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PERFORMANCE EVALUATION OF A THREE-PHASE INDUCTION MACHINE WITH AUXILIARY WINDING FED BY A LEADING REACTIVE CURRENT

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ABSTRACT
In this paper the performance of three-phase induction machine Equipped with a three-phase auxiliary winding which is only magnetically coupled to the stator main winding is evaluated. A capacitive load is connected in parallel to each phase of the Auxiliary winding and serves to inject a leading reactive current into the machine. Steady state and dynamic performance of the machine are evaluated under various loading and compensative conditions. The experimental results show that it possible to obtain a comparatively good power factor with a fixed capacitive load for various loadings of the asynchronous machine.

KEY WORDS
Induction machine, Auxiliary winding, Machine steady state and dynamic performance, Power factor enhancement

1. Introduction

Three-phase induction motors comprise the vast majority of all electric motors made in large sizes. They are rugged and reliable. They do not produce sparks like DC motors do, so they can be used in hazardous environment like oil refineries, mines, grain elevators, in grinding, pumping and blowing operations. The efficiency of small induction motors is usually less than or about 90%, while for larger size motors it could increase up to 97%.

Despite the advantages mentioned above, generally an induction machine 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 converters.

At starting the input power to an induction motor is mainly reactive. It draws 6 to 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 improves significantly 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. A motor with a high start-stop operation, in addition to being a nuisance to the surrounding loads, will have an overall poor power factor performance

In recent decades, several techniques to improve the power factor of induction motors have been suggested, naming: the synchronous compensation, fixed capacitors, fixed capacitors with switched inductor, solid-state power factor controller, and switched capacitors [1-6].

A three-phase induction motor equipped with two sets of winding on the stator which are only magnetically coupled has been suggested [1, 3, 5].This scheme is the subject of this paper.

2. Proposed Model

The basic model of the three-phase induction machine equipped with a three-phase auxiliary winding which is only magnetically couple to the stator main winding is shown in Fig.1. The three-phase auxiliary winding has smaller wire sizes in order to be accommodated in the same slot as the main winding. A capacitive load is connected in parallel to each phase of the auxiliary winding. The main winding has the same number of turns as the auxiliary winding, thus the transformation ratio is one.

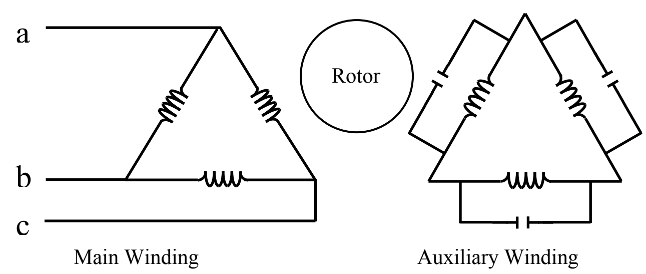

Figure 1. Basic model of three phase induction with Two sets of windings on the stator

3. Mathematical Model

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

$$V_{abcs} = r_1 I + p\lambda_{abcs} \qquad (1)$$

$V_{xyzs} = r_2 I + p\lambda_{xyzs}$ (2)
$V_{abcr} = r_r I + p\lambda_{abcr}$ (3)

where “abcs” means the stator main winding , “xyzs” three-phase auxiliary winding on the stator and “abcr” the corresponding voltages on the rotor, *p* is the derivative operator and :

$\lambda_{abcs} = L_{abcs} I_{abcs} + L_{abcr} I_{abcr} + L_{abcxyz} I_{xyz}$ (4)
$\lambda_{xyzs} = L_{xyzabcs} I_{abcs} + L_{xyzabcr} I_{abcr} + L_{xyz} I_{xyz}$ (5)
$\lambda_{abcr} = L_{abcrs} I_{abcs} + L_{abcr} I_{abcr} + L_{abcrxyz} I_{xyz}$ (6)

Furthermore, in order to simplify the analysis of this machine, it has been performed in the d-q reference frame and the equations are as written in 7-24:

$V_{q1} = R1\ I_{q1} + p\lambda_{q1} + \omega\lambda_{q1}$ (7)
$V_{d1} = R_1\ I_{d1} + p\lambda_{d1} - \omega\lambda q1$ (8)
$V_{01} = R1\ I_{01} + p\lambda_{01}$ (9)
$V_{d1} = R1\ I_{qr} + p\lambda_{qr} + (\omega - \omega_r)\ \lambda_{dr}$ (10)
$V_{dr} = R1\ I_{dr} + p\lambda_{dr} + (\omega - \omega_r)\ \lambda_{qr}$ (11)
$V_{0r} = Rr\ I_{0r} + p\lambda_{0r}$ (12)
$V_{q2} = R2\ I_{q2} + p\lambda_{q2} + \omega\lambda d2$ (13)
$V_{d2} = R2\ I_{d2} + p\lambda_{d2} - \omega\lambda q2$ (14)
$V_{02} = R2\ I_{02} + p\lambda_{02}$ (15)

Where the indices “ 1 “ main stator winding , “ 2 “ for the auxiliary winding and “ r “ for the rotor . And:

$\lambda_{q1} = (L_{ls} - L_{lm})I_{q1}+L_{lm}(I_{q1}+I_{q2})+L_m(I_{q1}+I_{q1}+I_{qr})$ (16)
$\lambda_{d1} = (L_{ls}-L_{lm})I_{d1} + L_{lm}(I_{d1} + I_{d2})+L_m(I_{d1}+I_{d2}+I_{dr})$ (17)
$\lambda_{01}=L_{ls}I_{01}+ L_{lm} (I_{01} + I_{02})$ (18)
$\lambda_{q2} = (L_{ls} - L_{lm})I_{q2}+L_{lm} (I_{q1}+I_{q2}) + L_m(I_{q1}+ I_{q1}+I_{qr})$ (19)
$\lambda_{d2}= (L_{ls}- I_{lm})I_{q1}+L_{lm}(I_{d1}+I_d)+L_m(I_{d1}+I_{d2}+I_{dr})$ (20)
$\lambda_{02}=L_{ls}I_{02} + L_{lm} (I_{01} + I_{02})$ (21)
$\lambda_{qr}=L_{lr}I_{qr} + L_m(I_{q1} + I_{q2} + I_{qr})$ (22)
$\lambda_{d2}=L_{lr}I_{02}+ L_m (I_{d1} + I_{d2} + I_{dr})$ (23)
$\lambda_{qr} = L_{lr}I_{0r}$ (24)

3.1 Equivalent circuit

The per phase equivalent circuit of the machine is easily obtained from equations (7) – (15) derived in the section 3 of this article. This is as drawn in Fig.2.

This equivalent circuit has two branches, each having separate resistance and leakage reactance together with a common mutual leakage inductance L_{lm}, which occurs due to the fact that the two set of windings occupy the same slots and therefore mutually coupled by their leakage flux. The mutual inductance that occurs between main winding and rotor is represented by Lm.

Other parameters of the equivalent circuit are: Main winding resistance R_1, Auxiliary winding resistance R_2, Main winding leakage reactance L_1, Auxiliary winding leakage inductance L_2; Mutual leakage inductance $L_{lm,}$ Rotor leakage inductance L_{lr}; and the rotor resistance R_r.

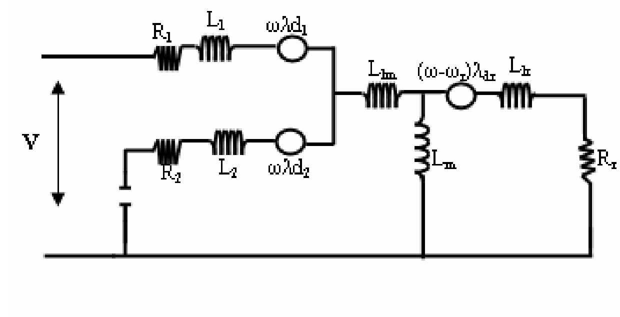

Figure 2. Per-phase Equivalent circuit

In this analysis there is no need to refer the auxiliary winding quantities to the main winding, because the two sets of windings are wound for the same number of turns with a transformation ratio of one.

4. Experimental Results

The tested three-phase induction motor has the specifications and parameters as in Table 1.

Table 1
Induction Motor Specification and Parameters

Description of data	Values
Output Power	4 KW
Main Winding Rated Voltage	380 V
Auxiliary Winding Rated Voltage	380V
Main winding connection	Delta
Auxiliary winding connection	Delta
Number of poles	4
Magnetizing Reactance Xm	37.86 Ω
Main winding phase resistance	4.33 Ω
Auxiliary winding phase resistance	18.1 Ω
Main winding leakage reactance	6.97 Ω
Auxiliary winding leakage reactance	6.97 Ω
Rotor leakage reactance	6.97 Ω
Full load main winding current	8.6 A
Full load auxiliary winding current	3 A

4.1 Steady state performance

4.1.1 Loading without compensation

The main and the auxiliary windings of the asynchronous machine are both connected in delta, with no compensation in the auxiliary winding. By varying only the load from in steps to the full load, measurements were respectfully taken and recorded as shown in table 2

Table 2
Loading Without Compensation

I_L (A)	P(W)	S(VA)	PF	Slip	RPM
5.43	678.6	3569.7	0.14	0.0026	1496
5.56	1734	3655.1	0.43	0.006	1491
6.02	1992	3957.5	0.49	0.0086	1487
6.88	2709	4522.9	0.61	0.0153	1477
7.74	3540	5088.2	0.70	0.0213	1468
8.6	4179	5653.6	0.74	0.056	1416

It is observed from table 2 that the power factor increases with load. The maximum power factor obtained is 0,74 at full load and at load current of 5.43 A ; which represent a light load the power factor of the machine is 0.14.

4.1.2 Loading with compensation

Keeping the main and auxiliary windings connected as indicated in section (a) above, the value of the capacitance is varied at no load. The results of this experiment are given in table 3. The power factor at no load for different compensations between 10 μF and 30 μF were much better compared to the power factor of the uncompensated machine shown in table 2.

Table 3
Various loading at different compensation

C(μF)	I_L (A)	PF	P(W)	S(VA)
10	3.731	0.15	396	2538
20	2.032	0.38	524.1	2383.6
30	1.795	0.83	1005.3	1216.8

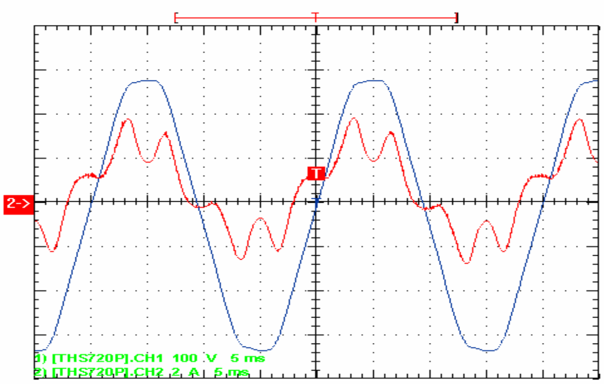

Figure 3. Oscilloscope results showing phase voltage and Current with compensation of 30 μF under no-load conditions

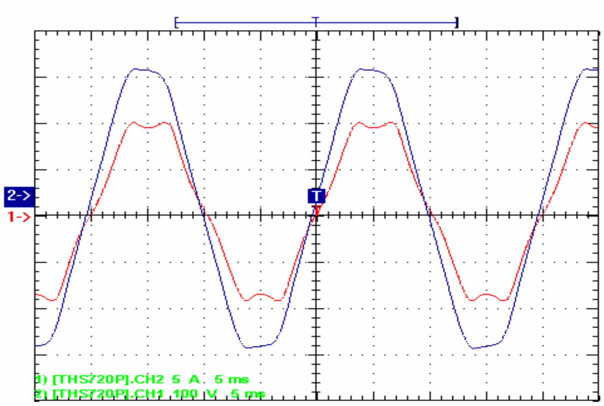

Figure 4. Oscilloscope results showing phase voltage and Current with compensation of 30 μF at full load conditions, the current is distorted with Total Harmonic Distortion of 8.5% due to the 5th and 7th harmonics.

The voltage and current waveforms of the machine with 30 μF compensation under no-load and full load conditions are shown respectively in figures 3 and 4. The presence of harmonics is obvious in the current wave forms of the machine on no-load as shown in figure 3. The harmonics contents is however very much improved at full load as shown in figure 4.

4.1.3 Loading with fixed compensation

During the experimental test, it has been observed that, with a fixed compensation of 28.3 μF per phase, a good power factor was obtained for the asynchronous machine at different loading conditions. Measured results as obtained from the experiment are given in table 4, while the current and voltage wave forms of the machine with 28.3 μF compensation as well as full load and light load conditions are respectively shown in figures 5 and 6.

The highest power factor obtained for the uncompensated machine is 0.74 at full load while that of the compensated machine is 0.98. This power factor improvement is obtained as a result of the introduction of auxiliary winding and capacitance connected to it.

Table 4
Fixed compensation at various loads

C(μF)	I_L	PF	P(kW)	S(kVA)
28.3	1.7	0.83	0.96	1.15
28.3	2	0.87	1.21	1.37
28.3	2.2	0.90	1.33	1.49
28.3	2.46	0.91	1.51	1.66
28.3	4.3	0.97	2.67	2.75
28.3	5.56	0.97	3.63	3.73
28.3	7.36	0.97	4.80	4.93
28.3	8.6	0.98	5.22	5.32

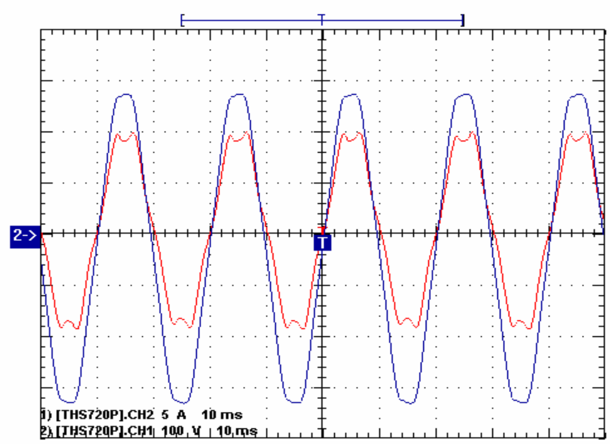

Figure 5. Oscilloscope results showing phase voltage and Current with compensation of 28.3 μF under full load conditions, the current is distorted with Total Harmonic Distortion of 8.6 % due to the 5th and 7th harmonics.

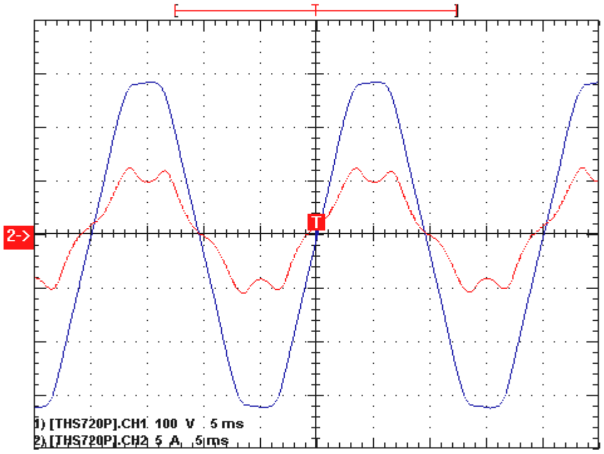

Figure 6. Oscilloscope results showing phase voltage and Current with compensation of 28.3 µF at half load, the current is highly distorted with Total Harmonic Distortion of 16.2 % due to the 5^{th} and 7^{th} harmonics.

4.2 Dynamic performance

At starting the slip is 1 and the input current to the induction machine is 6 to 10 times the rated current. The starting current depends on the supply voltage and the input impedance. The waveforms of the starting current of the machine at rated voltage, without compensation and with compensation of 28.3 µF are shown respectively in figures.7 and 8.

The magnitude of the starting current is not influenced by the presence of auxiliary winding and capacitance connected to it, but the magnitude of running current is reduced as displayed in figures 7 and 8.

The response of the machine compensated with 28.3 µF to a step change in load is shown in figure 9.

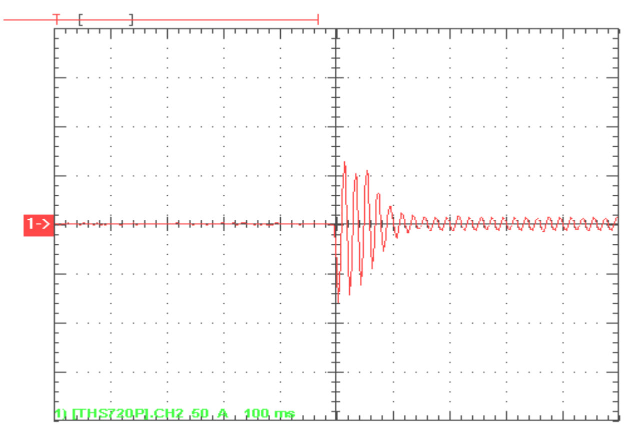

Figure 7. Oscilloscope results showing the dynamic starting current without compensation.

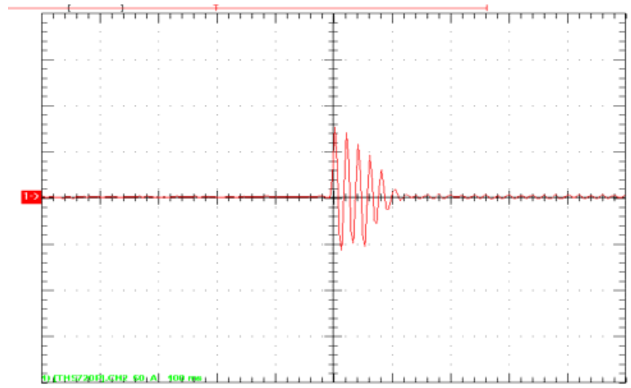

Figure 8. Oscilloscope results showing the dynamic starting current with compensation of 28.3µF

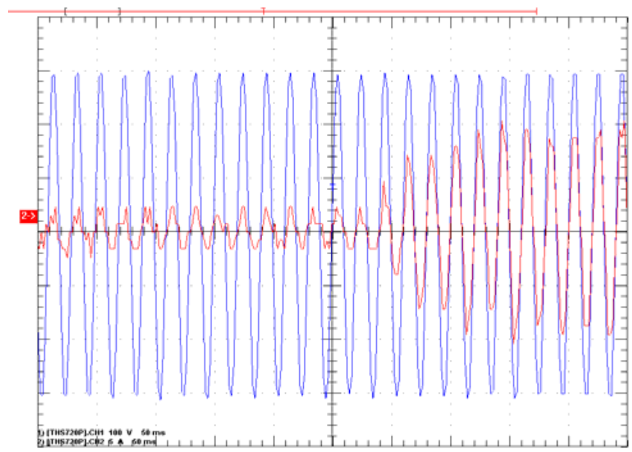

Figure 9. Waveforms of Voltage and current under compensation of 28.3µF showing the response of the machine to a step change in load.

5. Conclusion

In this paper the steady state and dynamic performance of 4 poles, 4 kW, 380 V three-phase induction machine equipped with three-phase auxiliary winding on the stator which is only magnetically coupled to the main winding have been evaluated. It has been found during experimental test that by connecting a capacitor of 28.3µF in parallel to each phase of the auxiliary winding which is in delta configuration, the power factor of the machine is enhanced throughout different loads. Thus, it shows that the need for additional element such as power electronic switches between the auxiliary winding and the capacitor, to control the power factor at different loading has to be reconsidered.

It was also observed during dynamic experimental test with a compensation of 28.3µF the starting current settles to a sensibly reduced value compared to none compensated machine.

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