Steady-State Performance of Dual Stator Winding Polyphase Induction Motor with Reactive Power Compensation

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Abstract- This paper describes the improvement in the steady-state performance of squirrel cage induction motor (SCIM) by using capacitor injected in the auxiliary winding of the modified dual stator winding SCIM. A balance capacitance load is connected at the terminals of the auxiliary winding, and by appropriate choice of the capacitor, the overall reactance of the machine is reduced with concomitant increase in output torque, power factor, and efficiency. The analytical prediction of the performance characteristics is validated with MATLAB simulation. From the simulation results, it was observed that the torque of the modelled machine was greatly improved to about 64Nm as against the 23Nm for the normal machine when a capacitor of 500µf was injected. Similarly, the power factor of the machine was equally improved to 0.92 as against 0.78 for the normal machine. The same maximum power factor was realized with 500µf capacitance injection. In addition, the efficiency of the modelled squirrel cage induction motor was increased from 60% to 80%.

Indexed Terms- Efficiency, Induction motor, Power factor improvement, Torque enhancement

I. INTRODUCTION

Three phase induction motor or simply induction motor is an alternating current (AC) electric motor in which the electric current in the rotor needed to produce torque is obtained by electromagnetic induction from the magnetic field of the stator winding [1]. Due to the simplicity, robustness, ruggedness and lower cost compared to permanent magnet synchronous motors, induction motors are used in various industrial applications and variable speed drives systems. Hence, the Squirrel Cage Induction Motor (SCIM) is always a stronger contender amongst motors including traction motors in Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs) [2].

One of the major disadvantages of induction motor that it requires reactive power for operation, hence, its power factor is inherently poor and it is worse especially when starting and running with light loads [3] and this obviously affect the output torque and efficiency of the motor. Researchers have shown that poor power factor adversely affects the distribution system and a cost penalty is frequently levied for excessive Volt-Ampere reactive (VAr) consumption [4], affects the loads nearby and limits the application range of the induction motor [3].

To improve the power factor and in effect enhance the torque output and efficiency of the induction motor, a mean of reactive power compensation is needed. Various techniques have been used to improve the power factor of induction machine by different authors. [2, 5] introduced the use of capacitors parallel to the induction motor by using thyristor/triac controllers; by adjusting the firing angle, the capacitance introduced in parallel with the motor becomes variable and thus compensating the power factor for any load. [6] considered the induction motor as Resistor-Inductor (RL) load and power factor is improved by inserting a variable capacitor (through a bridge converter) which is adjusted for unity according with the load. For the above methods, the capacitive injection is directly into the supply. Another method conceived for slip ring induction motor was to inject capacitive reactive power direct into the rotor circuit [6,7]. Other methods include synchronous compensation, fixed capacitors, fixed capacitor with switched inductor, solid-state power factor controller, and switched capacitors [3].

According [3], the synchronous compensation technique is complex and not cost effective. Other techniques incorporate directly the connection of capacitors, which lead to the problems of voltage regeneration and over-voltages, and very high inrush current during starting. Large harmonic current in the motor and in the line are generated in methods which uses controlled switches in the stator winding circuit for motor parameter enhancement. A variety of stator winding configurations incorporating capacitors have also been proposed [8], however, these configurations introduce asymmetry problems in the machine.

II. METHODOLOGY

The methodology employed in this paper to surmount the challenges posed by other techniques employed for reactive power compensation in induction is injection of capacitor in a modified dual stator winding induction motor. One set, the main winding (star or delta), is connected directly to the source. The other set of windings - auxiliary, is only magnetically coupled to the main winding. All windings have the same shape and pitch, and arranged in slots such that there is no phase shift between the two windings.

To achieve the laid down objectives, the induction motor formulas and mathematical relationships were first derived from basic motor principles. The auxiliary winding was then modelled and the relationship to the already existing induction machine was derived and modelled without adding the capacitance. After this, the capacitance was then included in the modelling and the effects of the capacitive reactance to the derived mathematical formulas were analysed and new relationships were formed to include the capacitance. The mathematical formulas derived in this section were used to design and model the machine on the MATLAB/Simulink 2018 CAD tool and the output performance of the modelled machine was analysed.

III. MATHEMATICAL MODELLING.

(a) Mathematical modelling of an induction machine without auxiliary windings

One way to analyse and understand the operation of an induction motor is by using its equivalent circuit. Since an induction motor can be analysed by considering the circuit of transformer. Hence, they are sometimes referred to as rotating transformers. Hence, induction motor can be representing using the circuit as shown in Figure 1

From Figure 1, L_1 and R_1 are the primary inductance and resistance while L_2 and R_2 are the secondary inductance and resistance respectively. V_1 is the input voltage, V_2 the output voltage and L_m is the mutual inductance

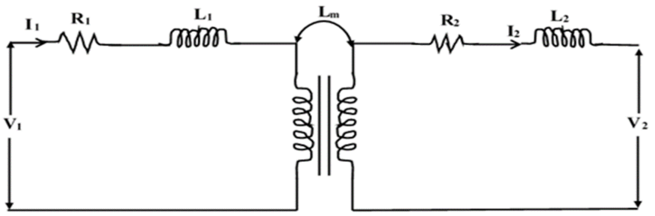

Figure 1: Schematic diagram of an induction motor as two coupled coils

From the circuit of Figure 1:

$$V_1 = L_1\frac{dI_1}{dt} + R_1 I_1 + L_m\frac{dI_2}{dt} \quad (1)$$

$$V_2 = L_2\frac{dI_2}{dt} + R_2 I_2 + L_m\frac{dI_1}{dt} \quad (2)$$

Putting $\mathrm{L_1}\frac{\mathrm{d}}{\mathrm{dt}} = \mathrm{jX_1}, \mathrm{L_2}\frac{\mathrm{d}}{\mathrm{dt}} = \mathrm{jX_2}, \mathrm{L_m}\frac{\mathrm{d}}{\mathrm{dt}} = \mathrm{jX_m}$ in (1) and (2) and dividing (2) by s

$$V_1 = R_1 I_1 + \mathrm{jX_1} I_1 + \mathrm{jX_m} I_2 \quad (3)$$

$$\frac{V_2}{s} = \frac{R_2 I_2}{s} + \mathrm{jX_2} I_2 + \mathrm{jX_m} I_2 \quad (4)$$

From (3) and (4), the exact equivalent circuit of the the polyphase Induction motor at any slip is obtained as shown in Figure 2.

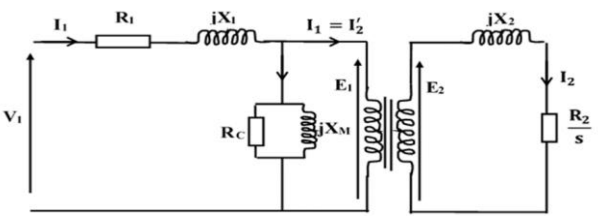

Figure 2: Exact equivalent circuit of the polyphase Induction motor at any slip

In the equivalent circuit of Figure (2), R_1 represents the resistance of the stator winding and X_1 the stator leakage reactance (flux that does not link with the air gap and rotor). Magnetising reactance required to cross the air gap is represented by X_m and R_c is usually added in parallel with X_m to account for the core losses (hysteresis and eddy current).

Manipulating (3) yielded (5) and that of (4) yielded (6). From (5) and (6), an equivalent circuit of the induction machine without auxiliary winding was drawn as shown in Figure 3.

$$V_1 = \left(R_1 + \mathrm{j}(\mathrm{X_1} - \mathrm{X_m})\right)I_1 + \mathrm{jX_m}(I_1 + \grave{I}_2) \quad (5)$$

$$\frac{V_2}{s} = \left(\frac{R_2}{s} + \mathrm{j}\left(\grave{X}_2 - \mathrm{X_m}\right)\right)\grave{I}_2 + \mathrm{jX_m}\left(I_1 + \grave{I}_2\right) \quad (6)$$

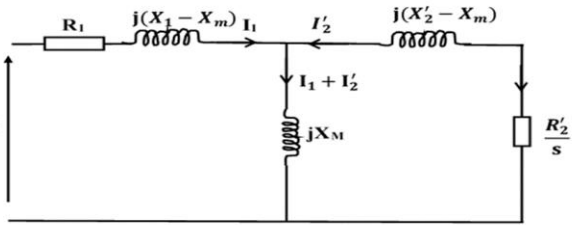

Figure 3: Equivalent circuit of induction motor

The simplified equivalent circuit allows us to calculate the operating parameters for an induction motor more readily.

Once the equivalent circuit parameters are known, it is easy to calculate the motor current, by reducing the circuit to an equivalent impedance (Z_{eq}) giving:

$$I_1 = \frac{V_1}{Zeq} = \frac{V_1}{R_1 + j(X_1 - X_m) + \left[\frac{\left(\frac{jX_m R_2'}{s}\right) - X_m\,(X_2' - X_m)}{\frac{R_2'}{s} + jX_2'}\right]} \quad (7)$$

Where I_1 ia the input current.

$$Z_{eq} = R_1 + j(X_1 - X_m) + \left[\frac{\left(\frac{jX_m R_2'^2}{s^2}\right) - X_m\frac{R_2'}{s}\,(X_2' - X_m) + \frac{X_m X_2' R_2'}{s} + jX_m X_2'(X_2' - X_m\right)}{\frac{R_2'^2}{s^2} + X_2'^2}\right] \quad (8)$$

$$(\text{Power factor (pf)} = \frac{\mathrm{R_e(Z_{eq})}}{|\mathrm{Z_{eq}}|} \quad (9)$$

Where $R_e\left(Z_{eq}\right) = R_1 + [\frac{\frac{X_m X_2' R_2'}{s} - \frac{X_m R_2'(X_2' - X_m)}{s}}{\left(\frac{R_2'^2}{s} + X_2'^2\right)}$ (10)

Power delivered to the connected load (P_m)=P_{out}

$$P_{out} = 3I_2^2\left(\frac{1-s}{s}\right)R_2' \quad (11)$$

$$\text{Torque } (T) = I_2^2\left(\frac{90R_2'}{\pi s n_s}\right) \quad (12)$$

$$\text{Efficiency} = \frac{3I_2^2\left(\frac{R_2'}{s}(1-s)\right)}{3I_2^2\left(\frac{R_2'}{s}(1-s)\right) + 3\left(I_1^2 R_1 + I_2^2 R_2'\right)} \quad (13)$$

(b) Mathematical modelling of an induction machine with auxiliary winding and reactive compensation

In this model, the stator winding of the motor to be modelled was divided into two equal parts or halves in which one part is taken as the stator main winding and the other as the auxiliary winding; both windings are tightly coupled in the same slot. The auxiliary winding is short-circuited; thus they are not electrically connected but magnetically linked.

The exert equivalent circuit of the modelled induction motor with auxiliary winding is shown in Figure 4.

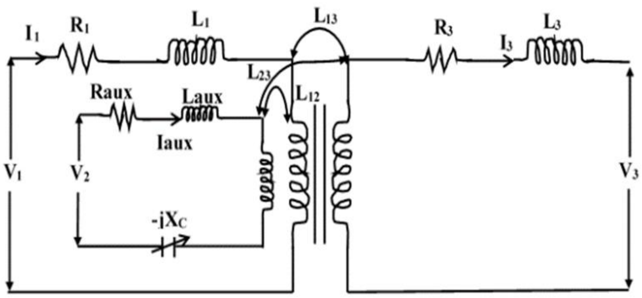

Figure 4: Modeled induction motor with auxiliary winding magnetically coupled and series capacitance injection

From Figure 4, the stator winding of the motor is magnetically coupled with the auxiliary winding, with Laux and Raux as the inductance and resistance of the auxiliary winding respectively. The stator and the rotor are linked together by the mutual inductance L_{13} while L_{12} and L_{23} link the auxiliary winding to the stator and the rotor respectively. V_1, V_3 and V_2

represent the stator, rotor and auxiliary voltages respectively while I_1, I_3 and I_2 represent the stator, rotor and auxiliary currents respectively.

When a capacitance is injected into the auxiliary winding of the machine by connecting capacitor in series with the auxiliary winding of the machine, the machine characteristics will be altered due to the additional reactive element that will attempt to cancel out some of the inductance effects of the windings. Those capacitors can be tuned to obtain the desired machine characteristics while meeting the current carrying capability of the windings.

Assuming the winding in the main and auxiliary winding to be the same and tightly coupled, from the Figure (4), the stator, rotor and auxiliary voltages can be given as:

$$V_1 = (R_1' + jX_1')I_1 + jX_{12}I_2 + jX_{13}I_3 \qquad (14)$$

$$\frac{V_3}{s} = \left(\frac{R_3}{s} + jX_3'\right) I_3 + jX_{13}(I_1 + I_2 + I_3) \qquad (15)$$

$$\mathrm{V_2 = (R_{aux} + jX_{aux} - jX_C)I_2 + jX_{12}I_1 + jX_{23}I_2} \qquad (16)$$

Equations (14), (15) and (16) were derived to form equivalent circuit of Figure 5

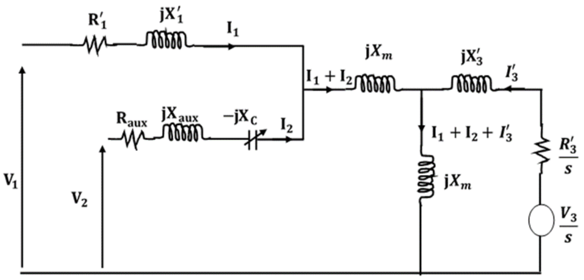

Figure 5: Equivalent circuit of induction motor with auxiliary winding and reactive power injection

Since the auxiliary winding is short-circuited, V2 = 0. In addition, the rotor is short circuited, thus V3 = 0.

Therefore, the equivalent circuit of Figure 5 is further simplified as shown in Figure. 6.

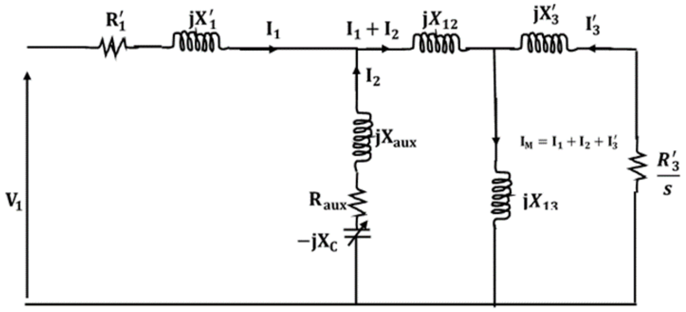

Figure 6: Equivalent Circuit of Induction Motor with Auxiliary Winding and Variable Capacitor

From Figure 6, the equivalent impedance of the modelled induction motor (Z_{eq})

$$Z_{eq} = (R_1' + jX_1') + Z' \qquad (16)$$

Where:

$$Z' = (Z + jX_m) \parallel (R_{aux} + jX'_{aux}) \qquad (17)$$

$$Z = \frac{R_3' jX_m - (X_m X_3')s}{j(X_m + X_3')s + R_3'} \qquad (18)$$

$$\text{Power factor (pf)} = \frac{R_e(Z_{eq})}{|Z_{eq}|} \qquad (19)$$

Input current (I_1)

$$I_1 = \frac{V_1}{|Z_{eq}|} = \frac{V_1}{R_1' + jX_1' + Z'} \qquad (20)$$

Output current (I_3)

$$\mathrm{I_3} = \left[\frac{jX_m * I_2}{\frac{R_3'}{s} + j(X_3' - X_m) + jX_m}\right] (21)$$

$$\text{Power Output } (\mathrm{P_{out}}) = 3I_3^2\left(\frac{R_3'}{s}(1-s)\right) \qquad (22)$$

$$\text{Motor Torque (T)} = \frac{90I_3^2R_3'}{\pi s n_s}$$

$$\text{Efficiency } (\varepsilon) = \frac{P_{out}}{P_{out} + losses} = \frac{\frac{3}{s}I^2_{3\,(1-s)}}{3I_3^2(\frac{R_3'}{s}(1-s)) + 3(I_1^2R_1' + I_2^2R_{aux} + I_3^2 R_3')} \qquad (23)$$

IV. DESIGN AND SIMULATION

The system design and model of the motor was carried out using MATLAB/Simulink 2018 Computer Aided Design (CAD) tool. A standard 10kW, 3 phase 4 pole AC Squirrel Cage Induction Motor parameter was used in the design and modelling of the motor. The parameter of the typical motor is shown in Table 1

Table 1: Squirrel Cage Induction Motor Parameter

PARAMETER	VALUE
Rating (kW)	10
Number of phase	3
Input voltage (V)	380
Number of poles	4
Speed (rpm)	1705
Magnetizing Reactance(X_m) (Ω)	37.86
Main winding resistance per phase(R_1) (Ω)	4.33
Main winding leakage reactance per phase(X_s) (Ω)	6.97
Referred Rotor resistance(R'_r) to primary(Ω)	1.35
Referred Rotor reactance(X'_r)$to\ primary$ (Ω)	1.97
Full load main winding current (A)	46.8
Frequency (Hz)	60
Torque(N-M)	23
Inertia (jkgm^2)	1.662

The motor parameter shown in Table 1 was reconfigured as a dual stator induction motor by splitting the stator winding into two equal parts to be known as the main winding and auxiliary windings. A capacitor was then injected into the auxiliary winding. With this modification, the parameters of the induction motor is as shown in Table 2

Table 2: Parameter of the Modelled Motor

PARAMETER	VALUE
Rating (kW)	10
Number of phase	3
Input voltage(V)	380
Number of pole	4
Motor speed (r.p.m)	1705
Magnetizing reactance(X_m) (Ω)	9.465
Main winding resistance per phase(R'_1)(Ω)	2.165
Main winding reactance per phase(X'_1)(Ω)	1.743
Auxillary winding resistance per phase (R'_{aux})(Ω)	2.165
Auxillary winding reactance per phase (X'_{Aaux})(Ω)	1.743
Rotor resistance referred to primary(R'_r)(Ω)	1.35
Rotor reactance referred to primary(X'_r)(Ω)	1.97

The formulas derived were used to design and model the motor on the Simulink platform. The motor was first simulated without the auxiliary winding, then with the auxiliary winding when capacitance is infinity (no capacitors connected) and lastly with various values of capacitors connected across the auxiliary winding to get the motor operating parameters, which are the torque, the power, the power factor, and efficiency.

The simulation model in the MATLAB/Simulink is shown in Figure 7.

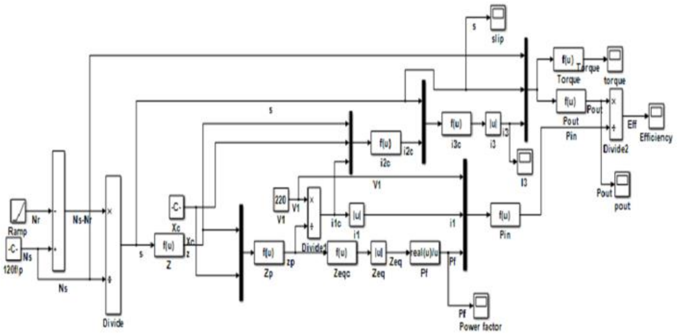

Figure 7: Simulink Model of the Induction Motor

V. RESULTS

At the first stage of the experiment, the speed of the modelled machine was kept constant at its rated value of 1705 rpm while the capacitance was varied from 0 – 1000 micro-Farads (μF).

As the capacitance increases, the input impedance decreases rapidly to attain a minimum value of 3.75Ω at 500μF; after which it increases slowly as shown in Figure 8. A minimum input impedance would produce a maximum output current and torque. The point at which this happens is referred to as a point of resonance. This implies that if a capacitor of capacitance 500μF is connected in the auxiliary winding of the machine, maximum torque enhancement will be achieved.

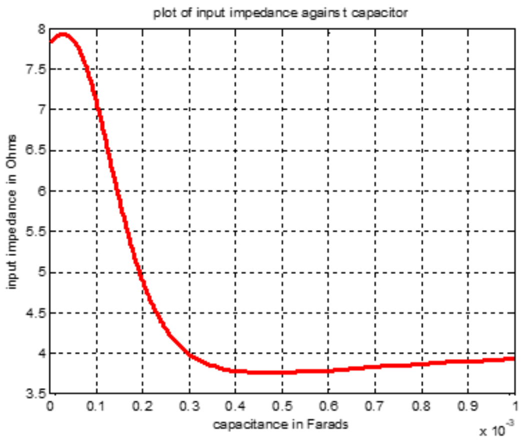

Figure 8: A plot of input impedance against capacitance

Having noted the value of capacitance at the resonant point, the performance of the machine was then analysed for different values of capacitors both above and below the point of resonance. At this stage, the speed of the machine was varied from 0 rpm to 1800 rpm i.e. from starting to synchronous speed. Capacitor values of 400μF, 500μF and 1000μF were used in the test and the results together with those of a normal induction motor were plotted as shown in Figures 9 to 12

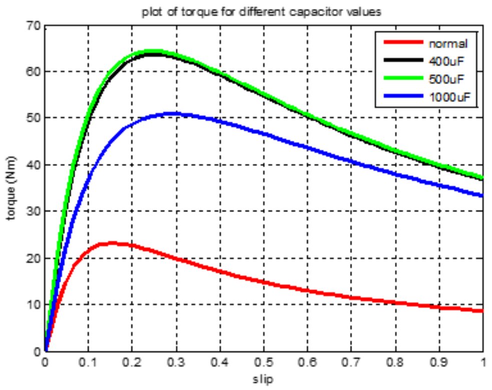

Figure 9: Torque response of both normal and modelled machine.

In Figure 9, the red curve represents the torque of the conventional induction machine; the black, green and blue curves represent the torque of the modelled machine for a capacitance of 400μF, 500μF and 1000μF respectively. It is seen from the curves that at any value of slip, the torque of the modelled machine is more than two times the torque of the conventional induction machine. We also see that the modelled machine has its maximum torque enhancement at capacitance, C = 500μF, followed very closely by the torque at C = 400μF. this is expected since from the graph of input impedance against capacitance, the minimum input impedance occurs at C = 500μF; impedance at C = 400μF being very close to that minimum value. Further away from the minimum point, at C = 1000μF, we see a significant reduction in torque enhancement as seen in the blue curve in Figure 9.

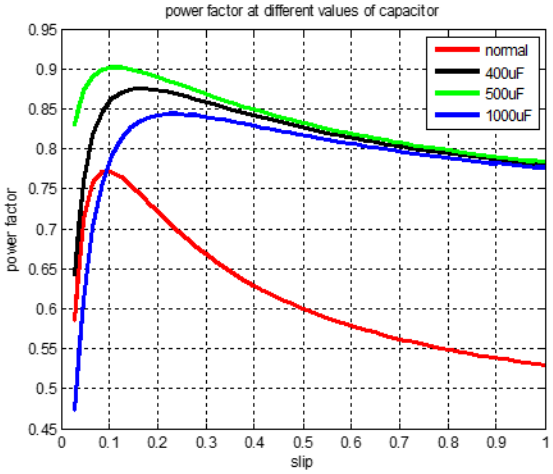

Figure 10: power factor at different capacitors and normal machine

When the power factor was plotted against slip for different values of capacitance, similar curves were obtained. At C = 500μF, the power factor is maximum for any value of slip or speed; ie. The capacitance that gives maximum torque enhancement also gives maximum power factor enhancement. This is also true for efficiency and input current as seen in Figure 11 and 12 respectively.

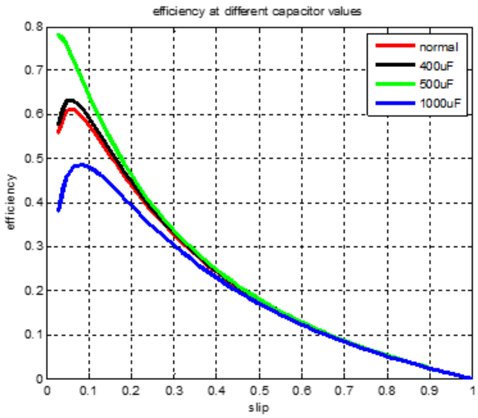

Figure 11: Efficiency at different capacitors and normal machine.

When the efficiency was plotted against slip for the selected values of capacitance, maximum efficiency was also obtained at 500µF as expected. At 400 µF, the motor efficiency was near the value at 500 µF for all values of slip. However, as the capacitance increases to 1000 µF, the efficiency drops below that of normal induction machine.

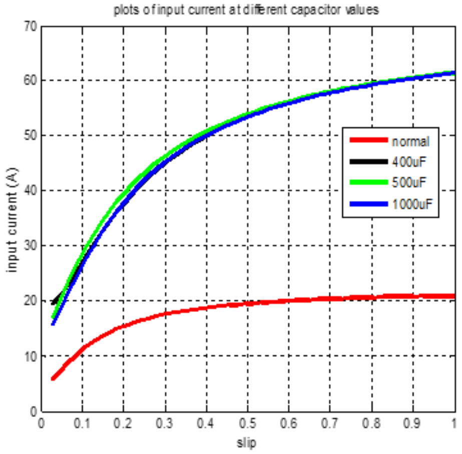

Figure 12: input current at different capacitor values and normal machine.

VI. CONCLUSION

The problem of low power factor and hence low torque associated to poly-phase induction motor (Squirrel-Cage Induction Motor) led to this work. Induction motors are naturally of low power factor at light loads, which have been of concern to the users. With the introduction of auxiliary winding that is magnetically coupled to the main windings and a series reactive power compensation connected to the auxiliary windings brought this enhancement

From the simulation results, it was seen that the torque of the modelled machine was greatly improved to about 64Nm as against the 23Nm for the normal machine when a capacitor of 500µf was injected. Similarly, the power factor of the machine was equally improved to 0.92 as against 0.78 for the normal machine. The same maximum power factor was realized with 500µf capacitance injection. The improvements were tested with varying slip of the motor. A common characteristic in all the results is that an enhanced output torque also results in an enhanced power factor and these are attended by increased current on the windings. This is an improvement on the existing performance of the steady state induction motor

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