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Steady State Analysis of a Dualwinding Induction Motor

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ABSTRACT : *A steady state analysis method is required for a better understanding of the operational behaviour of a dual winding induction motor. However, the motor is electrically isolated, but magnetically coupled, and consists of a squirrel cage rotor with a stator having two windings known as the main winding connected to a three-phase supply and the auxiliary winding connected to a balanced capacitor for excitation. This paper primarily addresses the steady-state analysis of a dual winding induction motor, including the development of a mathematical model using Park's transformation equations to describe the behaviour of the machine. An equivalent circuit of the steady state operation of the machine (DWIM) is obtained through a standard induction motor analysis method. The derived equations are used to perform a steady state simulation in the MATLAB.*

KEYWORDS *Dual Winding, Auxiliary Winding, Rotor Winding, D-Q Transformation, Modelling, Simulation.*

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I. INTRODUCTION

Multiphase induction machines in recent years have attracted more focused attention from researchers. Various researchers today have studied the operation of these machines as generators as well as motors with a view to analyzing their performance as compared to a standard three phase machines of similar ratings.Furthermore, the machine core performance indices such as starting torque and magnetizing current are not fully explored to the extent of predicting the influence of the machine in dynamic and steady state models [1-2]. The steady state model of the dual winding motor arrangement was mathematically derived and then, analyzed in the MATLAB to ascertain the level of improvement, if any, over the conventional winding configuration. One set of the winding is supplied directly from the main and the other winding is short-circuited through a balanced capacitor, the research was targeted at achieving the steady state analysis of a dual winding induction motor in order to attract a superior operation performance not attainable by existing conventional design concepts. [3-4].However, a comprehensive literature review from Ojo and Davidson (2000); Alfredo (1998); Munoz and Lipo (2000) revealed that induction motordraws large power to start, thereby causing voltage drop. It also operates with a lagging power factor with low efficiency. Literature also shows that the machine suffers from overheating due to excessive copper losses in the windings or incomplete utilization of the machine.

II. MATHEMATICAL MODEL OF THE INDUCTION MOTOR

The steady state model of this dual winding induction motor arrangement is mathematically derived by setting all the time varying constant in the dynamic model to zero then, analyzed it in MATLAB to ascertain the level of improvement over the conventional winding configuration.In order, to distinguished between the two set of windings, the winding connected to the supply is known as the Main winding and the one short-circuited across the balanced capacitor is termed the auxiliary winding. For ease of analysis, the electrical system of this machine as described above can be represented with an equivalent circuit. Though the zero- sequence circuit diagram is omitted because the system is assumed to be balanced. Therefore, the d-q voltage equations and the flux linkage equations suggest the equivalent circuit in Fig 2. In order to obtain a simplified mathematical model for the analysis of the dual winding induction motor, certain assumptions are considered as follows;

- The air-gap is uniform
- Eddy- current, friction, windage losses, are neglected.
- The windings are distributed sinusoidal around the air-gap.
- The windings are identical and have same resistance.

The voltage equations for each winding on the stator and rotor can be determined as follows in the machine variable;

$V_{abcs\,1} = r_{s1} i_{abcs\,1} + \frac{d}{dt}\lambda_{abcs\,1}$ (1)

$V_{ab\,cs2} = r_{s2} i_{abcs\,2} + \frac{d}{dt}\lambda_{abcs\,2} + V_{c_{abc}}$ (2)

$V_{abcr} = r_r i_{abcr} + \frac{d}{dt}\lambda_{abcr}$ (3)

III. STEADY-STATE ANALYSIS

The voltage equations that describe the balanced steady state operation of an induction machine may be obtained in many ways. But at steady state, all transients die down, this means that the time varying terms are equal to zero, that is $\frac{d}{dt}$ becomes zero. As earlier stated, the steady state of the rotor is zero for balanced conditions. It is known that for a balanced steady state the d-q-0 variables are sinusoidal in all reference frame except in the synchronously rotating reference frame where-in they are constant. Hence, one method of obtaining the steady state voltage equations for balanced conditions is to first re-call that in an asynchronously rotating reference frame, the steady state voltage is related by the expression below.

$F_{ds\,1} = jF_{qs\,1}$ (4)

And with; $\theta(0) = 0$

$F_{qs\,1} = jF_{as\,1}$ (5)

Similarly,

$F_{ds\,2} = jF_{qs\,2}$ (6)

$F_{qs\,2} = jF_{as\,2}$ (7)

Also, the steady state rotor variables are related by;

$F_{dr} = jF_{qr}$ (8)

$F_{qr} = jF_{ar}$ (9)

It follows that the voltage equation from equations (1), (2) and (3) will become;

$V_{ds\,1} = r_{s1} i_{qs\,1} + \omega_1 \lambda_{ds\,1}$ (10)

$V_{qs\,2} = r_{s2} i_{qs\,2} + \omega_2 \lambda_{ds\,2} + +\frac{1}{\omega}\left[\frac{i_{ds\,2}}{C}\right]$ (11)

$V_{qr} = r_r i_{qr} + \left(\frac{\omega_1+\omega_2}{2} - \omega_r\right)\lambda_{dr}$ (12)

In order to align the q_s and a_s-axis, the q equivalent of d quantities must be gotten by using the operators in equation (4), (6) and (9), Thus, equations (10)-(12) will become;

$V_{qs\,1} = r_{s1} i_{qs\,1} + \omega_1 (j\lambda_{qs\,1}) = r_{s1} i_{qs\,1} + \omega_1 j\lambda_{qs\,1}$ (13)

$V_{qs\,2} = r_{s2} i_{qs\,2} + \omega(j\lambda_{qs\,2}) + \frac{1}{\omega_2}\left[\frac{ji_{qs\,2}}{C}\right] = r_{s2} i_{qs\,2} + j\omega\lambda_{qs\,2} + \frac{1}{\omega C}(i_{qs\,2})$ (14)

$V_{qr} = r_r i_{qr} + \left(\frac{\omega_1+\omega_2}{2} - \omega_r\right)(j\lambda_{qr}) = r_r i_{qr} + j\left(\frac{\omega_1+\omega_2}{2} - \omega_r\right)\lambda_{qr}$ (15)

The flux linkage equations now become flux linkage per second with the units of volts as expressed;

$\lambda_{qs\,1} = X_{ls} i_{qs\,1} + X_m [\, i_{qs\,1} + i_{qs\,2} + i_{qr} \,]$ (16)

$\lambda_{ds\,1} = X_{ls} i_{ds\,1} + X_m [\, i_{ds\,1} + i_{ds\,2} + i_{dr} \,]$ (17)

$\lambda_{qs2} = X_{ls} i_{qs2} + X_m [\, i_{qs1} + i_{qs2} + i_{qr} \,]$ (18)

$\lambda_{ds2} = X_{ls} i_{ds2} + X_m [\, i_{ds1} + i_{ds2} + i_{dr} \,]$ (19)

$\lambda_{qr} = X_{ls} i_{qr} + X_m [\, i_{qs1} + i_{qs2} + i_{qr} \,]$ (20)

$\lambda_{dr} = X_{ls} i_{dr} + X_m [\, i_{ds1} + i_{ds2} + i_{dr} \,]$ (21)

Steady-state voltage equations that are well known are actually valid in all synchronously rotating reference frames. To obtain it, is by substituting for λ_{qs1}, λ_{qs2} and λ_{qr} respectively into equations (13), (14) and (15) and replace qs and qr variables with as and ar variables respectively in equations (5), (7) and (9). Taking each of equation (13) to (15) in turns, starting with equation (13), we have;

$V_{qs1} = r_{s1} i_{qs1} + j\omega\lambda_{qs1}$ (22)

From equation (16), Substituting λ_{qs1} into equation(13) yields;

$$V_{qs1} = (r_{s1} + j\omega X_{ls})i_{qs1} + j\omega X_m[i_{qs1} + i_{qs2} + i_{qr}](23)$$

Now by replacing qs and qr variables with as and ar variables, equation (23) becomes;

$$V_{as1} = (r_{s1} + j\omega X_{ls})i_{as1} + j\omega X_m[i_{as1} + i_{as2} + i_{ar}](26)$$

Similarly, in the auxiliary winding, to obtain V_{as2}, we have from equation (14);

$$V_{qs2} = r_{s2}i_{qs2} + j\omega\lambda_{qs2} + \frac{1}{\omega C}[i_{qs2}] \quad (27)$$

From equation (19), Substituting λ_{qs2} into equation(27) yields;

$$V_{qs2} = (r_{s2} + j\omega X_{ls})i_{qs2} + j\omega X_m[i_{qs1} + i_{qs2} + i_{qr}] + jX_C i_{qs2} \quad (28)$$

Now by replacing qs and qr variables with as and ar variables, equation (28) will yield;

$$V_{as2} = (r_{s2} + j\omega X_{ls})i_{as2} + j\omega X_m[i_{as1} + i_{as2} + i_{ar}] + jX_C i_{as2}(29)$$

Finally, for the rotor winding, to obtain V_{ar}, we have from equation (15);

$$V_{qr} = r_r i_{qr} + j(\omega - \omega_r)\lambda_{qr} \quad (30)$$

From equation (20), Substituting λ_{qr} into equation (30) yields;

$$V_{qr} = (r_r + j(\omega - \omega_r)X_{ls})i_{qr} + j(\omega - \omega_r)X_m[i_{qs1} + i_{qs2} + i_{qr}] \quad (31)$$

Again, now by replacing qs and qr variables with as and ar variables, equation (31) will yield;

$$V_{ar} = (r_r + j(\omega - \omega_r)X_{ls})i_{ar} + j(\omega - \omega_r)X_m[i_{as1} + i_{as2} + i_{ar}] \quad (32)$$

Recall, the slip "s" is defined as;

$$S = \frac{(\omega_s - \omega_r)}{\omega_s}(33)$$

$$S\omega_s = (\omega_s - \omega_r) \quad (34)$$

Replacing $(\omega_s - \omega_r)$ with $S\omega_s$ and substitute it into equation (32) will yield;

$$V_{ar} = (r_r + jS\omega_s X_{ls})i_{ar} + jS\omega_s X_m[i_{as1} + i_{as2} + i_{ar}] \quad (35)$$

Dividing equation (35) by s will yield;

$$\frac{V_{ar}}{s} = \left(\frac{r_r}{s} + jS\omega_s X_{ls}\right)i_{ar} + j\omega_s X_m[i_{as1} + i_{as2} + i_{ar}] \quad (36)$$

Now, the rotor in the motor is invariably shunt, therefore, the voltage is equal to zero.

$$\frac{V_{ar}}{S} = 0 = \frac{r_r}{s}i_{a_r} + jX_{l_r}i_{ar} + jX_m[i_{as1} + i_{as2} + i_{ar}] \quad (37)$$

$$0 = \frac{r_r}{s}i_{a_r} + jX_{l_r}i_{ar} + jX_m[i_{as1} + i_{as2} + i_{ar}](38)$$

Combining equations (26), (29) and (36), neglecting core losses will yield the equivalent circuit in Figure 2

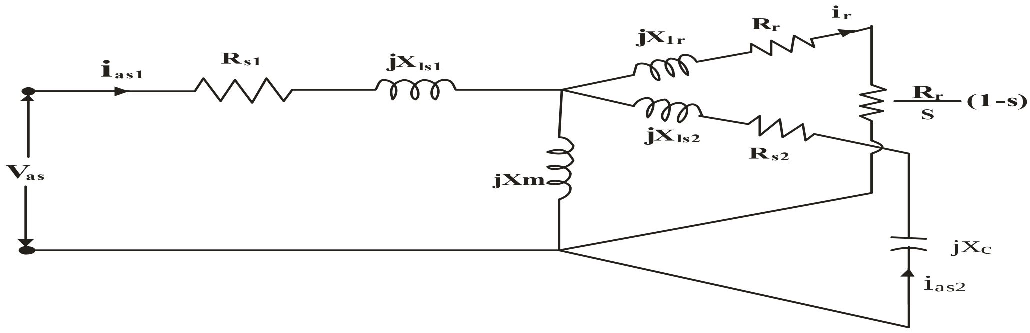

Figure 2. Steady State Equivalent Circuit.

In the squirrel cage induction motor, with the case of dual winding induction motor under review, the rotor winding is always short-circuited as mentioned earlier, it means V_{ar} will turns to zero. For ease of analyzing the circuit in Fig:(2) by neglecting coreLoss resistance and Let;

$$Z_{s1} = r_{s1} + jX_{ls1} \quad (39)$$

$$Z_{s1} = r_{s2} + j(X_{ls2} - X_c)(40)$$

$$Z_m = jX_m \quad (41)$$

$$Z_r = \frac{r_r}{s} + j(X_{lr})(42)$$

The rotor current may be found using Thevenin's equivalent circuit. For single-fed machine, $\frac{V'_{ar}}{S} = 0$, this implies that the rotor current referred to the stator side in-terms of stator current is given as;

$$\frac{V'_{ar}}{S} = 0 = \left(\frac{R'_r}{S} + jX_{lr}\right)i'_{ar} + jX_m(i_{as1} + i_{as2} + i'_{ar}) \quad (43)$$

$$0 = \left(\frac{R_r'}{S} + jX_{lr}\right) i_{ar}' + jX_m (i_{as1} + i_{as2} + i_{ar}') \qquad (44)$$

$$I_{ar}' = -\frac{jX_m (i_{as1} + i_{as2})}{\frac{R_r'}{S} + j(X_{lr} + X_m)} (45)$$

IV. ELECTROMAGNETIC TORQUE (Te) AND SPEED

The steady-state electromagnetic torque can be written in terms of currents by first writing the torque in terms of currents in the synchronously rotating reference frame. The torque developed is given as;

$$T_e = \frac{3(I_{ar})^2 R_r'}{\omega_s S} \qquad (46)$$

By substituting the values in equation (45) into equation (46) yields

$$T_e = 3\left(\frac{P}{2}\right)\left[\frac{X_m{}^2 (I_{as1} + I_{as2})^2}{\left(\frac{R_r}{s}\right)^2 + (X_{lr} + X_m)^2} * \frac{R_r}{s}\right] \qquad (47)$$

And the speed is given as;

$$\omega_r = \frac{P}{2j} \int (T_{em} - T_L) dt (48)$$

Voltage conditions for the main winding supply;

$V_a = V_m \cos(\omega t)$ (49)

$V_a = V_m \cos(\omega t + 2\pi f)$ (50)

$V_a = V_m \cos(\omega t - 2\pi f)$ (51)

The input power given to the motor is in the form of three-phase voltage and currents.

$$P_{input\ stator} = \sqrt{3} V_L V_L \cos \phi_i = 3 V_{sp} V_{sp} \cos \phi_i \qquad (52)$$

Where;$\cos \phi_i$is the power factor.

The power factor angle ϕ is given as;

$$\phi = -\tan^{-1}\left(\frac{Q_{in}}{P_{in}}\right) \qquad (53)$$

Finally, the efficiency η of the motor is given as;

$$\eta = 100 * \left(\frac{P_{out}}{P_{in}}\right) \qquad (54)$$

MACHINE DATA

Stator Resistance,	3.72Ω
Auxiliary Resistance,	3.72Ω
Rotor Resistance	2.12Ω
Mutual Inductance	0.022H
Stator Inductance	0.022H
Rotor Inductance	0.006H
Moment of Inertia	$0.066kgm^2$
Rated Voltage	415 V
No of Pole	4
capacitance	10-100µf
Load Torque	15Nm
Rated frequency	50Hz

VI. SIMULATION RESULTS AND DISCUSSION

The graphs below show the main stator current, torque, power factor and efficiency of the dual winding induction motor.

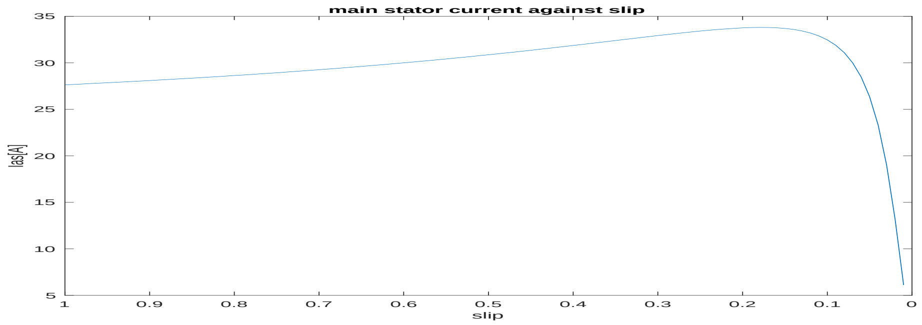

Fig 4. Main Stator Current Against Slip

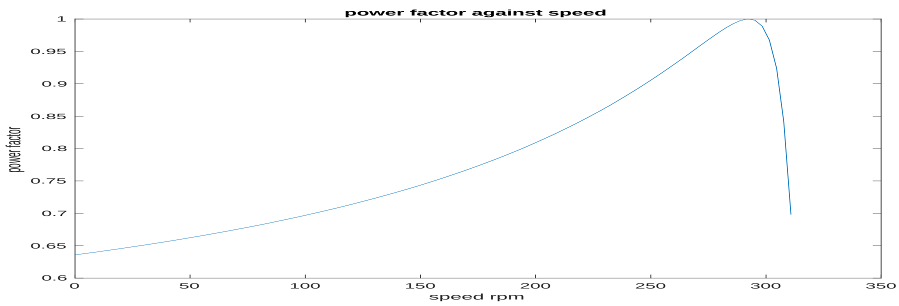

Fig. 6. Power Factor Against Slip.

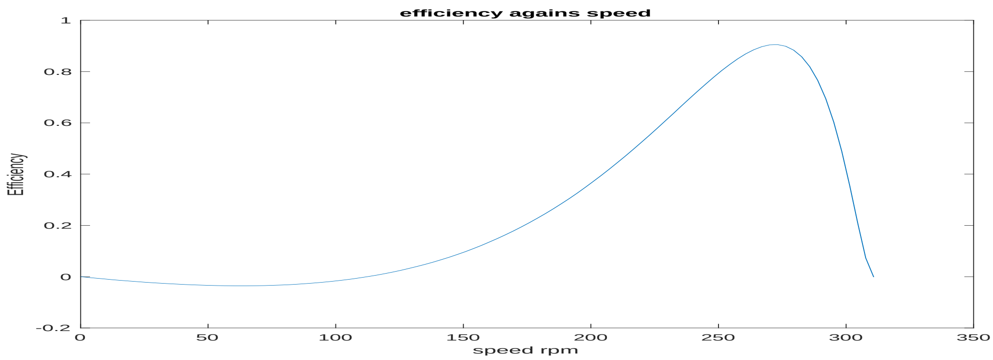

Fig. 7 Efficiency Against Slip.

The main objective of this research work is seen in the modification carried out by the addition of the auxiliary winding for the purpose of improving the poor power factor and efficiency of the motor. Therefore, it is important to concentrate on the behaviour of the motor parameter that involves power factor and efficiency as showed in Fig 6 and Fig 7 respectively. Fig 6 shows the graph of power factor against slip. The result shows that the dual winding induction motor has almost a unity factor of 0.99% compared to the conventional induction motor, it is as a result of the reactive power injected via the auxiliary winding. Fig 7 shows the plot of efficiency against slip. From Fig 7 it shows that, there is an improvement of 0.9% efficiency of the dual winding induction motor over the conventional induction motor.

V. CONCLUSION

From the MATLAB simulation of steady state analysis, it was concluded that the injection of the reactive power (capacitor) at the auxiliary winding reduces the high in-rush current experienced under starting condition in the conventional induction motor.This arrangement will reduce the known disadvantages of conventional induction motors by providing a system in which the magnetic flux density in the stator is maintained at a maximum level. The stability of the motor under variation of no load-to-load conditions is the main advantage of the model and the excitation of the auxiliary winding with a capacitor.

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