

Starting, Steady-State Modelling and Simulation Studies Of Single-Phase Transfer-Field Reluctance Motor, Operating In the Asynchronous Mode

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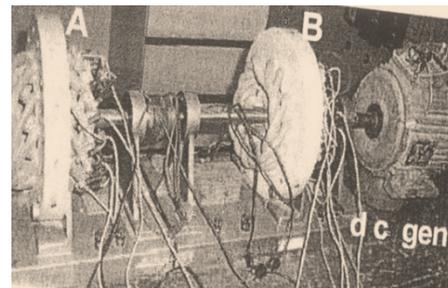
Abstract- The work presents starting, steady-state modelling and simulation studies of single-phase transfer field reluctance motor operating in the asynchronous mode from which the performance indices could be predicted. The machine is made up of two similar motors that are integrally wound and mechanically coupled together, but with their pole axes 0.5π degree out of phase in space. The transfer field machine in general is a low speed machine operating at half the synchronous speed of a normal induction machine. The equivalent circuit of the machine is derived using d-q-o transformation fundamentals. The speed range of the machine unlike the normal induction machine counterpart with slip range $0 \leq s \leq 2$, has a corresponding slip range $0.5 \leq s \leq 1.5$. The simulation results reveal a good similarity in its steady state characteristics with that of the existing normal single phase induction motor counterpart. Obviously, all single phase asynchronous motors are not self starting. They suffer the severe problem of getting the rotor rotate when started. The designed value of capacitor necessary for satisfactory starting performance of the machine is also discussed. Due to its inherent half speed characteristics, the possible areas of application are limited and are also suggested in the work.

Index Terms- asynchronous mode, single-phase transfer field machine, induction machine, slip, half-speed, clockwise rotating field, counter-clockwise rotating field.

I. INTRODUCTION

Basically, the asynchronous machines are those machines whose rotors rotate at speeds other than the synchronous speed of the rotating magnetic field in the air gap (Obute et al 2010). These machines are notably induction machines and transfer field machines. The asynchronous machine is reversible in the sense that it can operate as either a motor or a generator at a time. The mode of operation of the machine is a function of the speed of the rotating field in relation to the rotor. In reality, all asynchronous machines are basically motors. The single phase operation of the induction motor dates over several decades ago. However, the single phase operation of transfer field reluctance motor is new and gradually gaining ground in literature. In general, a reluctance machine is an electric machine in which torque is produced by the tendency of a movable part to move into a position where the inductance of an energized phase

winding is a maximum. The single phase transfer field reluctance machines are basically single-phase induction motors built with variable air-gap reluctance and with no d.c. supply on the rotor. The machine in its most primitive form comprises two identical salient-pole machines (A&B) whose rotors are mechanically coupled together but with their pole axes displaced by 0.5π electrical radians in space. Each machine unit has two sets of windings, identifiable as main and auxiliary windings respectively. The main windings of both machines are connected in series. The auxiliary windings are also connected in series but are transposed and short-circuited. No winding (conductor) is necessary in either of the rotors. The pictorial/connection diagrams are shown in fig. 1 (a and b) respectively. This class of machines has a peculiar advantage over the normal induction motor counterpart from the control point of view, since the auxiliary winding terminals, which act as the rotor conductors in normal induction machines are readily available without the use of slip-rings or current gears (Agu 1978).



(a)

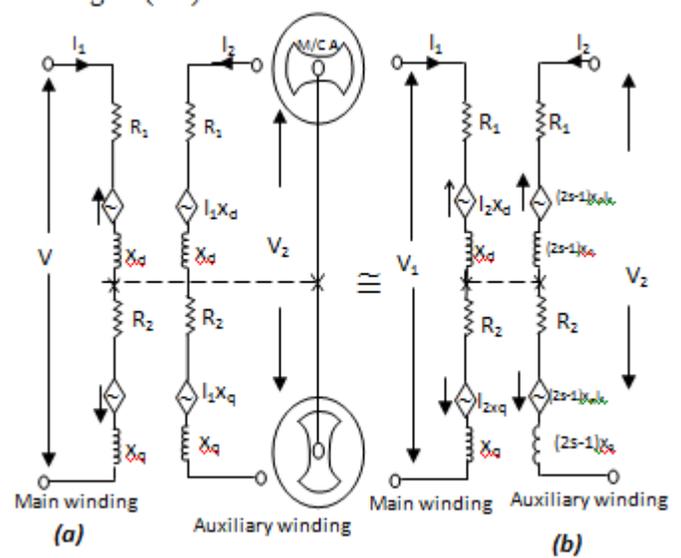
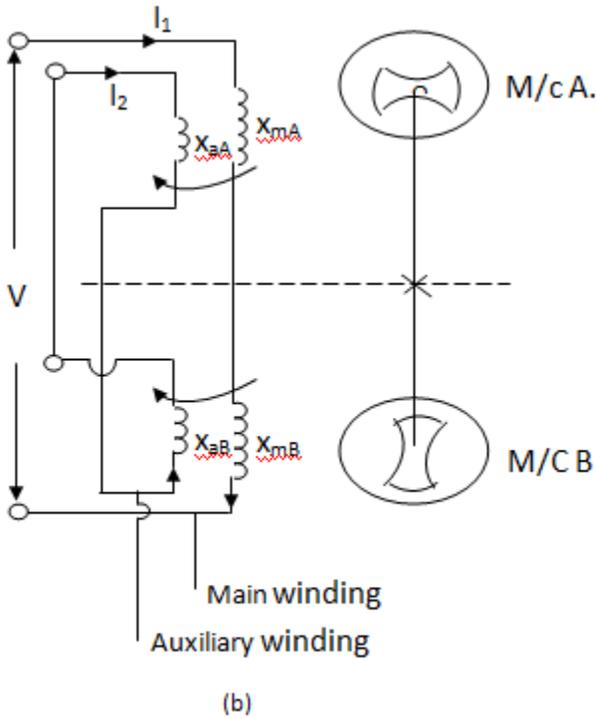


Fig. 2 - Modified circuit models of single phase transfer field reluctance motor

- a) – Motor under standstill condition ($s = 1$)
- b) – Motor under running condition at variable slip $(2s-1)$

Where

I_1 = Main winding current of machine A and B, I_2 = Auxiliary winding current of machine A and B, X_{mA} = Main winding reactance of machine A, X_{MB} = Main winding reactance of machine B, X_{aA} = Auxiliary winding reactance of machine A, X_{aB} = Auxiliary winding reactance of machine B, V = Supply voltage.

Fig. 1a – The pictorial diagram of transfer field reluctance motor (Courtesy of machine laboratory University of Nigeria Nsukka)

b – The connection diagram of transfer field reluctance motor

II. EQUIVALENT CIRCUIT OF SINGLE PHASE TRANSFER FIELD RELUCTANCE MOTOR

In the course of developing the equivalent circuit of single phase transfer field motor, fig. 1b is redrawn for clarity and then analysed as shown in Fig. 2 (a/b) below:

From fig 2a,

$$V_1 = I_1(R_1+R_2) + I_2 x_d - I_2 x_q + I_1(x_d+x_q)$$

$$= I_1 (R_1+R_2) + I_1 (x_d+x_q) + I_2(x_d-x_q) \dots 1$$

Since windings are identical, $R_1 = R_2$

$$\therefore V_1 = 2I_1 R_1 + I_1 (x_d+x_q-x_d+x_q) + I_1 (x_d-x_q) + I_2(x_d-x_q)$$

$$= 2I_1 R_1 + 2x_q I_1 + (x_d-x_q) [I_1+I_2] \dots 2$$

Similarly, from fig 2b,

$$V_2 = I_2(R_1+R_2) + (2s-1)x_d I_1 - (2s-1)x_q I_1 + (2s-1)x_d I_2 + (2s-1)x_q I_2 \dots 3$$

Since windings are identical, $R_1 = R_2$

$$\therefore V_2 = 2R_2 I_2 + I_2 [(2s-1)x_d + (2s-1)x_q] + I_1 [(2s-1)x_d - (2s-1)x_q]$$

$$\frac{V_2}{(2s-1)} = \frac{2R_2 I_2}{(2s-1)} + I_2 [x_d + x_q] + I_1 [x_d - x_q]$$

$$\Rightarrow \frac{V_2}{(2s-1)} = \frac{2R_2 I_2}{(2s-1)} + I_2 (x_d + x_q - x_d + x_q) + I_2 (x_d - x_q) + I_1 (x_d - x_q)$$

$$\Rightarrow \frac{V_2}{(2s-1)} = \frac{2R_2 I_2}{(2s-1)} + 2x_q I_2 + (x_d - x_q) [I_2 + I_1]$$

$$\frac{V_2}{(2s-1)} = \left[\frac{2R_2 + 2x_q}{(2s-1)} \right] I_2 + (x_d - x_q) [I_2 + I_1] \dots 4$$

From the analysis of the circuit of fig. 2, it could be observed that equations 2 and 4 result in an equivalent circuit shown in fig 3 below.

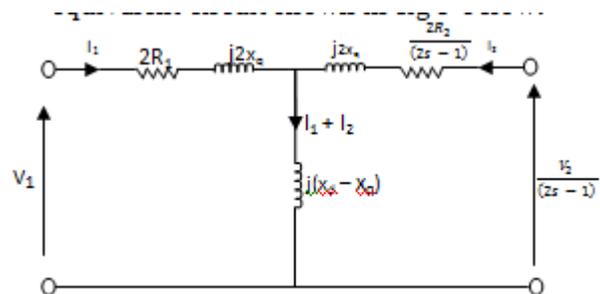


Fig. 3 - Equivalent circuit of single-phase reluctance motor
 Since the auxiliary winding of Fig. 1b is short-circuited; then fig. 3 yields $\frac{V_2}{2s-1} = 0$.
 Hence Fig 3 is redrawn as below;

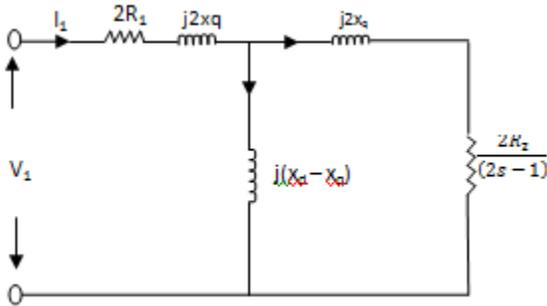


Fig 4 - Equivalent circuit of the machine when the output voltage $\frac{V_2}{2s-1}$ of Fig 3 is shorted.

Table 1 – Parameters of the experimental machine of fig. 1

Parameter	Value
L_{md}	133.3mH
L_{mq}	25.6mH
$L_m = L_a$	25.6mH
L_s	24mH
$r_m = r_a$	3.0Ω
r_s	2.5Ω
V	220V
F	50Hz
J	$1.98 \times 10^{-3} \text{ kgm}^3$
No of poles P	2

From fig. 4 and table 1.

If $2R_1 = r_m, 2X_q = X_m = X_a$
 $2R_2 = r_a, X_d - X_q = X_{ma}, NB - (X=2\pi fL)$

Then fig. 4 can be redrawn as below;

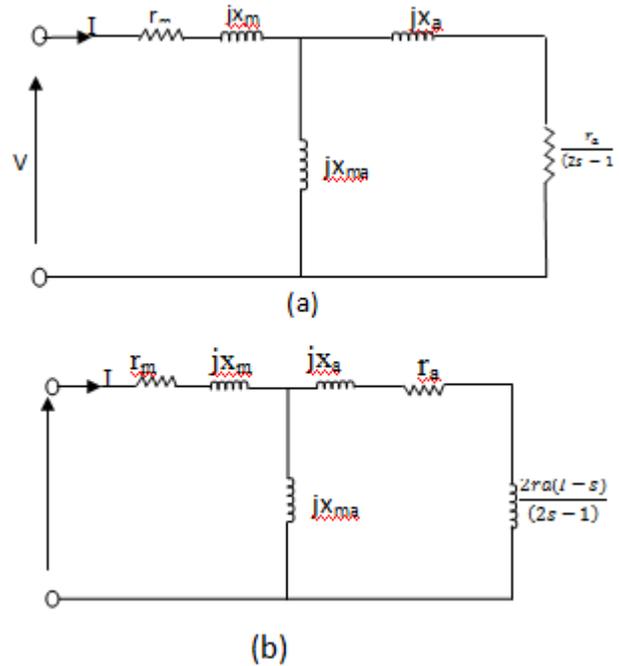


Fig. 5 (a/b) – Steady-state equivalent circuits of single phase transfer field motor with the machine parameters.

III. ROTOR SLIP WITH RESPECT TO TWO ROTATING FIELDS.

All single phase asynchronous motors suffer from a severe handicap. Since there is only one phase on the stator winding, the magnetic fields in all single-phase asynchronous motors do not rotate. Instead it pulses, getting first larger and then smaller, but always remaining in the same direction. Because there is no rotating stator magnetic field, all single-phase asynchronous motors have no starting torque.

However, once the rotor begins to turn, an induced torque will be produced in it. This stationary pulsating magnetic field of single phase motor can be resolved into two rotating magnetic fields, each of equal magnitude but rotating in opposite directions. The motor responds to each magnetic field separately, and the net torque in the machine will be the sum of the torques due to each of the two magnetic fields (Stephen Chapman 2005).

The flux density (B_s) of the stationary magnetic field is given by,
 $B_{s(t)} = B_{max} \cos\omega t \dots 1$

A clockwise-rotating magnetic field (B_{cw}) can be expressed as;

$B_{cw(t)} = (0.5 B_{max} \cos\omega t) \hat{i} + (0.5 B_{max} \sin\omega t) \hat{j} \dots 2$

Similarly, a counter clockwise –rotating magnetic field (B_{ccw}) can be expressed as;

$B_{ccw(t)} = (0.5 B_{max} \cos\omega t) \hat{i} + (0.5 B_{max} \sin\omega t) \hat{j} \dots 3$

Hence, equation 1 becomes;

$B_s(t) = B_{cw(t)} + B_{ccw(t)} \dots 4$

For the single phase transfer field reluctance motor, the reaction between the fields created by the current in the main winding, causes the rotation of the rotor. The difference between the rotor speed (ω_r) and the synchronous speed (ω) is the slip(s), usually given as a percentage of the synchronous speed.

The size of mechanical load on the motor varies directly as the slips (s) and inversely as the rotor speed (ω_r). So far, the

characteristic features of single phase reluctance motor is similar to that of a normal induction motor counterpart, but with synchronous speed being half that of the normal synchronous motor.

If we let us suppose that;

ω_R = synchronous speed of the transfer field motor, then from the foregoing expression;

$$\omega_R = 0.5\omega \quad \dots 5$$

Generally, for normal induction machine, slip s , ω_r and ω are related by;

$$\omega_r = \omega (1-s) \quad \dots 6$$

Similarly, for the half speed machine of our concern, the slip (S_{cw}) with respect to clockwise rotating field is given by;

$$S_{cw} = \frac{\omega_R - \omega_r}{\omega_R} \quad \dots 7$$

By substituting equation 5 into equation 7, we have;

$$S_{cw} = \frac{\omega - 2\omega_r}{\omega} \quad \dots 8$$

Also, the rotor direction of rotation is in opposition to that of the counter clockwise rotating field, therefore, the slip (S_{ccw}) with respect to the counter clockwise rotating field is;

$$S_{ccw} = \frac{\omega_R - (-\omega_r)}{\omega_R} = \frac{\omega_R + \omega_r}{\omega_R} \quad \dots 9$$

By substituting equation 5 into 9, we have;

$$S_{ccw} = \frac{\omega + 2\omega_r}{\omega} \quad \dots 10$$

Hence, substituting equation 6 into 8 and 10, we have;

$$S_{cw} = \frac{\omega - 2\omega(1-s)}{\omega} = 2s - 1 \quad \dots 11$$

Similarly,

$$S_{ccw} = \frac{\omega + 2\omega(1-s)}{\omega} = 3 - 2s \quad \dots 12$$

If the clockwise and counterclockwise rotation of the machine at slip s is considered, then fig 5a is modified as below;

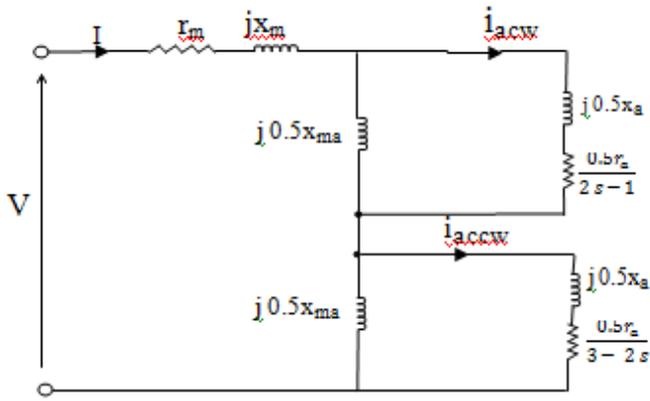


Fig. 6 – Modified equivalent circuit of single phase transfer-field reluctance machine rotating at slip s

From the modified equivalent circuit of fig. 6, let Z_{cw} and Z_{ccw} be the impedances due to clockwise and counter clockwise rotating field respectively.

$$\text{Hence, } Z_{cw} = \frac{\left(\frac{0.5r_a}{2s-1} + j0.5X_a\right)(j0.5X_{ma})}{\left(\frac{0.5r_a}{2s-1} + j0.5X_a\right) + (j0.5X_{ma})} \quad \dots 13$$

$$Z_{ccw} = \frac{\left(\frac{0.5r_a}{3-2s} + j0.5X_a\right)(j0.5X_{ma})}{\left(\frac{0.5r_a}{3-2s} + j0.5X_a\right) + (j0.5X_{ma})} \quad \dots 14$$

Similarly, for the series arm, let $Z_m = r_m + jX_m$... 15

$$\therefore \text{ Total impedance of the circuit } Z_T = Z_m + Z_{cw} + Z_{ccw} \quad \dots 16$$

$$\Rightarrow I = \frac{V}{Z_T} \quad \dots 17$$

More-still, by current division principle;

$$i_{acw} = \left[\frac{j0.5X_{ma}}{\left(\frac{0.5r_a}{2s-1} + j0.5X_a\right) + (j0.5X_{ma})} \right] I \quad \dots 18$$

Similarly;

$$i_{accw} = \left[\frac{j0.5X_{ma}}{\left(\frac{0.5r_a}{3-2s} + j0.5X_a\right) + (j0.5X_{ma})} \right] I \quad \dots 19$$

IV. POWER ACROSS AIR – GAP, OUTPUT POWER AND TORQUE IN SINGLE PHASE TRANSFER FIELD RELUCTANCE MOTOR.

Mechanical power and torque can be computed by application of power and torque relations. The torques produced by the clock-wise (cw) and counter clockwise (ccw) fields each can be treated. The interactions of the oppositely rotating flux and mmf waves cause torque pulsations and twice stator frequency but produce no average torque.

Hence, the performance characteristics of single-phase transfer field reluctance motor can be obtained by a close analysis of the circuit model of the motor given in fig. 6.

The air-gap power delivered by the stator winding to the clock-wise field ($P_{g_{cw}}$) and the counter clockwise field ($P_{g_{ccw}}$) are given by;

$$P_{g_{cw}} = \left(\frac{0.5r_a}{2s-1}\right) (i_{acw})^2 \text{ watts} \quad \dots 20$$

Similarly,

$$P_{g_{ccw}} = \left(\frac{0.5r_a}{3-2s}\right) (i_{accw})^2 \text{ watts} \quad \dots 21$$

$$\text{Also, the mechanical power output for the clockwise field } P_{m_{cw}} = 1 - (2s-1) p_{g_{cw}} = 2(1-s) P_{g_{cw}} = \left[\frac{r_a(1-s)}{2s-1}\right] [i_{acw}]^2 \text{ watts} \quad \dots 22$$

$$\text{Similarly, the mechanical power output for the counter clockwise field } P_{m_{ccw}} = [1 - (3 - 2s)] P_{g_{ccw}} = -2(1-s) P_{g_{ccw}} = -\left[\frac{r_a(1-s)}{3-2s}\right] [i_{accw}]^2 \text{ watt} \quad \dots 23$$

The mechanical net power output is the algebraic sum of equations 22 and 23.

$$\text{That is, } P_{mn} = P_{m_{cw}} + P_{m_{ccw}} = r_a (1-s) \left(\frac{(i_{acw})^2}{2s-1}\right) - \frac{(i_{accw})^2}{3-2s} \text{ watt} \quad \dots 24$$

The electromagnetic torque developed by the two fields can be expressed as;

$$T_{cw} = \frac{1}{\omega} P_{g_{cw}} \text{ (N-m)} \quad \dots 25$$

Putting equation 20 into 25 we have;

$$T_{cw} = \left[\frac{1}{\omega} \left(\frac{0.5r_a}{2s-1}\right) (i_{acw})^2\right] \text{ N-m} \quad \dots 26$$

$$\text{Similarly, } T_{ccw} = \frac{1}{\omega} P_{g_{ccw}} \text{ N-m} \quad \dots 27$$

Putting equation 21 into 27 yields;

$$T_{ccw} = -\left[\frac{1}{\omega} \left(\frac{0.5r_a}{3-2s}\right) (i_{accw})^2\right] \text{ N-m} \quad \dots 28$$

N.B: ω is the synchronous angular velocity in mechanical radians per second.

Since torque of the counter clock wise field (T_{ccw}) is in the opposite direction to that of the clockwise field (T_{cw}), the net internal torque (T_{net}) of the motor is;

$$\begin{aligned} T_{net} &= T_{cw} + T_{ccw} \\ &= \frac{1}{\omega} (P_{gcw} - P_{gccw}) \\ &= \left[\left(\frac{0.5ra}{\omega} \right) \left(\frac{(i_{acw})^2}{2S-1} - \frac{(i_{accw})^2}{3-2S} \right) \right] \text{ N-m} \quad \dots 29 \end{aligned}$$

V. TORQUE-SLIP CHARACTERISTICS OF SINGLE PHASE TRANSFER FIELD RELUCTANCE MOTOR.

If the values of the supply voltage, frequency and other machine parameters are given as in table 1, equations 26, 28, and 29 become essential tool for the steady state simulation of the machine performance characteristics.

Plots of the clockwise torque T_{cw} , counter clockwise torque T_{ccw} net torque T_{net} and the superimposition of T_{cw} , T_{ccw} and T_{net} against various values of slip s are shown in Fig. 8a, b, c, and d respectively.

VI. EFFICIENCY OF SINGLE PHASE TRANSFER FIELD RELUCTANCE MOTOR

Since the rotor currents produced by the two components air-gap fields are of different frequencies, the total auxiliary winding I^2R loss is the numerical sum of the losses caused by each field.

Thus; clockwise field rotor (auxiliary winding) I^2R loss = $(2s-1) P_{g_{cw}}$.

Counter clockwise field rotor (auxiliary winding) I^2R loss = $(3-2s) P_{g_{ccw}}$. This contributes immensely to the overall reduction in efficiency of the machine. More-still, the poor pull-out and starting torque of single phase transfer field motor to an extent affect its efficiency and thereby makes it inferior to those of a comparable single-phase induction motor counterpart (Anih and Obute, 2012). The overall effect of these losses is a reduction in the net mechanical power output of the machine and the corresponding efficiency.

The motor efficiency (ξ) is given by;

$$\xi\% = \frac{\text{Net mechanical power output}}{\text{Input power}} \times \frac{100}{1} \quad \dots 30$$

Where input power = $VI \cos \phi$...31

But the motor's power factor ($\cos \phi$) = $\frac{r_T}{Z_T}$

$$= \frac{r_m + r_{cw} + r_{ccw}}{Z_m + Z_{cw} + Z_{ccw}} \quad \dots 32$$

Where, r_m , r_{cw} , r_{ccw} are the real parts of Z_m , Z_{cw} and Z_{ccw} respectively.

\therefore Putting equations 17,24,31 and 32 into equation 30 we have;

$$\xi\% = \left[\frac{r_a(1-s) \left(\frac{(i_{acw})^2}{2S-1} - \frac{(i_{accw})^2}{3-2S} \right)}{(r_m + r_{cw} + r_{ccw})} \left(\frac{Z_m + Z_{cw} + Z_{ccw}}{V} \right)^2 \right] \times 100 \quad \dots 33$$

By careful substitution of the machine parameters with varying values of s within the stipulated range, a matlab plot of the efficiency ξ against slip s , for the operation of the machine is

obtained as shown in fig 9. It is seen that the optimum efficiency of the machine is very low at about 38%.

VII. STARTING OF SINGLE-PHASE TRANSFER FIELD RELUCTANCE MOTOR

All single phase asynchronous motors are not self starting. The problem in such single phase motor design is to get the rotor started. There are several ingenious methods for doing this. The method specially applied for this machine is the split-phase method. The principle of split-phasing is to create at starting a condition similar to a two-phase stator winding carrying two-phase current so that a rotating magnetic field is produced. This is achieved by providing, in addition to main single-phase winding, a starting winding which is displaced in space by 90° with the main winding on the stator slots (S.K Bhattacharya 2004). If two windings so placed are connected in parallel to a single phase source, the field produced will alternate but will not revolve, since the two windings are equivalent to one single phase winding. If, however, an impedance (resistance, inductance or capacitance) is connected in series with the one of these windings, the current is made to differ in time phase (Jone and Prior, 1972).

By proper selection of such impedance, the current may be made to differ by as much as 90° thereby producing a rotating field, likened to a two phase motor. However, if the difference between the two currents is less than 90° and the two mmfs are not equal, starting torque will be small, though may be sufficient to start the motor. Hence, accurate design of the impedance necessary to achieve the purpose becomes imperative. In this design, the single phase transfer field motor uses a single-valued capacitor for the starting purpose as shown in fig. 7

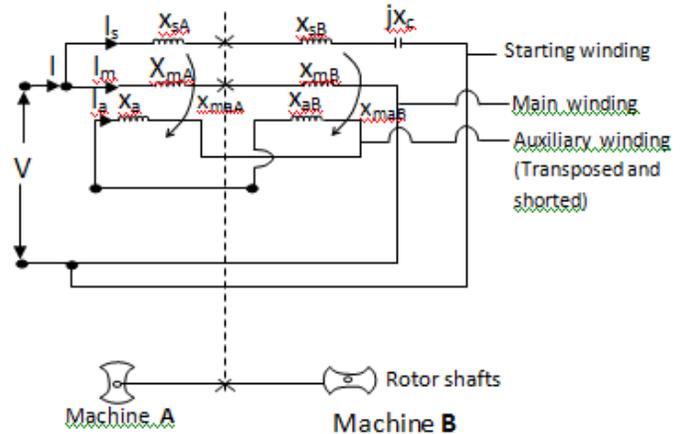


Fig 7- The single phase transfer field reluctance motor with starting windings and capacitor.

Where,

V = Applied voltage, I = Source Current, I_m = Main winding Current, I_s = Starting winding Current, I_a = Auxiliary winding Current, x_{mA} = Main winding of Machine A, x_{mB} = Main winding of Machine B, x_{aA} = Auxiliary winding of Machine A, x_{aB} = Auxiliary winding of Machine B, x_{SA} = Starting winding of

machine A, x_{sB} = Starting winding of machine B, jx_c = Capacitive reactance of the starting capacitor (c).

VIII/I – Designing for the value of the starting capacitor necessary to place the main and starting winding currents (i_m/i_s) in 90° phase shift.

With careful use of the machine parameters of table 1, the main winding impedances (for machine A and B) of fig. 7 can be calculated as below.

$$Z_{m(A/B)} = Z_{mA} + Z_{mB} \quad \dots 34$$

Since $Z_{mA} = Z_{mB} = Z_m$ (as $x_{mA} = x_{mB} = x_m$)
 $\Rightarrow Z_{m(A/B)} = 2Z_m$
 $= 2(r_m + jx_m)$...35

By substitution of machine parameters

$$Z_{m(A/B)} = 2(r_m + jx_m)$$

$$= 2(3 + j8.044)$$

$$= (6 + j16.088)$$

$$= 17.17 \angle 69.55^\circ \Omega$$

Obviously, the main winding current I_m lags behind the applied voltage V by 69.55° .

$$\text{Hence } I_m = \frac{V}{Z_{m(A/B)}} = \frac{220}{17.17 \angle 69.55^\circ}$$

$$= 12.81 \angle -69.55^\circ A$$

For an efficient design, the starting windings usually have almost the same size of wire and almost as many turns as the main windings. We therefore have that the starting winding impedance for the machine A/B, is

$$Z_{s(A/B)} = Z_{sA} + Z_{sB} \quad \dots 36$$

So far $Z_{sA} = Z_{sB} = Z_s$, $X_{sA} = X_{sB} = X_s$
 $\therefore Z_{s(A/B)} = 2Z_s$
 $= 2(r_s + jx_s) \Omega$

But from the machine parameters of table 1
 $Z_{s(A/B)} = 2(2.5 + j7.544) = (5 + j15.088) \Omega$

Since, time phase angle between starting winding current I_s and main winding current I_m is 90° , so starting winding current I_s must lead the applied voltage V by;

$$\phi_s = 90^\circ - 69.55^\circ$$

$$= 20.45^\circ$$

If X_c is the capacitive reactance of the capacitor connected in series with the starting winding, then impedance of the starting winding for the two machines A/B, will be given as

$$Z_{s(A/B)} = (5 + j15.088 - jX_c) = [5 + j(15.088 - X_c)] \Omega$$

But for starting winding,

$$T_{an} \phi_{s(A/B)} = \frac{15.088 - X_c}{5}$$

$$\Rightarrow X_c = 15.088 - 5 \tan \phi_s (A/B)$$

$$= 15.088 - 5 \tan(-20.45^\circ)$$

$$= 15.088 - (-1.864)$$

$$= 15.088 + 1.864$$

$$= 16.952 \Omega$$

$$\text{If } X_c = \frac{1}{2\pi f c}$$

$$\Rightarrow c = \frac{1}{2\pi f X_c}$$

$$= (2 \times 3.142 \times 50 \times 16.952)^{-1} F$$

$$= 188 \mu F$$

∴ From the above design, the value of the starting capacitor (C) necessary to place the main and starting winding currents (I_m/I_s) in quadrature is 188μF.

VIII. SUGGESTED AREAS OF APPLICATION

The transfer field machine in general is a low speed machine operating at half the speed of a normal induction machine (Agu 1978). Single phase motor without rotating windings will have future in a variety or special applications such as very slow speed fixed frequency drives, linear motor for small scale transport systems etc. It is common knowledge that a low speed machine will find application in domestic appliances requiring low speed drives such as grinding machines for perishables. However, many household are invariably supplied with single-phase, necessitating the development of single phase transfer field machine for the purpose of wider applications.

IX. DISCUSSION OF RESULTS/CONCLUSION

This paper has presented the equivalent circuit of a single phase transfer field machine from which the performance indices can be predicted. It may be noted that the torque slip curves due to clockwise, counter clockwise and resultant magnetic fields have been drawn for a slip range of $0.5 \leq s \leq 1.5$. From fig.8c, it is observed that;

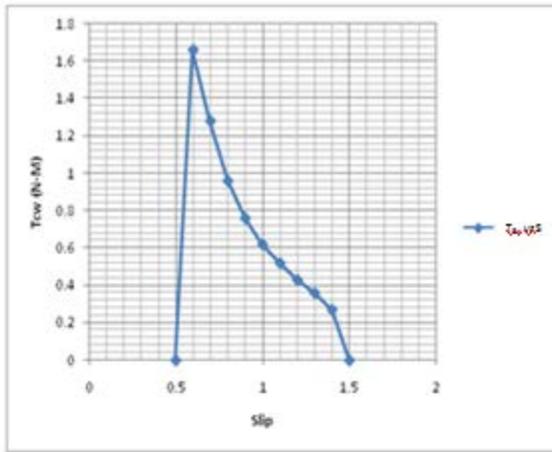
- a. Net torque T_{net} at standstill of the rotor is zero. That is at slip $s = 1$. The torques developed by the clockwise and counter clockwise fields cancel each other. This is responsible for the non self starting ability of the motor.
- b. Assuming the rotor is given an initial rotation in any direction, the net torque developed causes the rotor to continue to rotate in the direction in which it is started
- c. As a corollary to a, the net torque can also be zero at some values of rotor speed below the synchronous speed.

Additionally, the machine suffers severe electrical losses which account for its low efficiency when compared to an equivalent single phase induction motor counterpart. This is as a result its excessive leakage reactance. In addition, the intersegment of conductors between the two machine sections contributes to the leakage reactance and does not in any way contribute to energy transfer in the machine.

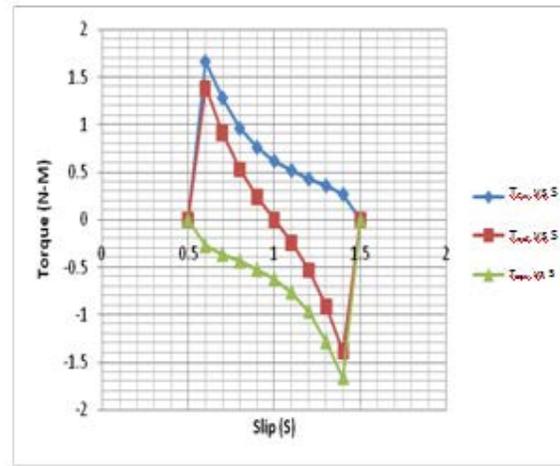
However, the design analysis for the improvement in the efficiency of the machine is on the pipeline as it is being studied by the authors.

X. ACKNOWLEDGEMENT

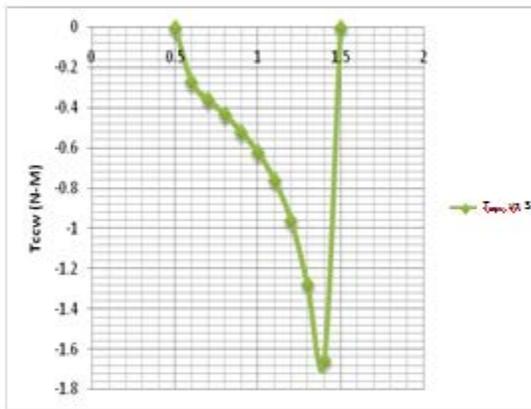
The authors acknowledge the academic staff of our departments for their constructive criticisms geared to make the work better. Our cardiac appreciation also goes to Electrical Engineering Department of University of Nigeria Nsukka for availing her prototype machines for experimentation and analysis.



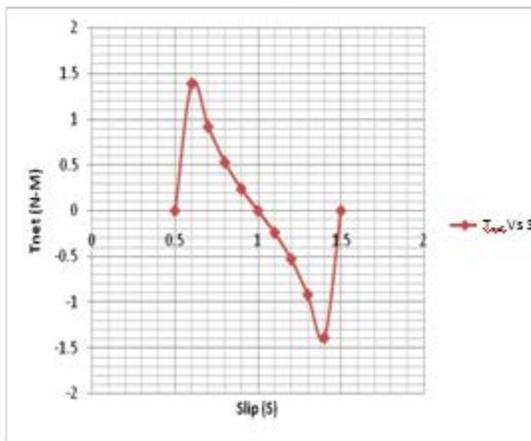
(a)



(d)



(b)



(c)

Fig 8: (a) – Torque developed due to clockwise rotating field
 (b) – Torque developed due to counter clockwise rotating field
 (c) – Torque developed due to reaction of (a) and (b)
 (D) Superimposition of (a), (b), and (c)

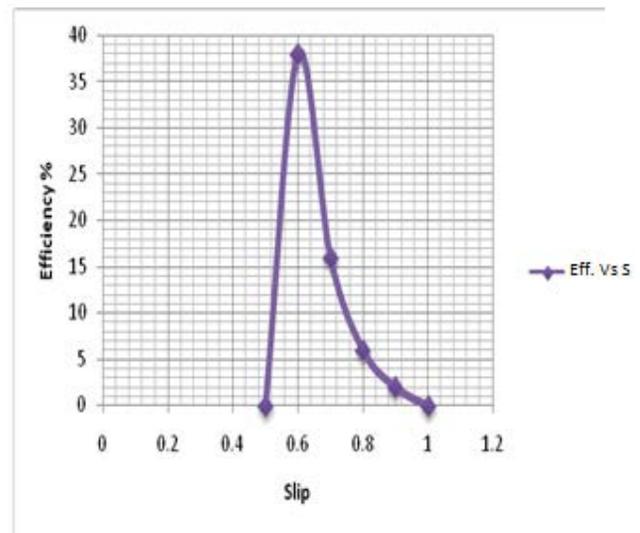


Fig 9: The machine efficiency at motoring mode

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