \quad (13)$$

$$\dot{Y}_{abc} = r_2 \dot{i}_{abc} + p \dot{\lambda}_{abc} \quad (14)$$

where the symbol "p" is used to represent $\frac{d}{dt}$.

Noting

$$\cos(\alpha) = \frac{e^{j\alpha} + e^{-j\alpha}}{2}$$

it is obvious that the inductance matrix in complex form, $L_{ABC,abc}$, can be expressed as

$$\begin{aligned} L_{ABC,abc} &= \frac{1}{2} L_{m12} \begin{pmatrix} 1 & a & a^2 \\ a^2 & a & 1 \\ a & 1 & a^2 \end{pmatrix} e^{j\theta_r} \\ &+ \frac{1}{2} L_{m12} \begin{pmatrix} 1 & a & a^2 \\ a & a^2 & 1 \\ a^2 & 1 & a \end{pmatrix} e^{-j\theta_r} \end{aligned} \quad (15)$$

where $\theta_r = (P_1 + P_2)\theta_{rm}$.

With $L_{ABC,abc}$ expressed in the form of (15), it is easy to show

$$\dot{\lambda}_{ABC} = \lambda_A + a\lambda_B + a^2\lambda_C = L_1 \dot{i}_{ABC} + L_m \dot{i}_{abc}^* e^{j\theta_r} \quad (16)$$

and

$$\dot{\lambda}_{abc} = \lambda_a + a\lambda_b + a^2\lambda_c = L_2 \dot{i}_{abc} + L_m \dot{i}_{ABC}^* e^{j\theta_r} \quad (17)$$

where

$$L_1 = L_{l1} + \frac{3}{2} L_{m1}$$

$$L_2 = L_{l2} + \frac{3}{2} L_{m2}$$

$$L_m = \frac{3}{2} L_{m12}$$

and "*" denotes the complex conjugate.

Substituting (16) and (17) into (13) and (14) yields

$$\dot{Y}_{ABC} = r_1 \dot{i}_{ABC} + L_1 p \dot{i}_{ABC} + L_m p \dot{i}_{abc}^* e^{j\theta_r} \quad (18)$$

$$\dot{Y}_{abc} = r_2 \dot{i}_{abc} + L_2 p \dot{i}_{abc} + L_m p \dot{i}_{ABC}^* e^{-j\theta_r} \quad (19)$$

To eliminate the sinusoidal coupling of (18) and (19) the following transformation is made,

$$\dot{f}_{qd1} = f_{q1} - jf_{d1} = \frac{2}{3} e^{-j\theta} \dot{f}_{ABC} \quad (20)$$

$$\dot{f}_{qd2} = f_{q2} - jf_{d2} = \frac{2}{3} e^{-j(\theta-\theta_r)} \dot{f}_{abc}^* \quad (21)$$

where "θ" is the angle by which q axis leads the axis of phase A, "1" denotes the ABC system and "2" denotes the abc system.

With such transformation, (18) and (19) can be rewritten as

$$\dot{Y}_{qd1} = r_1 \dot{i}_{qd1} + p \dot{\lambda}_{qd1} + j\omega \dot{\lambda}_{qd1} \quad (22)$$

$$\dot{Y}_{qd2} = r_2 \dot{i}_{qd2} + p \dot{\lambda}_{qd2} + j(\omega - \omega_r) \dot{\lambda}_{qd2} \quad (23)$$

where

$$\omega = p\theta$$

$$\omega_r = p\theta_r = (P_1 + P_2)\omega_{rm}$$

$$\dot{\lambda}_{qd1} = L_1 \dot{i}_{qd1} + L_m \dot{i}_{qd2}$$

$$\dot{\lambda}_{qd2} = L_2 \dot{i}_{qd2} + L_m \dot{i}_{qd1}$$

To determine the zero sequence component, the three rows of (1) are summed and the result is

$$v_A + v_B + v_C = (r_1 + pL_{l1})(i_A + i_B + i_C) \quad (24)$$

Dividing this equation by 3 and making use of the definition of the zero sequence component yields

$$v_{n1} = (r_1 + pL_{l1})i_{n1} \quad (25)$$

similarly,

$$v_{n2} = (r_2 + pL_{l2})i_{n2} \quad (26)$$

From (20), (21), (25) and (26), the transformation matrix can be obtained,

$$\begin{pmatrix} f_{q1} \\ f_{d1} \\ f_{n1} \end{pmatrix} = \frac{2}{3} \begin{pmatrix} \cos(\theta) \cos(\theta - \frac{2\pi}{3}) \cos(\theta + \frac{2\pi}{3}) \\ \sin(\theta) \sin(\theta - \frac{2\pi}{3}) \sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} \quad \frac{1}{2} \quad \frac{1}{2} \end{pmatrix} f_{ABC}$$

$$\begin{pmatrix} f_{q2} \\ f_{d2} \\ f_{n2} \end{pmatrix} = \frac{2}{3} \begin{pmatrix} \cos(\theta - \theta_r) \cos(\theta - \theta_r + \frac{2\pi}{3}) \cos(\theta - \theta_r - \frac{2\pi}{3}) \\ \sin(\theta - \theta_r) \sin(\theta - \theta_r + \frac{2\pi}{3}) \sin(\theta - \theta_r - \frac{2\pi}{3}) \\ \frac{1}{2} \quad \frac{1}{2} \quad \frac{1}{2} \end{pmatrix} f_{abc}$$

It can be shown that the torque equation under the transformation becomes

$$T_e = \frac{3}{2} (P_1 + P_2) (\lambda_{d1} i_{q1} - \lambda_{q1} i_{d1}) \quad (27)$$

and if there are no zero components the voltage equations become

$$\begin{pmatrix} v_{d1} \\ v_{q1} \\ v_{d2} \\ v_{q2} \end{pmatrix} = \begin{pmatrix} r_1 + L_1 p & -\omega L_1 & L_m p & -\omega L_m \\ \omega L_1 & r_1 + L_1 p & \omega L_m & L_m p \\ L_m p & -(\omega - \omega_r) L_m & r_2 + L_2 p & -(\omega - \omega_r) L_2 \\ -(\omega - \omega_r) L_m & L_m p & (\omega - \omega_r) L_2 & r_2 + L_2 p \end{pmatrix} \begin{pmatrix} i_{d1} \\ i_{q1} \\ i_{d2} \\ i_{q2} \end{pmatrix} \quad (28)$$

Based on the new equations in the transformed coordinates the d,q equivalent circuit shown in Figure 6 is suggested.

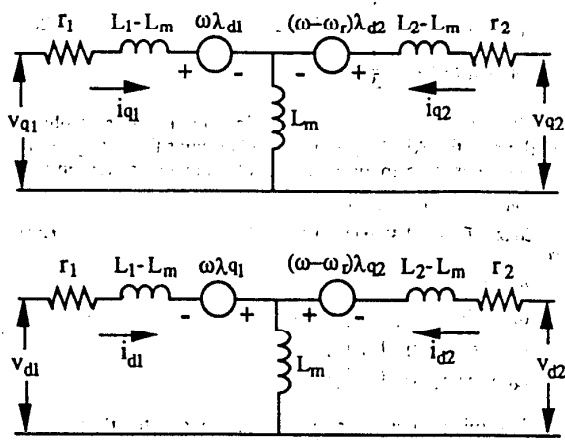


Fig. 6 Equivalent Circuit of the Doubly Excited Reluctance Motor Corresponding to the Equations Derived from d,q Transformation.

Setting $\omega=0$ and defining the "slip" as

$$S = \frac{\omega_2}{\omega_1}$$

it can be proven that the equivalent circuit for steady state operation of DERM has exactly the same form as that of a conventional wound rotor induction machine shown as Fig. 7.

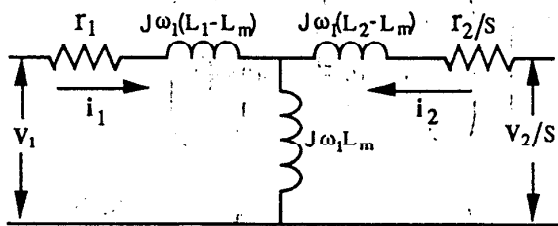


Fig. 7 Per-Phase Steady State Equivalent Circuit of Doubly Excited Reluctance Motor.

It is interesting to observe that the equations in the d-q-n frame and equivalent circuits have exactly the same forms as those of a doubly fed wound rotor induction machine, which implies that the doubly excited reluctance machine is equivalent to a wound rotor induction machine with equivalent pole pair number of P_1+P_2 .

APPLICATION OF THE MACHINE MODEL

With the transient model and steady state equivalent circuit developed, the performance and transient behavior can be evaluated. Since the model has the same form of that of a conventional wound-rotor induction motor, it can be expected that the performances of the DERM has the same feature as those of the wound-rotor machine.

While a detailed simulation study is outside the scope of this paper, as an example of the application of the model of DERM, the speed varying process of the DERM is investigated. In the simulation, the 6-pole winding is connected to a 60 Hz supply

which is referred to as the "primary" voltage in this paper and the other winding is connected to a frequency converter which is called the "secondary" voltage. The rotor speed is adjusted under a no-load condition.

Based on the above analysis, it can be known that the frequencies, ω_1 , ω_2 and ω_{rm} must satisfy the following constraint:

$$\omega_1 \pm \omega_2 = (P_1 + P_2)\omega_{rm} \quad (29)$$

("+" is used when the phase sequences of the two three-phase systems are the same). Obviously, the mechanical speed ω_{rm} can be adjusted just simply by changing ω_2 . However, it can be shown that the maximum torque will be decreased in such case. In order to improve performance, the voltage must be varied while the frequency is adjusted in accordance with the feedback speed signal to satisfy the constraint, Eq. (29). When the peak value of the secondary voltage is changed linearly from zero to 20 volts in 0.2 second and its sequence is the reverse of that of the primary voltage, the speed drops from the synchronous speed (900 rpm) to 795 rpm as shown in Fig. 8. The currents, voltage and torque are also shown in Fig. 8.

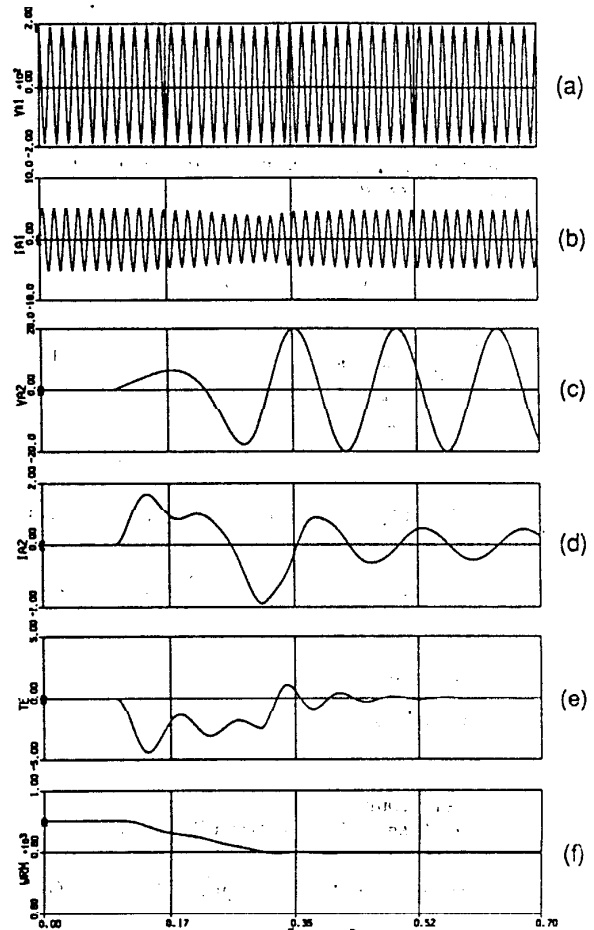


Fig. 8 Simulation Result of Speed Decreasing Process (a) Primary Voltage (b) Primary Current (c) Secondary Voltage (d) Secondary Current (e) Torque (f) Speed

To operate the machine in supersynchronous mode, the sequence of the two three-phase system should be the same. With the secondary voltage having the same change as in the previous case, the simulated speed, torque, currents and voltages are shown in Fig. 9. It can be noticed that in the transient process some electrical energy is pumped into the machine from the converter, which results in the development of the positive torque and an increase of the speed.

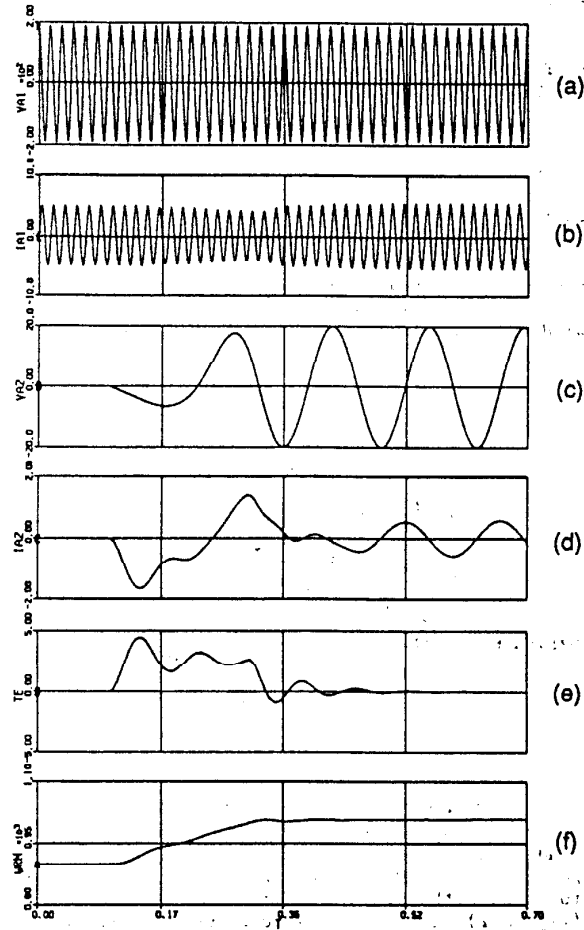


Fig. 9 Simulation Result of Speed Increasing Process
 (a) Primary Voltage (b) Primary Current (c) Secondary Voltage
 (d) Secondary Current (e) Torque (f) Speed

CONCLUSION

An analysis of a new doubly excited reluctance machine (DERM) has been presented in this paper. The analysis is based on the study of the electromagnetic coupling between the windings, the fundamental elements of an electric machine. The winding function theory provides a very useful means to calculate the inductances which describe the couplings. By applying the necessary condition for electromechanical energy conversion, the constraints on the factors determining the couplings, such as pole numbers and speed, can be derived. In spite of the fact that the machine is characterized by an air gap flux of pulsating amplitude, the inductive couplings have the same feature as that of conventional machines, i.e. a mutually induced voltage in a winding has the same frequency as that of

the current in the same winding. Because of this nature, the study approach for conventional machine, such as d,q,n transformation theory, can be employed with some necessary modification. Also the study of the such machines with non-sinusoidal air gap flux can be undertaken and similar results can be expected. By using such approach, it is shown that a DERM has the same model and equivalent circuits as those of a conventional wound-rotor induction machine. In summary, it can be claimed that a DERM can has the same advantages as that of a wound-rotor induction machine while eliminating the disadvantages such as complicated rotor, slip ring and therefore high production and maintenance cost. A machine of this type has been constructed and is undergoing experimental investigation at the University of Wisconsin.

References

- [1] G.A. Smith, "Static Scherbius System of Induction-Motor Speed Control", Proc. IEE, vol. 124, No. 6, 1977, pp. 557-560.
- [2] W. Shepherd and J. Stanway, "Slip Power Recovery in an Induction Motor by the Use of a Thyristor Inverter", IEEE Trans. on Industry and General Applications, vol. IGA-5, No. 1, 1969.
- [3] H.W. Weiss, "Adjustable Speed AC Drive Systems for Pump and Compressor Applications", IEEE Trans. on Industry Applications, vol. IA-10, No. 1, January/February 1974, pp. 162-167.
- [4] L.J. Hunt, "The Cascade Induction Motor", J. IEE, vol. 52, 1914, pp. 406-426.
- [5] F. Creedy, "Some Developments in Multi-Speed Cascade Induction Motors", J. IEE, vol. 59, 1921, pp. 551-552.
- [6] A. Kusko and C.B. Somuah, "Speed Control of a Single-Frame Cascade Induction Motor with Slip-Power Pump Back", IEEE Trans. on Industry Applications, vol. IA-14, March/April 1978, pp. 97-105.
- [7] A.R.W. Broadway and G. Thomas, "Single-Unit PAM Induction Frequency Convertors", Proc. IEE, vol. 114, 1967, pp. 958-964.
- [8] A.R.W. Broadway, L. Burbridge, "Self-Cascaded Machine: a Low-Speed Motor or High-Frequency Brushless Alternator", Proc. IEE, vol. 117, July 1970, pp. 1277-1290.
- [9] A.R.W. Broadway, "Cageless Induction Motor", Proc. IEE, vol. 118, 1971, pp. 1593-1600.
- [10] A.R.W. Broadway, "Brushless Stator-Controlled Synchronous-Induction Machine", Proc. IEE, vol. 120, August 1973, pp. 860-866.
- [11] A.R.W. Broadway and G. Thomas, "Brushless Cascade Alternator", Proc. IEE, vol. 121, 1974, pp. 1529-1535.
- [12] C.J. Heyne and A.M. El-Ahtably, "Reluctance and Doubly-Excited Reluctance Motors", Final Report, Oak Ridge National Laboratories, Report ORNL/SUB/81-95013/1, 123 pp.
- [13] L. Xu, F. Liang and T.A. Lipo, "Transient Model of a Doubly Excited Reluctance Motor", to be Presented at IEEE PES Summer Meeting, July 1990.
- [14] N.L. Schmitz and D.W. Novotny, "Introductory Electromechanics", (book), Ronald Press, New York, 1965.
- [15] T.A. Lipo, "Analysis of Synchronous Machines", University of Wisconsin, 1987, 297 pp.