Controlled Capacitance Injection into a Three-Phase Induction Motor through a Single-Phase Auxiliary Stator Winding

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***Abstract* — In this paper a controlled static switched capacitor with single-phase auxiliary winding, which is only magnetically coupled to the stator main winding, is explored for improving the starting and operating power factor of a three-phase induction motor. The scheme improves the power factor of the motor without compromising significantly on other performances. Important advantages of the scheme include preventing harmonics in the line current, and eliminating regeneration possibility as well as preventing high inrush currents at starting.**

***Index Terms* — Three-phase machines, Induction motors, Reactive compensation, Power factor correction.**

I. INTRODUCTION

A three-phase squirrel cage induction motor is widely accepted to be rugged, and inexpensive to manufacture and maintain. However, it requires reactive power for operation. Thus its power factor is inherently poor, and it is worse especially at starting and when running with light loads. The power factor of an induction machine has been observed to be poor also when operating with power electronics converter.

At starting the input power to an induction motor is mainly reactive. It draws 6-10 times its rated current at about 0.2 power factor, and takes a second or so to come to speed, where the power factor significantly improves to above 0.6, depending on the load. This initial high current at a poor power factor normally affects the loads nearby and limits the application range of the machine.

To improve the power factor of induction machine requires a means of reactive power compensation. Several techniques, which have been suggested for achieving this, include [1] synchronous compensation, fixed capacitors, fixed capacitor with switched inductor, solid-state power factor controller, and switched capacitors. Most of these techniques suffer certain drawback or another. The synchronous compensation technique is complex and not cost effective. Other techniques that incorporate the direct connection of capacitors lead to the problems of voltage regeneration and over-voltages, and very high inrush current during starting. Techniques incorporating controlled switches in the stator winding circuit generate large harmonic currents in the machine and in the line. A variety of stator winding configurations incorporating capacitors have also been proposed [2]. Most of these configurations introduce asymmetry problems in the machine.

The static switch capacitor has also been used for single-phase induction motors [3-5] with inconclusive results. In [6], a three-phase auxiliary winding fed by a three-phase PWM inverter is proposed with some positive results. This solution is, however, complex and there are some doubts about the controller presented. Other solution presented in [7, 8] is applicable only to a wound rotor machine, as the rotor is required to be connected to an external circuit.

In this paper a single-phase stator auxiliary winding that is connected to a simple switching scheme is used to inject leading reactive power into a three-phase squirrel cage induction motor to improve performance. The auxiliary winding is only magnetically coupled to the main winding. The power electronics static switch has a controller for optimizing the machine's performance.

II. PROPOSED MACHINE STRUCTURE

The proposed structure, shown in Fig. 1, has a single-phase auxiliary winding with the three-phase main winding on the stator. Both windings, which have different turn numbers and wire sizes, are arranged in the same stator slots.

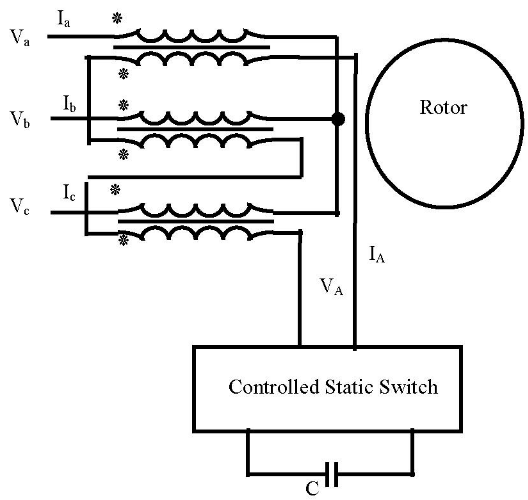

Fig.1 The high power factor three phase induction machine

A. The Controlled Static Switch

Fig. 2 shows the proposed static switch; the number of switches is very much reduced. The main capacitor C_1 is

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introduced in the auxiliary winding circuit via a bidirectional switch Sw_1 (shown in Fig.3) for a period of time depending on the duty cycle (δ) of the switching frequency; in this time the bidirectional switch Sw_2 is OFF. When Sw_1 is OFF, the capacitor is discharged and discharging current is limited by R_d.

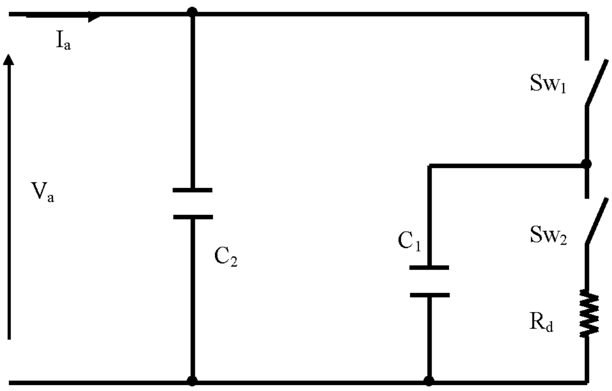

Fig.2 Variable capacitor scheme

The capacitor C_2, much smaller than C_1 is connected to mitigate the spikes during switching off the main capacitor. Thus, the equivalent capacitor can be written as:

$$C_{eq} = \delta \times C_1 + C_2 \quad (1)$$

The maximum value of the capacitor C_1 should be found from the conditions when the motor is working and draws maximum inductive reactive power.

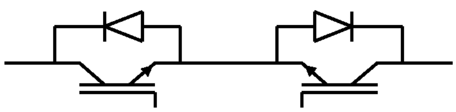

Fig.3 Bidirectional switch used

B. Mathematic model

First, the machine is treated as having two three-phase windings and the voltage equation system can be written as:

$$V_{abcs} = r_1 I_{abcs} + p\lambda_{abcs} \quad (2)$$

$$V_{xyzs} = r_2 I_{xyzs} + p\lambda_{xyzs} \quad (3)$$

$$V_{abcr} = r_r I_{abcr} + p\lambda_{abcr} = 0 \quad (4)$$

where "abcs" means the stator main windings, "xyzs" the three auxiliary windings on the stator and "abcr" the corresponding voltages on the rotor; p is the derivative operator and:

$$\lambda_{abcs} = L_{abcs} I_{abcs} + L_{abcr} I_{abcr} + L_{abcxyz} I_{xyz} \quad (5)$$

$$\lambda_{xyzs} = L_{xyzabcs} I_{abcs} + L_{xyzabcr} I_{abcr} + L_{xyz} I_{xyz} \quad (6)$$

$$\lambda_{abcr} = L_{abcrs} I_{abcs} + L_{abcr} I_{abcr} + L_{abcrxyz} I_{xyz} \quad (7)$$

Further and due to the asymmetry introduced by the particular connection of the auxiliary windings, the analysis has been performed in the "d-q-0" frame and the equations system is:

$$V_{q1} = r_1 I_{q1} + p\lambda_{q1} + \omega\lambda_{d1} \quad (8)$$

$$V_{d1} = r_1 I_{d1} + p\lambda_{d1} - \omega\lambda_{q1} \quad (9)$$

$$V_{01} = r_1 I_{01} + p\lambda_{01} \quad (10)$$

$$V_{qr} = r_r^{'} I_{qr} + p\lambda_{qr}^{'} + (\omega - \omega_r)\lambda_{dr}^{'} \quad (11)$$

$$V_{dr} = r_r^{'} I_{dr} + p\lambda_{dr}^{'} + (\omega - \omega_r)\lambda_{qr}^{'} \quad (12)$$

$$V_{0r} = r_r^{'} I_{0r} + p\lambda_{0r}^{'} \quad (13)$$

$$V_{q2} = r_2 I_{q2} + p\lambda_{q2} + \omega\lambda_{d2} \quad (14)$$

$$V_{d2} = r_2 I_{d2} + p\lambda_{d2} - \omega\lambda_{q2} \quad (15)$$

$$V_{02} = r_2 I_{02} + p\lambda_{02} \quad (16)$$

where the indices "1" is used for main stator winding, "2" for the auxiliary winding and "r" for the rotor.
And:

$$\lambda_{q1} = (L_{ls} - L_{lm}^{'})I_{q1} + L_{lm}^{'}(I_{q1} + I_{q2}) + L_m(I_{q1} + I_{q2} + I_{qr}^{'}) \quad (17)$$

$$\lambda_{d1} = (L_{ls} - L_{lm}^{'})I_{d1} + L_{lm}^{'}(I_{d1} + I_{d2}) + L_m(I_{d1} + I_{d2} + I_{dr}^{'}) \quad (18)$$

$$\lambda_{01} = L_{ls} I_{01} + L_{lm}^{'}(I_{01} + I_{02}) \quad (19)$$

$$\lambda_{q2} = (L_{ls} - L_{lm}^{'})I_{q2} + L_{lm}^{'}(I_{q1} + I_{q2}) + L_m(I_{q1} + I_{q2} + I_{qr}^{'}) \quad (20)$$

$$\lambda_{d2} = (L_{ls} - L_{lm}^{'})I_{d2} + L_{lm}^{'}(I_{d1} + I_{d2}) + L_m(I_{d1} + I_{d2} + I_{dr}^{'}) \quad (21)$$

$$\lambda_{02} = L_{ls} I_{02} + L_{lm}^{'}(I_{01} + I_{02}) \quad (22)$$

$$\lambda_{qr} = L_{lr}^{'} I_{qr} + L_m(I_{q1} + I_{q2} + I_{qr}^{'}) \quad (23)$$

$$\lambda_{dr} = L_{lr}^{'} I_{dr} + L_m(I_{d1} + I_{d2} + I_{dr}^{'}) \quad (24)$$

$$\lambda_{qr} = L_{lr}^{'} I_{0r} \quad (25)$$

C. Equivalent model

Using equations (8)-(25), an equivalent circuit could be drawn for the 3-phase windings in the two stator windings i.e 'abc' and 'xyz'. But observing the connections of the winding 'xyz' forming a single phase winding by series connection of the three windings, it can be written: $I_x = I_y = I_z = I_X$. Using this condition of current in the expansion that results to equations (8) – (25) it can be written: $I_{d2} = I_{q2} = 0$, thus the resulting expression from this can be represented in a d-q-0 equivalent circuit of figures shown below: Fig. 4 shows the "q" equivalent circuit, Fig. 5 – the "d" equivalent circuit and Fig. 6 – the "0"equivalent circuit.

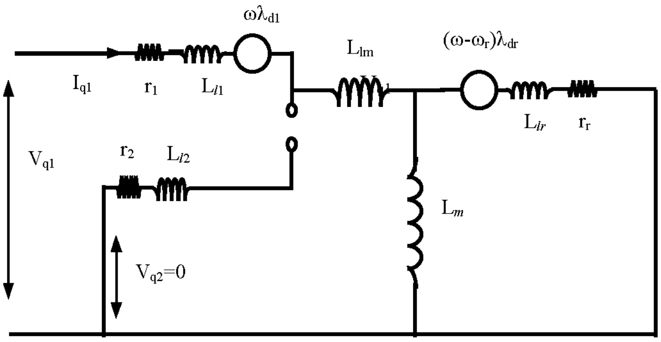

Fig. 4 The "q" equivalent circuit

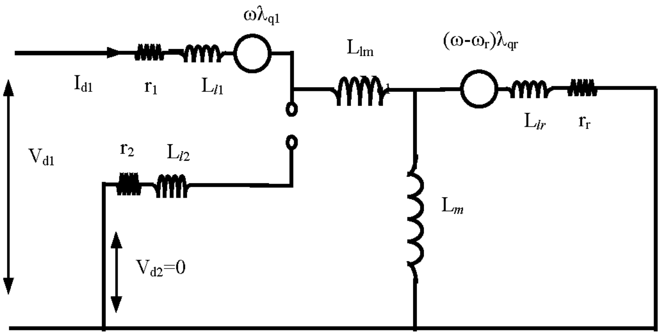

Fig. 5 The "d" equivalent circuit

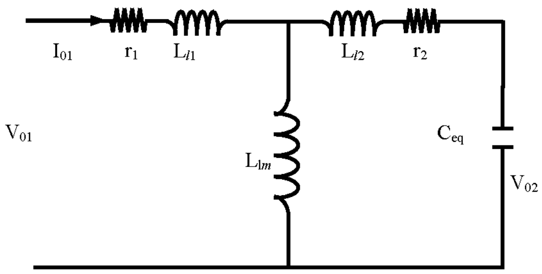

Fig. 6 The "0" equivalent circuit (stator winding)

The particularity of connecting the auxiliary windings in a single phase winding creates an asymmetrical situation which brings about the relevance of the zero sequence.

The power factor of the machine could be defined by the argument of Z_a, which is V_a/I_a. And this is expressed as:

$$Z_a = \frac{V_a}{I_a} = \frac{V_{q1} + V_{01}}{I_{q1} + I_{01}} \tag{25}$$

$$V_{01}(C) = (-j\omega C + Z_{02}) \times I_{02} \times \frac{(Z_{01} + Z_{lm})}{Z_{lm}} \tag{26}$$

As can be observed from the equations (25) and (26), the power factor of the machine depends on C_{eq} and thus it can be brought to unity by means of adjusting the equivalent capacitance.

III. Simulation Results

Based on Matlab platform, an equivalent simulation model has been created using the internal parameters of a 1.5 kW induction motor whose specifications and parameters are as shown in table I.

TABLE I: 1.5 kW INDUCTION MOTOR SPECIFICATIONS AND PARAMETERS

Designation of data	Values
Power	1500 watts
Rated voltage line-to-line	525Volts
Full load line current	2.8 A
Connection	Wye
Number of poles	Four
Stator phase resistance	R=0.5 Ω
Magnetizing reactance, X_m	164 Ω
R_m	1020 Ω
Stator leakage reactance	2.19 Ω
Rotor leakage reactance	2.19 Ω

For the motor under study a capacitor C_1 of 500μF has been used and 1 μF for C_2. The switching frequency has been chosen 5 kHz and the load of the motor (s) has been varied; then the influence of the switching frequency has been investigated. Fig. 7 shows the simulation model used in this study.

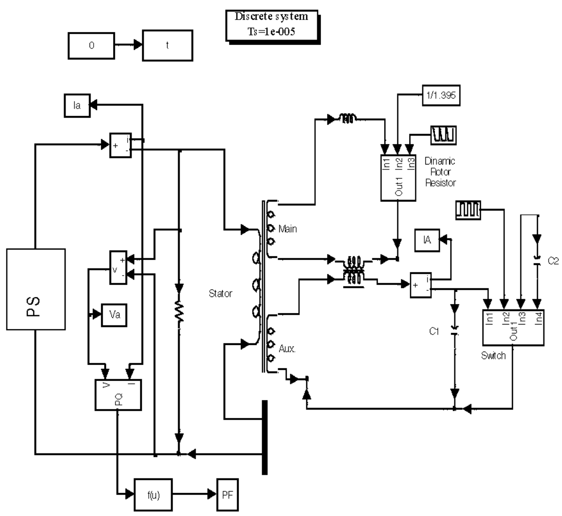

Fig. 7 Simulation Model

A. Steady-state parameters

Fig. 8 shows the phase voltage, auxiliary current and phase current for a slip of 0.002 (no-load) and a duty cycle (δ) of 5 percent and Fig. 9 shows the unity power factor for the same slip after compensation.

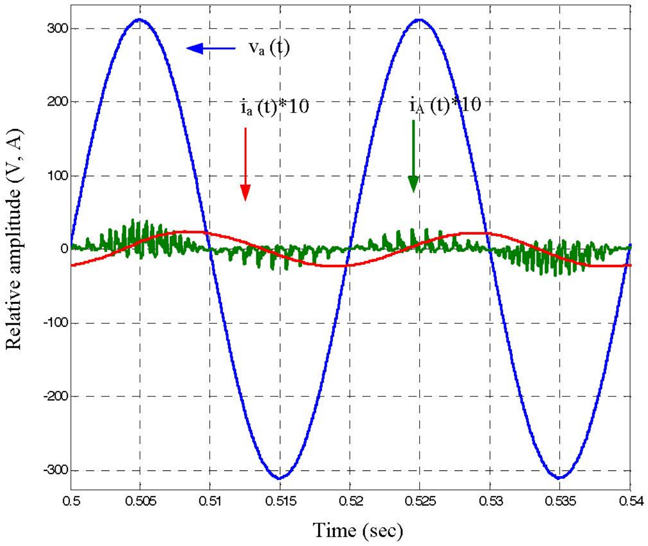

Fig. 8 Steady state parameters for s=0.002 and δ=0.05

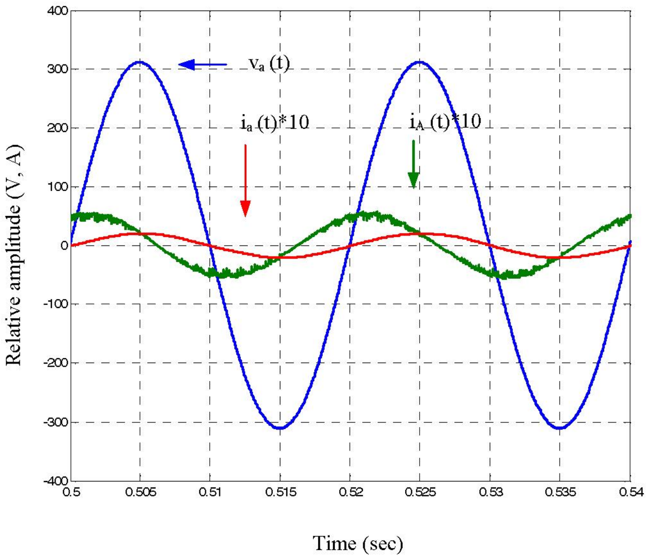

Fig. 9 Steady state parameters for s=0.002 and δ=0.8

From the Fig. 9 one can see the input current after compensation is in phase with the phase voltage.

B. Switching frequency influence

The influence of the switching frequency has been also investigated. Fig. 10 shows the same parameters as above, for a load that give s=0.05 with a switching frequency of 1 kHz and Fig. 11 for 5 kHz.

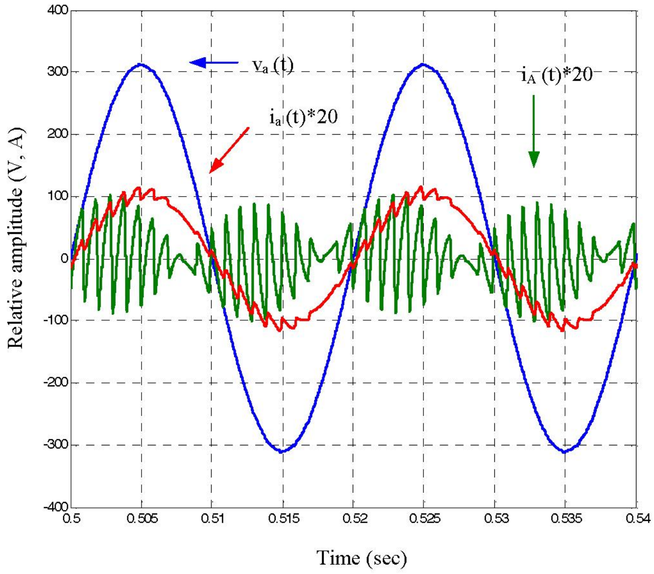

Fig. 10 Steady wave forms for s=0.05 and f = 1kHz

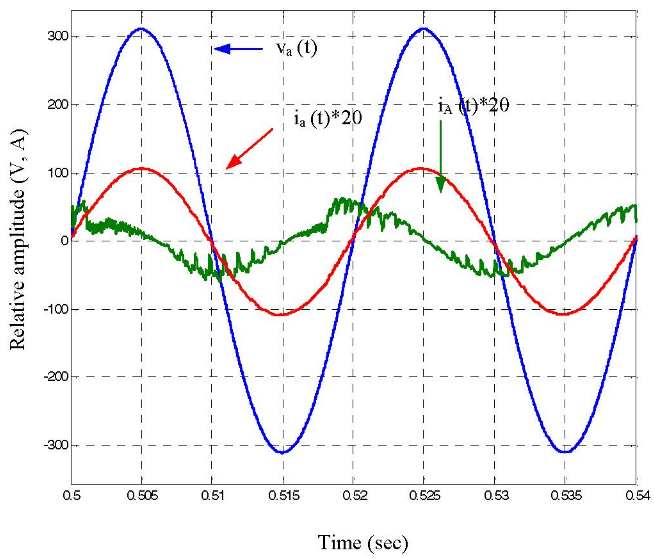

Fig. 11 Steady waveforms for s=0.05 and f = 5 kHz

As can be noticed from the above figures, the 5 kHz switching frequency has a negligible influence upon the phase current.

IV. Experimental Results

The experimental setting comprised the motor coupled with a DC motor working as generator in order to create a load (Fig. 12). For these tests, the duty cycle has been adjusted manually.

Fig. 12 Experimental setup

The load was set for the nominal, which represent an approximate 2.8 A and the graphs for phase voltage and current shown in Fig. 13 are for a switching frequency of 1kHz; Fig. 14 shows the same wave forms for a switching frequency of 5 kHz.

As can be noticed from the figure 15, the capacitance injection compensates the power factor to unity and for a frequency of 5 kHz the switching influence is negligible.

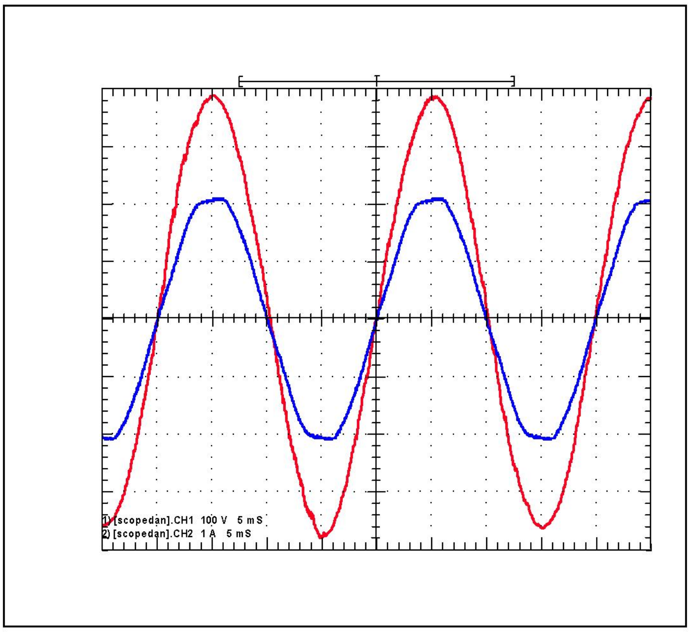

Fig. 13 Waveforms for s=0.05 and f = 1kHz

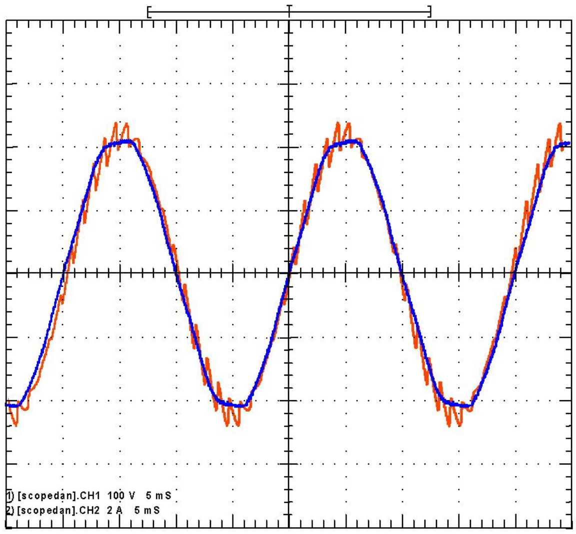

Fig. 14 Waveforms for s=0.05 and f = 5 kHz

Fig. 15 shows the power factor for the uncompensated machine and after compensation. As can be noticed the power factor can be compensated to near unity.

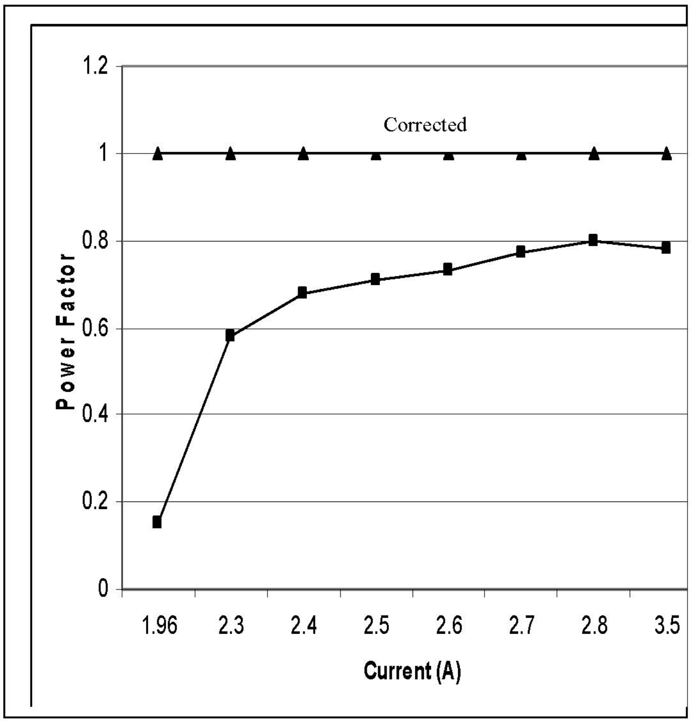

Fig. 15 Power factor versus current for the original machine and the corrected using the proposed scheme

V. Conclusions

In this paper, a three-phase induction motor with an auxiliary single-phase stator winding, which is only magnetically coupled to the stator main winding and capacitance injection is explored for improving the starting current and operating power factor. The scheme improves the power factor and starting current while keeping a low level of distortion of the supply current.

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