A NOVEL CONFIGURATION OF FEEDBACK'S ELECTRIC MACHINE TUTOR (EMT) MODEL 180 AS AN ASYNCHRONOUS MULTIPHASE RELUCTANCE MACHINE WITHOUT ROTOR CONDUCTORS

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ABSTRACT

This paper reports a successful adaptation of a laboratory teaching machine - Electrical Machine Tutor (EMT) model 180 as an asynchronous composite polyphase electric motor without rotor conductors. The device comprises two such identical machines without rotor conductors, all the conductors being on the stator side, which are mechanically coupled together such that their pole axes are in space quadrature. The torque mechanism of the device is shown as the interaction between the mmf due to the excitation current and that due to the circulating current inherent in the novel configuration and explains the cyclic contribution of the net torque of the device by the two machine elements comprising the composite reluctance motor. Details of the connection scheme of the device and its analysis are also presented and possible applications suggested.

LIST OF SYMBOLS

B_1 = flux density distribution in machine A

B_2 = flux density distribution in machine B

e_{aR} = induced voltage in the red phase of machine A by the first component of equation 3.

e_{aY} = induced voltage in the yellow phase of machine A by the first component of equation 3.

e_{aB} = induced voltage in the blue phase of machine A by the first component of equation 3.

e_{bR} = induced voltage in the red phase of machine B by the first component of equation 4.

e_{bY} = induced voltage in the yellow phase of machine B by the first component of equation 4.

e_{bB} = induced voltage in the blue phase of machine B by the first component of equation 4.

E_{aR} = induced voltage in the red phase of machine A by the second component of equation 3.

E_{aY}= induced voltage in the yellow phase of machine A by the second component of equation 3.

E_{aB} = induced voltage in the blue phase of machine A by the second component of equation 3.

E_{bR} = induced voltage in the red phase of machine B by the second component of equation 4.

E_{bY}= induced voltage in the yellow phase of machine B by the second component of equation 4.

E_{bB} = induced voltage in the blue phase of machine B by the second component of equation 4.

m_1 = the instantaneous mmf of machines A and B

M_o = the peak amplitude of the instantaneous mmf

M_1 = Peak amplitude of the instantaneous mmf due to current i_1

M_2 = Peak amplitude of the instantaneous mmf due to current i_2

M_A = the instantaneous combined mmfs of machine A

M_B = the instantaneous combined mmfs of machines B

N = Number of turns of the primary windings

P = permeance distributions of the salient rotor.
P_o = the constant part of the permeance distribution.
P_1 = the peak amplitude of the variable part of the permeance distribution.
t = time in seconds
ω_o = synchronous angular speed
ω = rotor angular speed
X = angular distance roundair gap
Z_1 = impedance of machine A.
Z_2 = impedance of machine B.
δ = load angle
φ = combined impedance angle of machines A and B
β = impedance angle of the component machines
T_e = electromagnetic torque
ω_f = energy stored in the air gap
S = reluctance of the air gap
s = Slip

1.0 INTRODUCTION

Electrical machines tutor (EMT) model 180 is a veritable instrument for teaching electrical machines at both the undergraduate and postgraduate levels in universities the world over. The machine is manufactured by Feedback Instruments Ltd, England and has an almost 'infinitude' of possible experiments in electrical machines. However, the operation of the device as an electric motor without rotor conductors has not been fully investigated. The paper presents the details of the successful adaptation of the device as a composite reluctance motor without rotor conductors.

The operation of the device in this mode will undoubtedly broaden the repertoire of possible experiments that could be performed with the machine and thus advance the understanding of electrical machines. The possibilities of a machine operating without rotor conductors are academically stimulating and have practical interests. Such machines will have a future in a variety of applications such as very low speed fixed frequency drives, linear motors for industrial transport systems, small brushless synchronous motors and generators [1]. Brushless polyphase reluctance machines without rotor conductors have become well-known in the form of a variable frequency motor drive and is now widely used in control systems. Additionally, brushless electric motors without rotor conductors overcome the problem of sliding contacts necessary to make physical connections with moving windings. They have the advantage of reliable operation at high speeds and potential for long life in a hostile environment. Permanent magnet machines with rotating magnets can be used to fulfill this objective. What is described in this paper is how to achieve this with Feedback Electrical Machines Tutor Model 180 with all windings on the stator side.

2.0 THE TEST MACHINE

The test machine is a laboratory teaching machine - Electrical Machines Tutor (EMT) model 180, manufactured by feedback Instruments Ltd England. It is a 12-slot, 2-pole machine with l04mm diameter stator bore and 33mm active stack length and air gap length of 0.3mm. The pole arc is 53% of the pole-pitch. Two such identical machines are mechanically coupled together such that their pole axes are mutually orthogonal in space and their windings interconnected in parallel.

2.1 Description of the scheme

The composite electric motor comprises two identical Electrical Machines Tutor (EMT) 180. Each machine has 12 slots and carries a total of 12 coils with 2 coils in series per path and each has a span of 3 slot pitches. Each machine is also wound for 2-poles by having appropriate coils connected in series and organized as a two- independent 3-phase star connected systems. The 3-phase systems of the two machines comprising the composite machine are connected in parallel phase by phase and connected to the supply such that their applied fields rotate in the same sequence; while their 2-pole salient rotors derived by removing one pair of opposite poles from the armature and hub of the standard 4-pole set as shown in fig. 1 are mechanically coupled together such that their d-axes are $1/2\pi$ electrical radians out of phase.

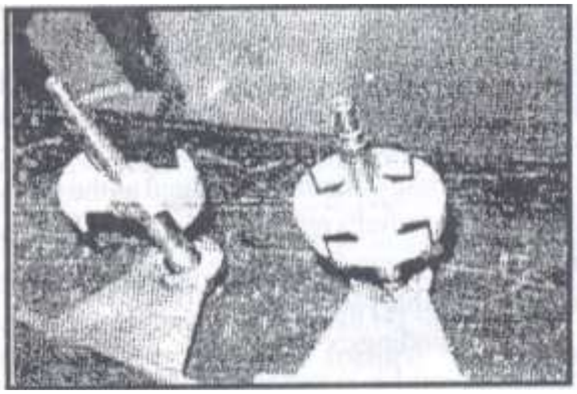


Fig.1: The two-pole rotor coupled to form a 4-pole rotor

An alternate configuration of the machine can be obtained by holding one half of the machine (stator and rotor) while the other half (stator and rotor) is rotated until the pole axes of the two rotor halves are in alignment (i.e. co-phasal in space or coincident) and the axes of the primary windings are out of alignment by 90°. The machine can comprise any number of identical axial sections with these alternative configuration. If there are n sections, the primary windings axes will shift (n-l)/n)π radians between one section and the one before and the axes of the auxiliary windings will shift - (n-l)/n)π. A closely related machine of this class is that described by Russell and Norsworthy [2]. Essentially the two sections of the machines are independently wound and connected in parallel to the supply. The primary windings provide the path for both circulating and excitation currents. The schematic diagram of the composite machine is shown in Fig. 2.

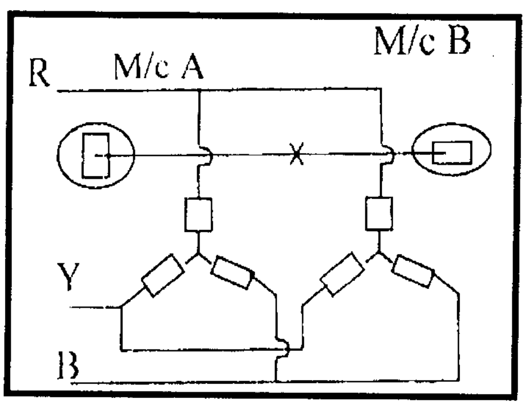


Fig 2: The schematic diagram of the Composite machine.

3.0 THE CONNECTION SCHEME

A wiring diagram of the machine is shown in Fig. 3. Each machine has a total of twelve coil numbered sequentially, 1-12. The windings of each machine are organized as two independent star connected 3-phase systems designated as the main and auxiliary windings respectively. The full lines indicate the main windings while the broken line indicate the auxiliary windings.

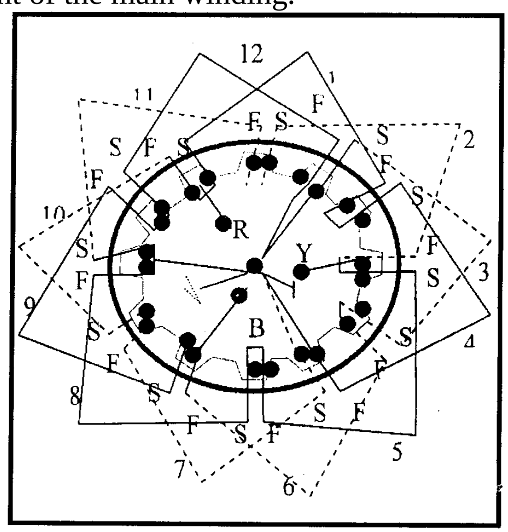
For the main windings:

The finish of coil 1 is in series with the start of coil 4 and form the R-phase.

The finish of coil 5 is in series with the start of coil 8 and form the Y -phase.

The finish of coil 9 is in series with the start of coil 12 and form the B-phase.

The finishes of coils 4,8 and 12 form the star point of the main winding.



S = *Start of winding*

F = finish of winding

Fig. 3: *Wiring diagram of each unit EMT 180 machine.*

For the auxiliary windings, the phases corresponding to R, Y and B above are formed by:

(i) The start of coil 10 in series with the finish of coil 7.

(ii) The start of coil 2 in series with the finish of coil 11.

(iii) The start of coil 6 in series with the finish of coil 3.

The auxiliary windings have star points

comprising the starts of coils 7, 11 and 3. The star points of the component machines A and B comprising the motor and wound as shown in Fig. 2 are connected together. The supply lines RYB of the two machines are connected in parallel to the utility supply.

4.0 OPERATION / PERFORMANCE

The machine can be started direct on-line if a 3-phase variac/transformer is not available. The machine possesses an appreciable self-starting torque even though an induction motor effect is not obvious since there are no windings on the rotor. The threshold voltage for the asynchronous electromechanical energy conversion is observed as 50V. Higher operational voltage is possible if the machine windings are connected in series but the leakage reactance will of course be larger. The composite machine runs stably against appreciable load torque at a speed somewhat less than half synchronous speed $1/2U_o$ on an a.c. supply only, and if dc. excitation is then switched on, the rotor will be pulled into synchronism at exactly half synchronous speed. The power factor, which varies with de excitation and load can be controlled by altering the dc excitation and improved efficiencies can be achieved by this strategy. Alternatively, it will run at the synchronous speed if the stator also has salient poles. The latter requires a rotor designed to match. The photograph of the test composite machine energized through a variac is shown 'in Fig. 4.

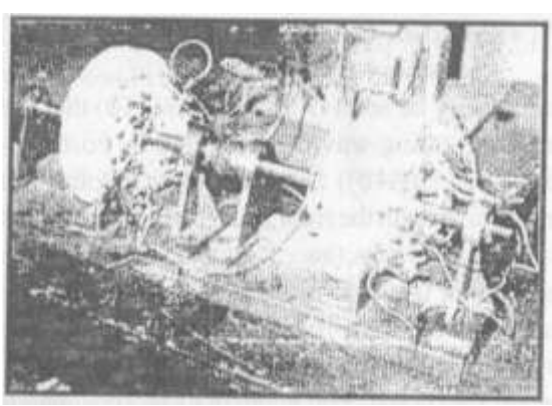


Fig. 4. Photograph of the coupled machines

5.0 ANALYSIS OF THE COUPLED MACHINES

The analysis of this machine derives from the studies on coupled machines [3,4], The usual assumption of a sinusoidally distributed air-gap mmf is made. The air-gap permeance distribution is assumed to have a constant and a fundamental component and there are no harmonics. The excitation mmf of the device is given by:

$m_1 = M_o \cos(x-\omega_o t)$ .... (1)

Since the rotor is of the salient pole type, the air-gap permeance distribution may be expressed as:

$P = P_o+P_1 \cos2(x-\omega t-\delta)$ .... (2)

The air gap flux density distribution is expressed as:

$B_1 = M_o \cos(x-\omega_o t)$ -* $(P_o+P_1 \cos2(x-\omega_o t-\delta)$

$= M_o P_o \cos(x-\omega_o t)$

$+ 1/2 M_o P_1 \cos(x +(\omega_o - 2\omega)t-2\delta)$

$+ 1/2 M_o P_o \cos(3x - (\omega_o + 2\omega) t-2\delta)$…..(3)

If this expression stands for the flux density distribution in section A part of the composite machine, then the flux density distribution in the other section, section B with its d-axis displaced by $1/2\pi$ rads from the first is obtained by substituting $\delta + 1/2\pi$ for δ in equation 2 and derived as:

$B_2 = M_o \cos(x-\omega_o t)$ -* $(P_O – P_1\cos2(x-\omega_o t-\delta)$

$= M_o P_o \cos(x-\omega_o t)$

$- 1/2 M_o P_O$ COS$(x +(\omega_o - 2\omega)t-2\delta)$

$- 1/2 M_o P_1\cos(3x - (\omega_o + 2\omega) t-2\delta)$…..(4)

The rotating flux density distribution $M_o P_o\cos(x- \omega_o t)$ will induce emfs of mains frequency ω_o in the windings of the machines and these induced emfs will oppose the supply voltage. These emfs are indicated by e_{aR}, e_{aY}, e_{aB} and e_{bR}, e_{bY}, e_{bB} in machines A and B respectively. These voltages are equal in magnitude and in time phase. Consider the emfs induced by the second components of the flux density distribution of equations (3) and (4) viz: $\pm 1/2 M_o P_1\cos(x+(\omega_o -2\omega_o)t-2\delta)$.

These fluxes rotate in the opposite direction to the main flux provided $\omega_o >2\omega$ and will induce negative sequence emfs in each phase of the machines windings of angular frequency (ω_o -2ω). If the direction of the induced emf is positive in machine A, it will be negative in machine B. These negative sequence induced emfs are indicated as E_{aR} E_{aY}, E_{aB} and E_{bR}, E_{bY}, E_{bB} for machines A and B respectively. And these negative sequence induced emfs are additive and will consequently circulate harmonic current of (ω_o -2ω) or (2s-1)ω_o frequency in the loop formed by the stator (primary) windings without interfering with the supply.

The third space harmonic components of equations 3 and 4 cannot circulate current in the stator primary windings if those windings are connected in star. The per phase equivalent circuit of the machine is shown in Fig.5 for the red phase only.

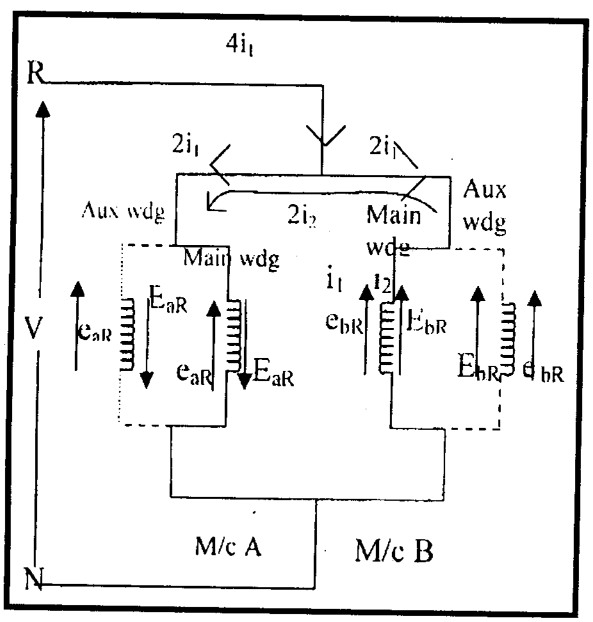


Fig. 5: The per phase equivalent circuit of the machine

The overall current in each phase of the machine is the combination of the mains current, which is divided equally between the two machines and a circulating current. The circulating current aid the mains current in one machine and opposes it in the other machine. The circulating current i_2 and mains current i_1 are given respectively as:

$$i_2 = \frac{E_{aR}+E_{bR}}{Z_1+Z_2} = I_2\cos((\omega_o - 2\omega)t - \frac{\pi}{2} - \emptyset) \quad \ldots (5a)$$

For asynchronous operation $\omega = (1 - S)\omega_o$

Therefore;

$$i_2 = I_2\cos((2s-1)\omega_o t - \pi/2 - \phi \qquad (5b)$$

$$i_2 = \frac{e_{aR}+e_{bR}}{Z_1+Z_2} = I_2\cos((\omega_o t - \frac{\pi}{2} - \beta) \qquad (6)$$

For machine A:

The rotating mmfs distributions due to the mains and circulating currents are given respectively as:

$$Ni_1 = M_1\cos(x + (1-s)\omega_o t - \frac{\pi}{2} - \beta) \quad (7)$$

and

$$Ni_1 = M_2\cos(x + (2s-1)\omega_o t - \frac{\pi}{2} - \phi) \quad (8)$$

The combined air-gap mmfs is given by:

$$M_A = M_1\cos(x - \omega_o t - \frac{\pi}{2} - \beta) + M_2\cos(x + (2s-1)\omega_o t - \frac{\pi}{2} - \phi) \quad \ldots\ldots(9)$$

By adding and subtracting $M_1\cos(x - (\omega_o t - \pi/2) - \beta)$, equation (9) can be rewritten as:

$$\begin{aligned} M_A &= (M_1 - M_2)cos(x - \omega_o t - \pi/2 - \beta) \\ &+ M_2 cos(x - \omega_o t - \pi/2 - \beta) \\ &+ M_2 cos(x + (2s-1)\omega_o t - \pi/2 - \phi) \\ &= (M_1 - M_2)cos(x - \omega_o t - \pi/2 - \beta) \\ &+ 2M_2 cos(x - (1-s)\omega_o t - \pi/2 - 1/2(\beta + \phi)) * \cos(s\omega_o t - (\beta - \phi)1/2)) \quad \ldots\ldots\ldots(10) \end{aligned}$$

It can easily be seen from equation (10) that the forward rotating wave represented by $cos(x - (1-s)\omega_o t - \pi/2 - 1/2(\beta + \phi))$ is a wave which rotates in synchronism with the rotor and will therefore Impart a synchronous reluctance torque on the rotor even though that it is operating asynchronously. The amplitude of the torque producing mmf wave however pulsates in accordance with $2M_2\cos(s\omega_o t - 1/2(\beta - \phi)$. The wave $(M_1 - M_2)cos(x - \omega_o t - \pi/2 - \beta)$ does not produce torque since it does not rotate in step with the rotor.

For Machine B:

The rotating mmf distributions due to the mains current i_1 and circulating current i_2 are analogously given respectively as:

$Ni_1 = M_1\cos(X - \omega_o t - \pi/2 - \beta)$ ....(11)

and $Ni_1 = -M_2 cos(x + (2s-1)\omega_o t - \pi/2 - \phi)$ (12)

The combined air-gap mmf is given by:

$$M_B = M_1 cos(x - \omega_o t - \pi/2 - \beta) - M_2 cos(x + (2s-1)\omega_o t - \phi)$$
$$= (M_1 - M_2) cos(x - \omega_o t - \pi/2 - \beta) + M_2 cos(x - \omega_o t - \pi/2 - \beta) - M_2 cos(x + (2s-1)\omega_o t - \phi)$$
$$= (M_1 - M_2) cos(x - \omega_o t - \pi/2 - \beta) + 2M_2 \sin(x - (1-s)\omega_o t - \frac{\pi}{2} - 1/2(\beta - \emptyset)) * \sin(s\omega_o t - 1/2(\beta - \phi)) \ldots\ldots\ldots\ldots (13)$$

Similarly, the forward rotating wave represented by $sin(x - (1-s)\omega_o t - \pi/2 - 1/2(\beta + \phi))$ is a wave which rotates at the same angular speed $(1-s)\omega_o$ with the rotor and in the same direction and will therefore impart a reluctance torque on the rotor. The amplitude of the torque producing mmf wave again pulsates in accordance with $2M_2\sin(s\omega_o t - 1/2(\beta - \phi)$.

5.0 TORQUE MECHANISM OF THE DEVICE

The device has composite induction motor stators but the rotors have salient poles which rotate at angular speed w with its axis at some angle δ to the axis of the stator mmf which rotates at synchronous speed ω_o. As long as the angle δ is not zero degree or some multiples of 90 electrical degrees, a reluctance torque will be set up even though there are no windings on the rotors.

The torque can be expressed in terms of energy stored in the air gap as:

$$T_e = \frac{\partial\omega}{\partial\theta} = \frac{1}{2}\phi^2\frac{\partial s}{\partial\theta} = \frac{1}{2}\frac{\partial s}{\partial\theta}\cdot\frac{N1^2}{s} = \frac{1}{2}\frac{\partial s}{s^2\partial\theta}(mm)f^2$$

It can be readily seen from eqn. 14 that torque is directly proportional to the square of mmf *($T_e \propto mmf$)*·

From eqn 10 and 13 the forward rotating mmf components responsible for torque production in machines A and B viz: $cos(x - (1-s)\omega_o t - \pi/2 - 1/2(\beta + \phi))$ and $sin(x - (1-s)\omega_o t - \pi/2 - 1/2(\beta + \phi))$ are seen to be in time quadrature. Additionally, their pulsating peak amplitudes $2M_2 cos(s\omega_o t - 1/2(\beta - \phi)$ and $2M_2 sin(s\omega_o t - 1/2(\beta - \phi)$are also in time quadrature. The physical interpretation of this phenomenon is that the two machines A and B operate complementarily in a periodic manner to produce the net torque of the composite machine. When the torque produced by machine A is a maximum say, that due to machine B is a minimum, while the net torque remains constant. That is, the torque alternates periodically from one machine to the other.

Equations 10 and 13 show that the nature of the torque developed by the machine is synchronous (i.e. synchronous torque) while operating asynchronously; since in this mode, the torque-producing mmf of the machine moves in synchronism with the rotor speed.

The torque slip curve of the machine is as shown in fig. 6.

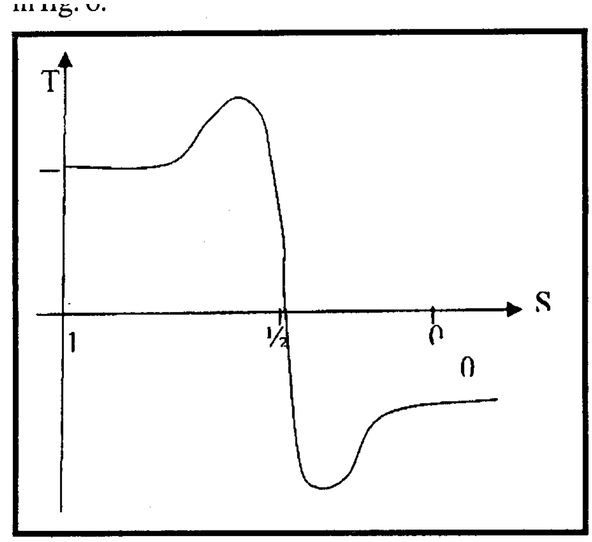


Fig. 6: Torque-slip curve of the machine

For ½ < s < 1 the device operates as a motor, and as a generator for 0 < s < ½ if the rotor shaft is driven beyond half synchronous speed point ($w_o/2$ or s = 1/2) by an external mechanical drive such as a pony motor. If the torque slip curve of the device is superimposed on that of an induction motor, it becomes very obvious that its torque-slip curve resembles that of an induction motor having twice as many magnetic poles and with its operational range squeezed between 0< s < 1.

At $\omega = \omega_o/2$ (s = 1/2*)* the circulating current produces a stationary field with respect to the stator. If the stator is also fed with direct current to produce a stationary field as well, a synchronous torque will then be developed.

For one unit of the coupled machines to possess the features of self-starting and running requires the additional unique features that the number of stator poles differs from the number of rotor poles and that there will be another set of windings with a different number of poles [7]. When the first winding which determines the number of stator poles is connected to the mains supply and the second winding is short circuited, it circulates a harmonic current of (2s-1)ωo frequency. The interaction of the currents in two windings produces torque.

6.0 COMPARISON OF THE NOVEL CONFIGURATION IN THE ASYNCHRONOUS MODE WITH A CONVENTIONAL INDUCTION MACHINE.

Performance of the coupled machine set in the asynchronous mode is inferior to that of the conventional induction motor of comparable size on account of lower pull-out and starting torque. The lower starting torque is attributable to the high ratio of effective secondary (auxiliary) winding leakage reactance to its effective resistance. The lower pull-out is due to the high leakage reactance compared to an induction machine. This leakage reactance comprises the normal leakage reactance and the quadrature axis reactance. The high leakage reactance is apparent because the operation of the machines dependent in a part only of the main flux for power transfer while the other part is for magnetization of the core, such that the magnetization current is therefore higher than that of induction machine. Additionally, the primary leakage reactance is of the same order as that of the secondary and results in high reactance drop, which reduces the voltage available for power transfer.

In order to improve the output of the machine set, the leakage reactance must be minimized by optimizing the rotor design. This can be achieved by any strategy that provides a high direct to quadrature axes reactance. Since leakage reactance is the sum of the conventional leakage reactance and quadrature axis reactance X_q ... any design that optimizes X_d/X_q ratio must additionally bring about a reduction in X_q

7.0 CONCLUSION/COMMENTS

A successful adaptation of Feedback Electrical Machine Tutor (EMT) 180 as a composite asynchronous reluctance motor without rotor conductors has been presented. This unusual application of the feedback EMT 180 machine demonstrates primarily that reluctance machines without rotor conductors can be made to run stably in the asynchronous mode. The device develops synchronous torque at asynchronous speeds. However, the output torque of the device is relatively poor. The poor torque could be easily explained from the fact that the design of the machine (EMT 180) of course could not have had the present application in mind and consequently, the design is very far from being optimal for the present purpose. This explains why efficiency tests and other quality performance tests were not considered. Additionally, the circulating current of (2s-1)u_o frequency which is responsible for starting and running of the device in the asynchronous mode is very small when compared to the u_o frequency current and accounts for low output torque in the asynchronous mode, especially at starting [6]. Any strategy, which boosts the harmonic current, will invariably enhance the starting torque and efficiency in this mode. Improvement of the output torque is being investigated and will be reported soon.

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