# Modelling and Simulation of Single-Phase Transfer-Field Reluctance Motor, Using Symmetrical Component Technique

**Oduka P.I.[1], Enemuoh F.O.[1] Obute K.C.[1]**

1 ï Department of Electrical Engineering Nnamdi Azikiwe University, Awka, Anambra State, Nigeria.

Corresponding Author - Obute Kingsley Chibueze.

Department of Electrical Engineering, Nnamdi Azikiwe University, Awka, Anambra State, Nigeria.

Email Address: obutekingsley77@gmail.com

Phone Number: +2347031575699

**ABSTRACT:** This work presents the mathematical modelling and steady ï state simulation study of single phase transfer field reluctance motor, operating in the asynchronous mode, using symmetrical components of unbalanced voltages of a 3 ï phase system approach. In electrical Engineering and other allied disciplines, the method of symmetrical components simplifies analysis of unbalanced 3 ï phase Power System both normal and abnormal conditions. The analysis of unsymmetrical fault conditions, using the method of symmetrical components, is a well known means of resolving an unbalanced three-phase system of impedances into three equivalent single-phase systems with independent impedance parameters. The above illustration simply reveals that any unbalanced three-phase system of voltages or currents can be seen as due to the super-position of two symmetrical three phase systems, having opposite phase sequence and a zero phase sequence, being equal to ordinary single-phase voltage or current system. In static machines like the transformer, the sequence impedance offered by the system are the same for positive and negative sequence currents. In case of rotating machines, like the transfer-field reluctance motor, the positive and negative sequence impedance are different (Electrical4u.com). From the fore-going, a synthesized equivalent circuit for a single-phase transfer field reluctance motor is obtained when it is considered as a three-phase transfer field reluctance motor with one of its stator windings disconnected. Empirical values were assigned to the equivalent circuit parameters. Matlab plots for the Torque/slip and Efficiency/Slip relationships for the newly existing single-phase transfer field reluctance motor with slip range $0.5 \leq s \leq 1.5$ were obtained. The curves obtained were compared with those of the normal old-aged existing single phase induction motor counter-part with slip range $0 \leq s \leq 2.0$. The curves confirmed great similarities in their performance characteristics.

**KEY WORDS:** Asynchronous Machine, Symmetrical components, Unbalanced 3- phase systems, Normal induction machine, Transfer field reluctance machine, Clockwise rotating magnetic field, Anticlockwise rotating magnetic field, Slip, Torque.

## 1 – Introduction

The development of symmetrical component analysis depends upon the fact that in balanced system of impedances, sequence currents can give rise only to voltage drops of the same sequence. Once the sequence networks are available, these can be converted to single equivalent impendence.

The theory and application of normal induction machine dates over several decades ago. Conversely, the theory and application of transfer field reluctance machine is new in the field of electrical machine.

In its broad definition, 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 maximum. Structurally, the transfer field machine is basically a reluctance machine. It differs from the simple reluctance machine in two important respects namely;

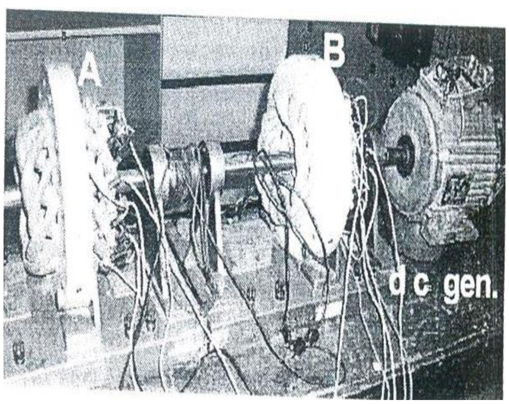
a) it has two sets of windings instead of one winding
b) each winding has a synchronous reactance which is independent of rotor position whereas the winding reactance of a simple reluctance machine varies cyclically (Agu L.A. 1984).

The primitive poly-phase transfer ï field (TF) machine was first presented as a flux bridge machine with a two air-gap three element construction (Agu L.A. 1978). Following a careful study of the equations describing the air-gap flux density distribution, it was found that a topology manipulation yields an equivalent single air-gap two-element machine of much simpler mechanical construction. The equivalent circuit of the poly-phase TF machine operating in the asynchronous mode has been reported. Thus far, studies on the TF machine have been majorly limited to the poly-phase TF machine, and to the best of our knowledge, very few researchers have considered the single ï phase operation of the TF machine. The single phase transfer field (SPTF) machine is expected to have wider applications than the poly-phase version, because most residential houses, offices and rural areas are supplied with single phase ac rather than 3-phase as power requirements of individual load items are rather small. Furthermore, single phase ac machines are invariably used in home appliances such as fans, refrigerators, vacuum clearers, washing machines, potable tools etc.

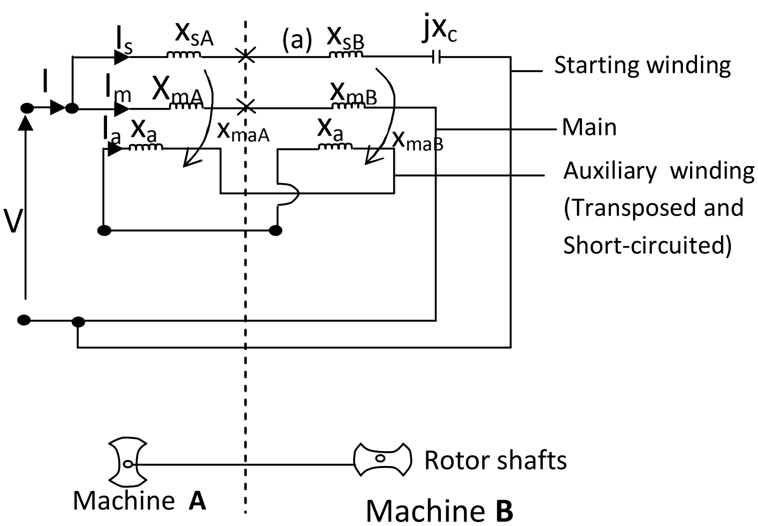
This work re-examines some aspects of the poly-phase TF machines operating in the asynchronous mode and develops the steady state equivalent circuit of the SPTF machine operating in the asynchronous mode, from which the steady state performance characteristics can be predicted. The single phase equivalent circuit of the TF machine operating in the asynchronous mode is derived in a manner which is consistent with the derivation of a single-phase induction motor by disconnecting one of its supply lines and using the concept of symmetrical component (Obute et al 2016)

## 2 ï Physical arrangement of the single-phase Transfer field reluctance machine.

The single phase transfer field reluctance (SPTF) 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 $0.5\pi$ electrical radians in space. Each unit machine comprising the TF machine has two sets of windings known as the main and auxiliary windings respectively. The two windings are electrically isolated but mechanically coupled and occupy the same stator slots for maximum coupling. The two windings are integrally wound for the same number of poles as the rotor poles. The main windings of the respective halves are connected in series and energized from the utility supply, while the auxiliary windings are connected in series opposition between the two halves of the machine as shown in fig 1b. The machine is brushless and there are no windings on the rotor; the main and auxiliary windings being located on the stator side only. The machine is not self starting and has a torque-slip curve similar to that of a single phase induction machine except that its synchronous speed is $0.5\omega_0$ instead of $\omega_o$ as obtainable in induction machines. Analogously to an induction machine the relationship between the frequency of the current in the main and auxiliary windings is; $\omega_o$: $[(\omega_o - 2\ \omega_r) = (2s\ ï\ 1)\ \omega_o]$ (Agu L.A. et al 2002). In this novel configuration, the auxiliary windings mimic the role of the rotor windings in an induction machine. The roles of the main and auxiliary windings can be interchanged and will produce the same result.




(a)




(b)

Fig 1, a ï The pictorial diagram of single phase transfer field (TF) machine

b. ï The connection diagram of single phase TF machine

## 3 ï Single-Phase Transfer Field Reluctance Machine Concept

Obviously, if one line of a three-phase transfer-field reluctance machine is opened by the way of disconnection, while the motor is running with moderate load, the machine maintains running although at a slower speed. This condition is single-phase operation and it gives the implication that the three-phase transfer-field motor has eventually become a single-phase counterpart.

The single ï phase transfer field motor is analogous to three-phase transfer field motor counterpart in which a single-phase winding replaces the three-phase windings. A single-phase current in a single-phase winding produces a pulsating, not a rotating magnetic field. Since there is only one phase on the stator winding, the magnetic fields in all single-phase asynchronous machines 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 machine responds to each magnetic field separately, and the net torque in the machine will be the cumulative sum of the torque due to each of the two magnetic fields (Stephen J.C. 2005)

The flux density ($B_s$) of the stationary magnetic field is given by;

$$B_{s(t)} = B_{max}\ \cos \omega t \qquad é\ 1$$

Equation 1 has two components.

The first component represents the resolving field moving in the positive direction, while the second component represents the revolving field moving in the negative direction, all having amplitude equal to $B_{max.}$

The fields in the positive and negative direction are known as clockwise and counter-clockwise ï rotating magnetic fields. The two fields rotate at synchronous speed $\omega_s$.

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

$B_{cw(t)} = (0.5\, B_{max}\, \mathrm{Cos}\omega t)\, \hat{\imath} + (0.5\, B_{max} \sin \omega t)\, \hat{\jmath}$ é 2

Similarity, a counter clockwise-rotating magnetic field ($B_{ccw}$) can be expressed as;

$(B_{ccw})(t) = (0.5\, B_{mas}\, \mathrm{Coswt})$ [illegible] $+ (0.5\, B_{max} \sin \omega t)\, \hat{\jmath}$ é 3

Hence, equation 3.1 becomes;

$B_s(t) = B_{cw(t)} + B_{ccw}(t)$ é 4

The resulting instantaneous torque developed due to the revolving fields has four components, viz;

(i) A torque due to the interaction of the clock-wise travelling stator winding and auxiliary windings magneto-motive force (mmf) distributions.
(ii) A torque due to the interaction of the counter-clockwise travelling stator and rotor winding mmf distribution.
(iii) A torque due to clockwise travelling stator winding mmf distribution and the counter-clockwise travelling rotor winding mmf distribution
(iv) A torque due to counter-clockwise travelling stator winding mmf distribution and the clock-wise travelling rotor winding mmf distribution.

The first component gives steady non-pulsating torque acting on the rotor in the clockwise direction and gives rise to a component torque/slip characteristic of the form obtainable from a poly-phase TF motor. The second component gives rise to a similar torque/slip character; stic, the torque acing in the opposite, counter-clockwise direction. The third and fourth components give rise to torque which pulsate at twice supply frequency and do not contribute to the mean torque of the motor. This oppositely travelling mmf distribution do not contribute the mean torque.

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 ($\omega$r) and the synchronous speed ($\omega$) is the slip (s), usually given as the percentage of the synchronous speed.

The size of mechanical load on the motor varies directly as slip(s) and inversely as the rotor speed ($\omega$r). So far, as stated before, the characteristics features of single phase reluctance motor is similar to that of a normal induction motor counterpart, but with synchronous speed being half of the normal induction motor.

If we let us suppose that;

$\omega_R$ = synchronous speed of the transfer field Motor, then from the fore going expression;

$\omega_R = 0.5\omega$ é 5

Generally, for normal induction machine, the relationship between s, $\omega_r$ and $\omega$ is given by;

$\omega_r = \omega\,(1\text{-}s)$ ...6

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

$s_{cw} = \frac{\text{[illegible]}}{\text{[illegible]}}$ é 7

If we substitute equation 5 into equation 7, we obtain;

$s_{cw} = \frac{\text{[illegible]}}{\text{[illegible]}}$ é 8

Like-wise, the rotor direction of rotation is in opposition to that of the counter clock-wise rotating field, therefore, the slip ($s_{ccw}$) with respect to the counter clockwise rotating field is;

$$s_{ccw} = \frac{\square_{\square\square}(\square\square_{\square})}{\square_{\square}} = \frac{(\square_{\square}\square\ \square_{\square})}{\square_{\square}} \qquad é\ 9$$

By substituting equation 5 into equation 9, we have;

$$s_{ccw} = \frac{\square\ \square\square\square_{\square}}{\square} \qquad é\ 10$$

If equation 6 is put into equations 8 and 10, we have;

$$s_{cw} = \frac{\square\ \square\ \square\square\ (\square\square\square)}{\square} = 2s ï 1 \qquad é\ 11$$

Similarly

$$s_{ccw} = \frac{\square\ \square\ \square\square\ (\square\square\square)}{\square} = 3\text{-}2s \qquad é\ 12$$

**3 ï Equivalent Circuit of Single-Phase Transfer Field reluctance Machine**

This forms the nucleus of this work. The equivalent circuit of the motor is derived, using symmetrical components of unbalanced three-phase systems approach.

The derivation is obtained on the assumption that the motor is a three-phase type with one of its stator windings disconnected as illustrated in fig 2 below

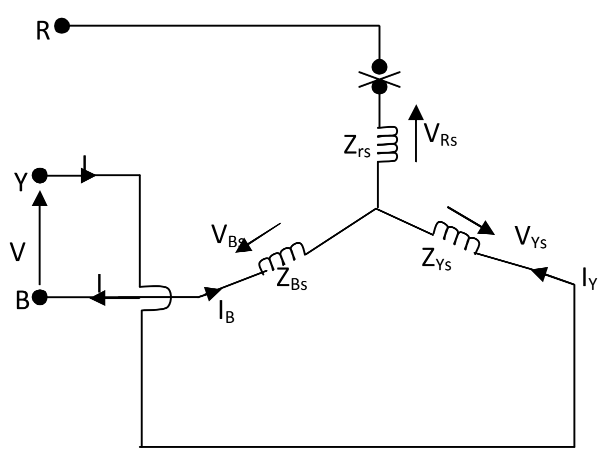



Fig 2 ï The single ï phase operation of a three phase system of supply with disconnected red phase.

From fig 2, it can be observed that;

$$\left.\begin{aligned} I_R &= 0 \\ I_Y &= I \\ I_B &= -I_Y = -I \end{aligned}\right\} \qquad 13$$

$$\left.\begin{aligned} V &= V_{YS} + (-V_{BS}) = V_{YS} - V_{BS} \\ V_{YS} &= -V_{BS} = \frac{\square\square}{\square} \\ V_{RS} &= 0 \\ Z_{YS} &= Z_{BS} \end{aligned}\right\} \qquad 14$$

Where I = Input current, $I_R$ ï Current at the Red phase, $I_Y$ ï Current at the yellow phase, $I_R$ = Current at the blue phase, $V_{RS}$, $V_{YS}$, $V_{BS}$ are voltage drops across the Red phase, yellow phase and Blue phase of the stator windings respectively.

In conformity with **C.L fortesque** theorem, the symmetrical component of fig 2 can be resolved as the sum of fig 3.3 (a,b,c) below.

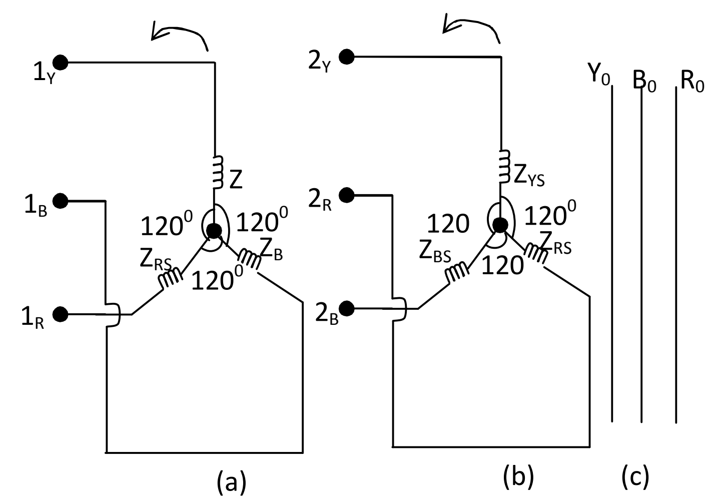



Fig 3- (a) = Positive sequence phasor
(b) = Negative sequence phasor
(c) = Zero sequence phasor (J.B. Gupta 2008)

For the positive (+)sequence phasor, taking the Yellow (Y) phasor as reference phasor as in fig 3a, we obtain that;

$I_{1Y} = I_{1Y}\, e^{jo} = I_{1Y}$ (Reference phasor)
$I_{1B} = I_{1Y} = \angle - 120^0 = a^2\, I_{1Y}$ é 15
$I_{1R} = I_{1Y} = \angle\ 120^0 = a\, I_{1Y}$

Similarly, for the negative (-) sequence quantities as in fig 3b;
$I_{2Y}\ e^{jo} = I_{2Y}\ (1+j0)$ (Reference phasor)

$I_{2B} = I_{2Y} = \angle\ 120^0 = a\ I_{2Y}$ é 16
$I_{2R} = I_{2Y} = \angle -120^0 = a^2\, I_{2Y}$

Also, for the Zero (0) phase sequence of fig 3c.

$Y_0 = B_0 = R_0$ é 17

Where a = phase sequence operator
For the unbalanced system of current of fig 2,

$I_Y = I_{IY} + I_{2Y} + I_{0Y}$
$I_B = a^2\, I_{1Y} + aI_{2Y} + I_{0Y}$ ...18
$I_R = aI_{1Y} + a^2 I_{2Y} + I_{0Y}$

The compact form of equation 18 can be put in matrix form as below:

$I_{\square}$ I I I $1_{\square\square}$
$\square I_{\square} \square = \square I$ $a^{\square}$ $a$ $\square\square 1_{\square\square}\square$ é 19
$I_{\square}$ I a $a^{\square}$ $1_{\square\square}$

The inverse form of equation 19 is given as;

$1_{\square\square}$ I I I $I_{\square}$
$\square 1_{\square\square}\square = \frac{\square}{\square}\ \square I$ a $a^{\square}\square\square I_{\square}\square$ é 20
$1_{\square\square}$ I $a^{\square}$ a $I_{\square}$

N.B: Equations (17-20) hold for voltage also.
In phase sequence representation;

$V_{YS} = V_{Y+} + V_{R-} + V_{R\mathbf{0}}$ é 21

Similarly;

$V_{BS} = V_{B+} + V_{B-} + V_{B\mathbf{0}}$

But form equation 20 equation 21 yields;

$V_{Y+} = V_{1Y} = \frac{\square}{\square}(V_{YS} + aV_{BS} + a^2\ V_{RS})$ é 23

Similarly;

$V_{Y-} = V_{2Y} = \frac{\square}{\square}(V_{YS} + a^2V_{BS} + aV_{RS})$ é 24

As l the Red phase is disconnected, $V_{RS} = 0V$
Hence, equations 3.23 and 34 yield;

$V_{Y+} = \frac{\square}{\square}(V_{YS} + aV_{BS})$

$= \frac{\square}{\square}(V_{YS} - aV_{YS})$ (as $V_{YS} = -V_{BS}$)

$= \frac{\square}{\square} V_{YS}$ (1 ï a)

Similarly;

$V_{Y-} = \frac{\square}{\square}(V_{YS} + a^2V_{BS})$

$= \frac{\square}{\square}(V_{YS} - a^2V_{YS})$

$= \frac{\square}{\square} V_{YS}\ (1 - a^2)$ é 26

Also, $V_{R\mathbf{0}} = \frac{\square}{\square}(V_{YS} + V_{BS} + V_{RS})$

$= \frac{\square}{\square}(V_{YS} + V_{BS})$

$= \frac{\square}{\square}(V_{YS} - V_{YS})$

$= 0$ é 27

Substituting equations (25 ï 27) into equation 21, we have;

$V_{YS} = \square\frac{\square}{\square}\ \square_{\square\square}\ \square 1 - \square\square + \frac{\square}{\square}\ \square_{\square\square}\ \square 1 - \square^{\square}\square + 0\ \square$

$= \frac{\square}{\square}\ \square_{\square\square}$ (1-a) (a+2)

$= (a+2)V_{Y+}$ é 28

Similarly, from equation 22;

$V_{B+}$, $V_{B-}$ and $V_{B\mathbf{0}}$ can be obtained as belowô

For + sequence phasor (taking blue phase as the reference phasor), we have;

$I_{IB} = I_{IB}e^{jo} = I_{IB}$ (reference phasor)
$I_{IR} = a^2I_{IB} = I_{IB} \angle - 120^0$ é 29
$I_{IY} = aI_{IB} = I_{IB} \angle\ 120^0$

For the – sequence quantity

$I_{2B} = I_{2B}\ (1+j\ 0) = I_{2B}$ (reference phasor)
$I_{2R} = I_{2B} \angle\ 120^0 = aI_{2B}$ ...30
$I_{2Y} = I_{2B} \angle - 120^0 = a^2I_{2B}$

As before;

$$\left.\begin{aligned} I_B &= I_{1B} + I_{2B} + I_{0B} \\ I_R &= I_{1R} + I_{2R} + I_{0R} = a^2I_{1B} + aI_{2B} + I_{0B} \\ I_Y &= I_{1Y} + I_{2Y} + I_{0Y} = aI_{1B} + a^2I_{2B} + I_{0B} \end{aligned}\right\} \quad \text{é } 31$$

Equation 31 in its compact form yields;

$$\begin{bmatrix} I_{\square} \\ I_{\square} \\ I_{\square} \end{bmatrix} = \frac{\square}{\square}\begin{bmatrix} I & I & I \\ I & a^{\square} & a \\ I & a & a^{\square} \end{bmatrix}\begin{bmatrix} 1_{\square\square} \\ 1_{\square\square} \\ 1_{\square\square} \end{bmatrix} \quad \text{é } 32$$

Inverting the matrix of equation 32 yields;

$$\begin{bmatrix} I_{\square\square} \\ I_{\square\square} \\ I_{\square\square} \end{bmatrix} = \frac{\square}{\square}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^{\square} \\ 1 & a^{\square} & a \end{bmatrix}\begin{bmatrix} I_{\square} \\ I_{\square} \\ I_{\square} \end{bmatrix} \quad \text{é } 33$$

Solving for $V_{B+}$, $V_{B-}$ and $V_{B0}$ as in $V_{Y+}$ , $V_{Y-}$ and $V_{Y0}$ yieldsl;

$$V_{B+} = \frac{\square}{\square}(V_{BS} + aV_{RS} + a^2V_{YS})$$

$$= \frac{\square}{\square}(V_{BS} + a^2V_{YS})$$

$$= \frac{\square}{\square}(a^2V_{YS} + V_{RS})$$

$$= \frac{\square}{\square}V_{YS}(a^2 - 1) \quad \text{é } 34$$

Similarly

$$V_{B-} = \frac{\square}{\square}(V_{BS} + a^2V_{RS} + aV_{YS})$$

$$= \frac{\square}{\square}(aV_{YS} \text{ ï } V_{YS})$$

$$= \frac{\square}{\square}V_{YS}(a - 1) \quad \text{é } 35$$

$$\therefore V_{BS} = V_{B+} + V_{B-} + V_{B0}$$

$$= -\frac{(\square\square\square)}{(\square\square\square)}V_{Y-} \quad \text{é } 36$$

The equation for supply voltage V can be obtained by substituting equations 28 and 36 into equation 14 as below;

$$V = V_{YS} \text{ ï } V_{BS}$$

$$= (a+2)V_{Y+} \text{ ï } \square - \frac{(\square\square\square)}{(\square\square\square)}\square_{\square\square}\square$$

$$= (a+2)V_{Y+} + \frac{(\square\square\square)}{(\square\square\square)}\square_{\square\square} \quad \text{é } 37$$

Taking similar step as in the symmetrical components analysis of voltages, the symmetrical components of the currents can be obtained as below;

$$I_{Y+} = \frac{\square}{\square}(I \text{ ï } aI)$$

$$= \frac{\square}{\square}I(1 \text{ ï } a) \quad \text{é } 38$$

Similarly;

$$I_{Y-} = \frac{\square}{\square}(I \text{ ï } a^2I)$$

$$= \frac{\square}{\square}(1 \text{ ï } a^2) \quad \text{é } 39$$

$$I_{Y0} = 0 \quad \text{é } 40$$

Transposing equations (38 ï 40) for I we have;

$$I+ = \frac{\square\square_{\square\square}}{\square\square\square} \quad \text{é } 41$$

$$I- = \frac{\square\square_{\square\square}}{\square\square\square^{\square}} \quad \text{é } 42$$

The total input impedance of fig 2 is given by;

$$Z = \frac{\square}{\square} \quad \text{é } 43$$

Substituting equations 37, 41 and 42 into equation 43, yields;

$$Z = \frac{\square_{\square\square}}{\square_{\square\square}} + \frac{\square_{\square\square}}{\square_{\square\square}}$$

$$= Z_+ + Z_- \quad \text{é } 44$$

Where

Z+ = Positive phase sequence impedances

Z- = Negative phase sequence impedances

For a three-phase transfer field reluctance motor, the phase-sequence network with positive + and negative – sequence is shown in fig 4 (a/b) respectively as below.

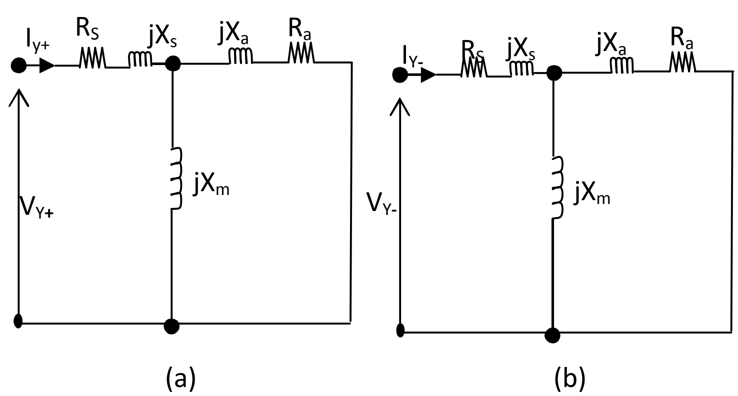



Fig 4 ï (a) Per phase + sequence of 3 – phase transfer field motor at stand-still (s = 1)
(b) Per phase – sequence of 3 – phase transfer field motor at stand-still (s = 1).

Where, $R_s$ = resistance of main (stator) winding

$X_s$ = Leakage reactance to main (stator) winding.

$X_m$ = Magnetizing reactance

$R_a$ = Stand-still auxiliary resistance to main winding

$X_a$ = Stand-still auxiliary winding leakage reactance to main winding

$I_{Y+}$, $I_{Y-}$ = Main winding currents

V = Applied voltage

To realize the equivalent circuit of the single-phase transfer field reluctance motor, the positive (+) and negative (-) phase sequence networks of fig 4, must be inter-connected in series, and on the condition that only $V_{Y+}$ produces the voltage source as in fig 5 below.

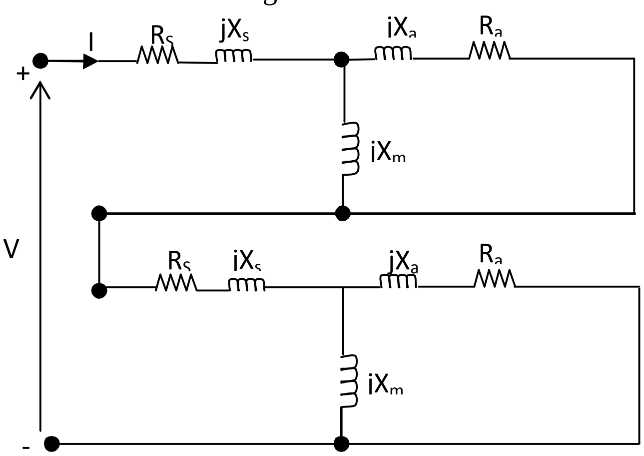



Fig5 ï Equivalent circuit of single ï phase transfer field reluctance motor at stand-still (s = 1)

Since the pulsating magnetic field is revolved into clockwise and counter clockwise fields, having equal and opposite fluxes with the motor (9), the magnitude of each rotating flux is one half of the alternating flux. Therefore, it is assumed that the two rotating fluxes are acting on the separate rotors. Hence, we then assume that the single-phase transfer field motor consists of two rotors having a common stator winding (as in induction motors) and two imaginary rotors as shown in fig 3.6 below. At stand-still, the impalance of each auxillary winding referred to the stator (main) winding is $0.5R_a + j0.5\ X_a$.

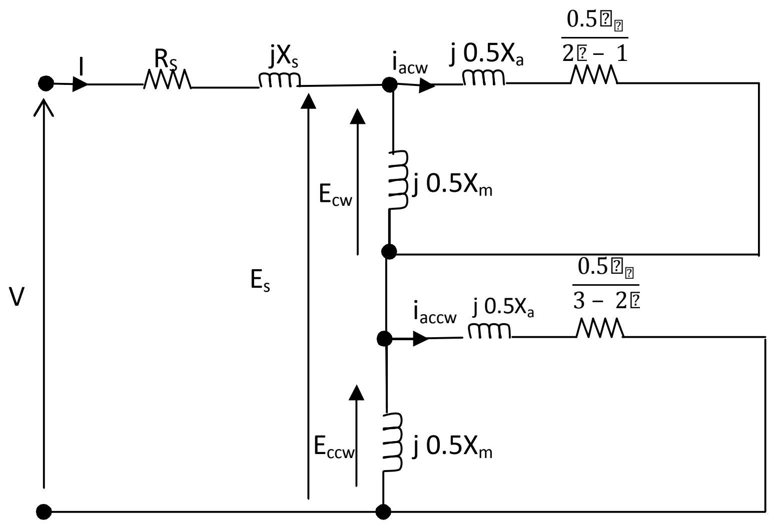



Fig 6 - Equivalent circuit of single phase transfer field reluctance motor rotating at slip s.

## 4 – Performance Characteristics of Single Phase transfer-field reluctance motor

The performance characteristics of the motor can be determined from its equivalent circuit of fig 7 for a range values of slip $0.5 \leq s \leq 1.5$. The data of the experimental machine are given in table 1 below.

**Table 1** – Parameters for steady state analysis of single phase TF machine

| S/N | Parameter | Value |
|---|---|---|
| 1 | $R_S$ | 1.20q |
| 2 | $R_a$ | 1.20q |
| 3 | $X_s$ | 1.90q |
| 4 | $X_a$ | 1.90q |
| 5 | $X_m$ | 33.82q |
| 6 | $X_{st}$ | 7.54q |
| 7 | $r_{st}$ | 2.5 q |
| 8 | F | $50H_z$ |
| 9 | No of Poles | 2 |
| 10 | V | 220v |

ISSN 2250-3153

From fig 7, the e.m.F induced in the main (stator) winding by the clock-wise and counter-clockwise fluxes are $E_{cw}$ and $E_{ccw}$ respectively.

Hence, the resultant induced e.m.f ($E_s$) in the main winding is given by;

$E_s = E_{cw} + E_{ccw}$ é 45

Since the circuits of the auxiliary (rotors) windings due to the clockwise and counterclockwise fields are identical at stand -still, we can write that;

$E_{cw} = E_{ccw}$ é 46

From equations 45 and 46,

$E_{cw} - E_{ccw} = 0.5E_s$ é 47

The auxiliary winding impedance $Z_{cw}$ due to clockwise rotating field is;

$Z_{cw} = R_{cw} + jx_{cw}$

$= \square\frac{\square.\square\square_\square}{\square\square\square\ \square} + \square 0.5\square_\square\square // \square 0.5\square_\square$

$= \frac{\square\frac{\square.\square\square\ \square}{\square\square\square\ \square}\square\ \square\square.\square\square_\square\square\square\square.\square\square_\square\ \square}{\square\frac{\square.\square\square\ \square}{\square\square\square\ \square}\square\ \square\square.\square\square_\square\square\square\ \square\square\square.\square\square_\square\ \square}$ é 48

Similarly, the auxiliary winding impedance $Z_{ccw}$ due to counter clockwise rotating field is;

$Z_{ccw} = R_{ccw} + jx_{ccw}$

$= \square\frac{\square.\square\square_\square}{\square\square\ \square\square} + \square 0.5\square_\square\square // \square 0.5\square_\square$

$= \frac{\square\frac{\square.\square\square_\square}{\square\square\ \square\square}\square\ \square\square.\square\square_\square\square\square\square.\square\square_\square\ \square}{\square\frac{\square.\square\square_\square}{\square\square\ \square\square}\square\ \square\square.\square\square_\square\square\square\ \square\square\square.\square\square_\square\ \square}$ é 49

Hence equation 45 yields;

$E_s = I\,(Z_{cw} + Z_{ccw})$

$V = I\,(Z_s + Z_{cw} + Z_{ccw})$

$\Rightarrow I = \frac{\square}{\square_\square\square\ \square_{\square\square}\ \square\ \square_{\square\square\square}}$ é 50

Where, $Z_s = R_s + jX_S$

More-still, by current division principle;

$i_{acw} = \square\frac{\square\square.\square\square_\square}{\square\frac{\square.\square\square_\square}{\square\square\square\ \square}\square\ \square\square.\square\square_\square\square\square\ (\square\square.\square\square_\square)}\square I$ é 51

Similarly;

$i_{acw} = \square\frac{\square\square.\square\square_\square}{\square\frac{\square.\square\square_\square}{\square\square\ \square\square}\square\ \square\square.\square\square_\square\square\square\ (\square\square.\square\square_\square)}\square I$ é 52

**6 – 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 ($T_{cw}$) and counter clock-wise ($T_{ccw}$) fields each can be treated. The interactions of the oppositely rotating flux and mmf waves cause torques pulsation and twice stator frequency but produce no average torques.

Still from fig 7, the air-gap power delivered by the stator (main) winding of the machine to the clock-wise field ($P_{gcw}$) and the counter clockwise field ($P_{gccw}$) are given by;

$P_{gcw} = \square\frac{\square.\square\square_\square}{\square\square\square\ \square}\square\,(i_{acw})^2$ Watts é 53

Similarly,

$P_{gccw} = \square\frac{\square.\square\square_\square}{\square\square\ \square\square}\square\,(i_{accw})^2$ Watts é 54

More still mechanical Power output for clockwise field $(Pm_{cw}) = 1- (2s-1)\,P_{gcw} = 2(1-s)\,P_{gcw}$

$= \square\square\frac{\square_\square\ (\square\square\ \square)}{\square\square\square\ \square}\square\ \ \square\square_{\square\square\square}\ \square^\square\square$Watts é 55

Similarly, the mechanical power output for the counter clock-wise for rotating field $Pm_{ccw} = [1- (3-2s)]\,Pg_{ccw}$

$= -2(1-s)\,Pg_{ccw}$

$= \square\square\frac{\square_\square\ (\square\square\ \square)}{\square\square\ \square\square}\square\ \ \square\square_{\square\square\square\square}\ \square^\square\square$ Watts é 56

The mechanical net power output ($Pm_n$) is the cumulative sum of equations 55 and 56

$\Rightarrow Pm_n = Pm_{cw} + Pmc_{cw}$

$\square\square_\square\ (1 - \square)\ \square\frac{\square\square_{\square\square\square}\ \square^\square}{\square\square\square\ \square} - \frac{\square\square_{\square\square\square\square}\ \square^\square}{\square\square\ \square\square}\ \square\square$ Watts é 57

The Electromagnetic torque ($T_{cw}$ and $T_{ccw}$) developed by the two rotating fields can be expressed as;

$T_{cw} = \frac{\square}{\square}\,Pg_{cw}$ Nï m é 58

Substituting equation 53 into 58 we have;

$T_{cw} = \square\frac{\square}{\square}\ \square\frac{\square.\square\square_\square}{\square\square\square\ \square}\square\ \square\square_{\square\square\square}\ \square^\square\square$N-m é 59

Similarly, $T_{ccw} = \frac{\square}{\square}\,Pg_{ccw}$ N-m é 60

Putting equation 54 into 60 yields;

$T_{ccw} = -\ \square\frac{\square}{\square}\ \square\frac{\square.\square\square_\square}{\square\square\ \square\square}\square\ \square\square_{\square\square\square\square}\ \square^\square\square$N-m é 61

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

Minus sign attached to equation 61 is due to opposite direction of the field to the clockwise rotating field, hence, producing a negative torque.

Therefore, from the fore-going, since the 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 transfer field (TF) machine is given by;

$$T_{net} = T_{cw} + T_{ccw}$$

$$= \frac{[illegible]}{[illegible]} (Pg_{cw} + Pg_{ccw})$$

$$= [illegible] \text{ N-m} \quad ...62$$

$$\left.\begin{array}{l} \omega = 2\pi n_s \\ n_s = \frac{[illegible]}{[illegible]} \text{ r.p.s} \end{array}\right\} \quad é\ 63$$

**7 – Torque – Slip characteristics of Single phase transfer field reluctance motor**

The slip/speed-torque characteristics of all asynchronous motor are quite importance in the selection of motor drives.

In addition, the ratio of maximum torque to rated torque, ratio of starting current to rated current, ratio of starting torque to rated torque, and the ratio of no-load current to rated current are equally significant.

The above characteristics can be conveniently determined by means of the equivalent circuit of such motor. (J.B. Gupta 2014).

**8 – Efficiency of Single Phase transfer field reluctance motor**

Obviously, it is the internal losses (both electrical and mechanical) of a machine that contribute majorly to reduction in its performance. Machine performance is characterized by its efficiency. Owing to the fact that the rotor currents produced by the two components air-gap fields are of different frequencies, the total auxiliary winding $I^2Ra$ loss is the numerical sum of the losses caused by each field.

Thus clockwise field rotor (auxiliary winding) $I^2Ra$ loss equals (2s-1) $pg_{cw.}$ Conversely, counter clockwise field rotor (auxiliary winding $I^2Ra$ loss equals (3-2s) $pg_{ccw.}$

These contribute immensely to the overall reduction in efficiency of the motor. More-still, the poor pullð out and starting torque of single phase transfer field motor to an extent affect its performance and thereby makes it (for now) inferior to those of a comparable single ï phase induction motor counterpart. The overall effect of these losses is a reduction in the net mechanical power output of the motor and the corresponding efficiency

The motor efficiency (ȝ) is given by;

$$ȝ\% = \frac{[illegible]}{[illegible]} \times \frac{[illegible]}{[illegible]} \quad é\ 63$$

Where;

$$\text{Motor input power} = VI \cos \phi \quad é\ 64$$

But the motor power factor $(\cos \phi) = \frac{[illegible]}{[illegible]}$

$$= \frac{[illegible]}{[illegible]} \quad é\ 65$$

Where, $R_s$, $R_{cw}$, and $R_{ccw}$ are the real parts of $Z_s$, $Z_{cw}$ and $Z_{ccw}$ respectively

∴ Putting equations 50, 57, 64 and 65 into equation 63 we have;

$$ȝ\% =$$

$$[illegible] \times 100 \quad é\ 66$$

Motor losses are assumed negligible.

**9 – Simulation And Results**

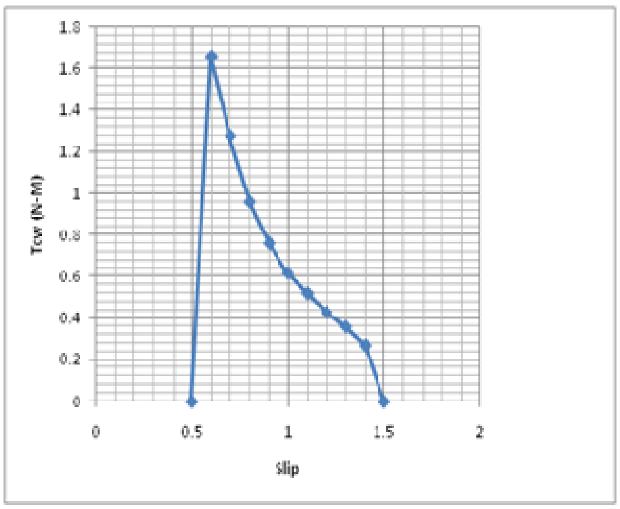
In this work, simulation is carried out with the models developed.

ISSN 2250-3153

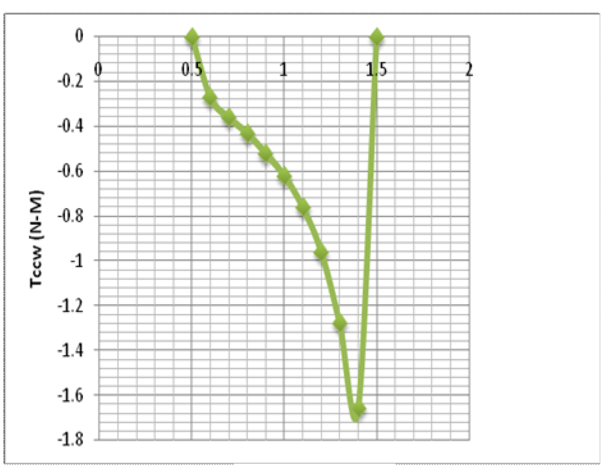
If the machine parameters of table 1 are effectively used, equations 59, 61 and 62 become essential tool for the steady ï state simulation plots, characterizing the machine performance indices.

The matlab plots for 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 varying values of slip s, ranging from $0.5 \leq s \leq 1.5$ are shown in fig 7 a,b,c, and d respectively.

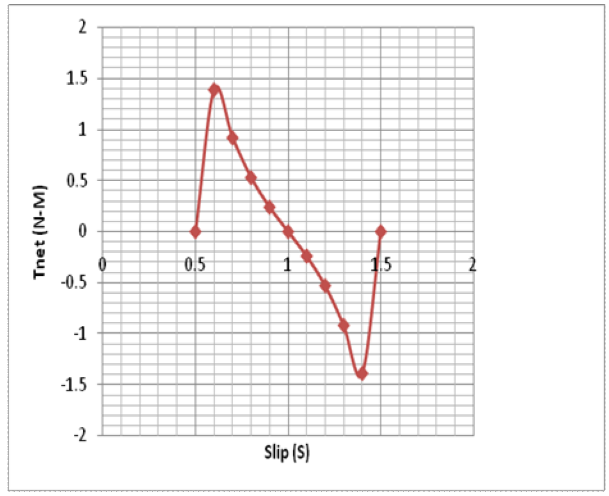
Morestill, by careful use of the machine parameters and equations 50 ï 66 with varying values of slip s, a matlab plot for the machines efficiency against slip(s) during operation is obtained as shown in fig 8.



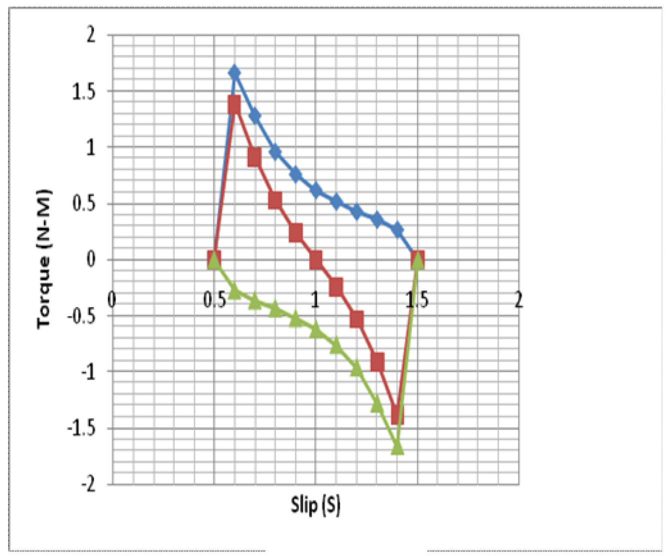

(a)




(b)




(c)




(d)

**Fig 7 (a) –** Plot for the clockwise torque ($T_{cw}$) against slip (s)
**(b) –** Plot for the counter clockwise torque ($T_{ccw}$) against slip(s)

**(c) –** Plot for net torque ($T_{net}$) against slip(s)

**(d) –** Plot for the superposition of a, b, c against slip(s) (Obute KC et al, 2017)

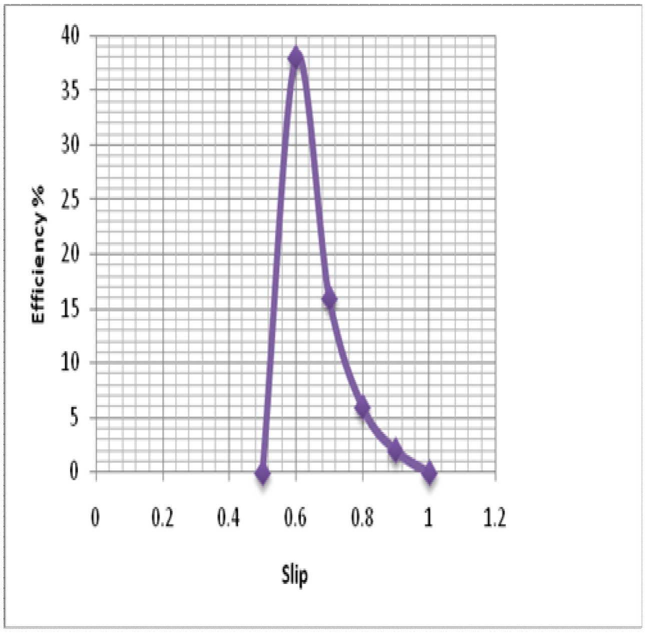



**Fig 8 –** Plot for efficiency against slip(s) for the transfer field motor

**9 – Discussion Of Result/Analysis**

The equivalent circuit of a single-phase transfer-field reluctance motor from which the performance indices can be predicted has be presented. Though, the single phase transfer field machine and the induction machine counterpart belong to two different class of machine and quite different in physical configuration, yet both display similar torqueï slip and Efficiencyï slip characteristics.

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. 7c, 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.

Though as an asynchronous machine, the single phase transfer field machine is capable of synchronous operation when;

(i) The auxiliary winding runs at half the source frequency or when the slip is half (s=0.5) and a direct current is applied to the auxiliary winding to produce a d.c field at this speed (ie $\omega = 0.5\omega$)

(ii) The auxiliary winding (rotor) is brought up to synchronous speed of applied field, $\omega_o$, by an auxiliary with the main and auxiliary windings of the transfer field machine connected to the supply. In this mode, the motor will operate as a synchronous machine utilizing one side of the coupled transfer field machine (Eleanya M.N. 2015)

**10 – Suggested Areas Of Application, Recommendation And Conclusion**

The transfer field machine in general is a low speed machine operating at half the speed of a normal induction machine (Agu L.A.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.

It is hoped that these identical characteristics of the single phase transfer field machine with that of the single phase induction machine counterpart should be harnessed to design and construct more robust transfer field machines, as this will increase its industrial acceptance as well as augmenting the role of induction machine as the work horse of the electric power industry. It is therefore recommended that detailed study should be carried out on the output power to size ratio of the transfer field machine. This will to a large extent help in the design and construction of a cheaper (TF) machine of variable sizes and ratings, for industrial and domestic applications.

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

**Acknowledgement**

The authors acknowledge God Almighty for his protection and their families for their endurance, tolerance and support during the research work.

## REFERENCES

1) Agu L.A. (1978). The transfer field machine, Electric Machine and Electro Mechanics, pp 403-418
2) Brodway ï ARW, Tan SCF, 1973. Brushless stator ï controlled synchronous induction machine. Pro. IEE, Pp 120, 860-866
3) Gupta J.B., 2006. Theory and performance of Electrical machine. S.K Katania and Sons 4424/6 Guru Namak Market, Naisarak Delhi-110006, Pp578-579
4) Agu L.A., Anih L.U 2002. Couple Poly phase reluctance machine without rotating windings. A technical Transactions of Nigeria society of Engineers, Pp 37, 46-53
5) Anih L.U 2009 Magnetic of an idealized Asynchronous reluctance machine with no moving conductors. The pacific journal of science and Technology, vol 10 Pp 3-4
6) Anih L.U, Obe E.S 2001: Performance analysis of a composite Dual winding machine PP 2,3, of 17
7) Obute et al 2016. Analytical determination of steady state performance indices of single-phase induction motor, using symmetrical components of unbalanced voltages of 3-phase system. International journal of recent advances in multi-disciplinary research vol.03, issue 11 November pp 1913-1918
8) Anih, Obute 2012. The steady-state performance characteristics of single phase transfer field machine operating in the asynchronous mode. Nigeria journal of technology vol 31, No 3, November 2012 pp 219-226
9) Stephen J. Chapman 2005. Electric machinery fundamentalò. 1221 Avenue Americas New York Mc. Graw Hill Inc, Ny 10020. Forth edition
10) S.K. Bhatta Charryan (2009) Electrical machines (second edition). Published by Tasta McGraw-hill Publishing company Limited 7 wesst pastel Nagar, New Delji 110008 pp495
11) Obute K.C. et al (2017) Starting, steady-state modeling and simulation studies of single-phase transfer field reluctance motor, operating in the asynchronous mode. International journal of scientific research publications vol 7 issue 1 Jan 2017 pp 182-188
12) Eleanya M.N. (2015), Comparative Analysis of a transfer field machine and induction machine. Unpublished thesis submitted to the Department of Electrical Engineering University of Nigeria Nsukka pp 72
13) J.B. Gupta ï A course in power systems. Published by Sanjeev Kumar Kataria for S.K. Kataria and Sons. 6 Guru Nanak Market, Nai Sarak, Delhi ï 11006. Tenth edition. Pp- 66-67.