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POWER FACTOR ENHANCEMENT OF INDUCTION MACHINES BY MEANS OF SOLID STATE EXCITATION

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Abstract

A new concept for power factor correction of induction machines is introduced which employs an auxiliary three phase stator winding together with a PWM inverter to supply excitation power to the machine. When the PWM inverter is modelled as an equivalent capacitor it is shown that two values of capacitance will yield unity power factor at a given operation condition. The effect of machine parameters on the critical value of capacitance is examined. A control algorithm to ensure unity power factor at the terminals of the main stator windings is presented and its satisfactory operation verified by means of a detailed analog computer simulation.

Introduction

One major drawback of an induction machine compared to synchronous machines is its lack of flexibility in the choice of power factor. While the reactive power required by a synchronous machine can be taken from the power source or supplied by the machine itself by adjustment of the field current, the power factor of an induction machine is always lagging and set by external quantities (i.e. the load and terminal voltage). Poor power factor adversely affects the economics of the transmission and distribution system and a cost penalty is frequently levied for excessive VAR consumption. Power factor is typically improved by installation of capacitor banks but these banks can cause problems at light load conditions or during loss of supply. Comparatively expensive switchgear is required to vary the capacitance value as the load changes and to disconnect the bank during loss of supply.

The problems involved with discrete switching of capacitors can be greatly overcome by use of solid state reactive power compensators. A variety of reactive power compensators have been developed to provide power factor correction [1-6]. However, these compensators are typically also harmonic generators and require additional capacitors and inductors to provide filtering for the harmonics introduced by the solid state compensator itself.

In this paper a new configuration employing a combination of a special purpose induction machine and a PWM voltage inverter is proposed. In particular, the machine is equipped with two electrically isolated but magnetically coupled three phase windings. One three phase winding set (main winding) is connected to the utility supply while the other winding set (auxiliary winding) is supplied by a PWM inverter as shown in Fig. 1. The voltage harmonics introduced by the inverter are filtered by the inherent inductances of the machine itself and at sufficiently high PWM frequencies the approach should not require additional filtering. In addition, since the inverter requires only a single low cost dc capacitor rather than three ac capacitors and switchgear is not needed to prevent overexcitation, this arrangement could eventually become a cost competitive alternative to more conventional methods of power factor correction of single machine units requiring on site correction.

Principle of Operation

When the PWM converter of Fig. 1 is instrumented with a suitable feedback control, the main winding of the induction machine can be controlled to carry only the active power while the flow of power in the auxiliary winding is solely the reactive component. Since the auxiliary winding carries only the reactive power, the PWM inverter dc voltage can be supported by a dc capacitor only and need not be connected to a power source. In effect the PWM inverter serves to act as a buffer to circulate reactive power between the machine windings and the dc capacitor. The PWM inverter can be controlled in such a manner so as to always provide the desired power factor at the terminals of the main winding. With sufficient ampere-turn capability of the auxiliary winding, unity power factor operation at the terminals of the main winding is possible over a wide range of load conditions including rated load. This paper sets forth the analysis of the steady-state characteristics of this power factor correction scheme as well as a discussion of the control algorithm required to realize this mode of operation.

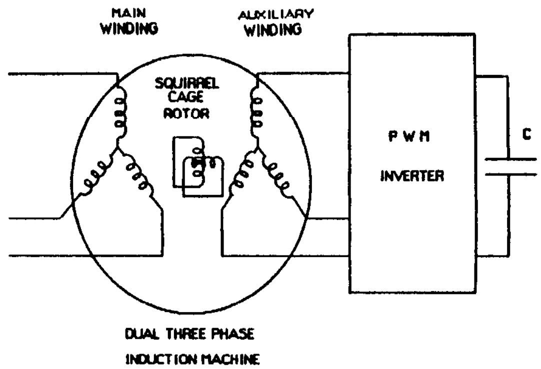

Fig. 1 Induction Machine with Auxiliary PWM Inverter Excitation.

Equivalent Circuit Analysis

The principle of solid state excitation of an induction motor can be examined by means of the "per phase" equivalent circuit of Fig. 2 [7]. It can be noted that the rotor circuit and the main magnetic circuit are identical to that of a three phase machine. The dual stator windings can be effectively modeled by two branches each having separate resistance and leakage reactance together with a common mutual inductance X_{lm} which occurs due the fact that the two sets stator windings occupy the same slots and are therefore mutually coupled by their leakage flux (i.e. non-air gap component of stator flux.) [7]. When the PWM converter is controlled to pass only reactive power its effect can be represented in the equivalent circuit by a variable capacitor which is functionally dependent on the voltage across and the current through the capacitor [8,9].

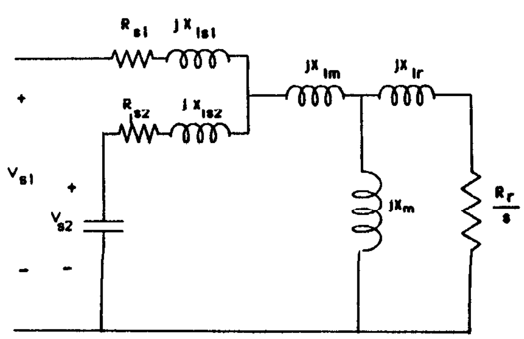

Fig. 2 Equivalent Circuit of a Dual Three Phase Induction Machine.

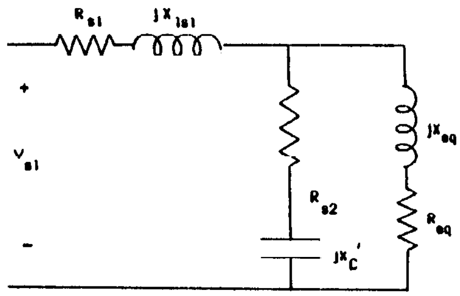

Fig. 3 Modified Equivalent Circuit.

To reduce the complexity of this analysis, it is useful to simplify the equivalent circuit to that of Fig. 3 wherein, for a fixed slip s,

$$X_c' = \frac{1}{\omega C} - X_{ls2} \tag{1}$$

$$X_{eq} = \text{Imag of } [jX_{lm} + (\frac{R_r}{s} + jX_{lr}) \,//\, X_m] \tag{2}$$

$$R_{eq} = \text{Real of } [\frac{R_r}{s} + jX_{lr} \,//\, X_m] \tag{3}$$

At a specific slip the circuit of Fig. 3 will operate at unity power factor when the imaginary part of the stator impedance viewed from the main winding becomes zero. The impedance of the rotor circuit in parallel with the auxiliary winding circuit can be written as

$$Z = \frac{(R_{s2} R_{eq} - X_c' X_{eq}) + j(X_c' R_{eq} + X_{eq} R_{s2})}{(R_{s2} + R_{eq}) + j(X_c' + X_{eq})} \tag{4}$$

The imaginary part of the impedance is

Imag $Z =$ (5)

$$\frac{(X_c' R_{eq} + X_{eq} R_{s2})(R_{s2} + R_{eq}) - (R_{s2} R_{eq} - X_c' X_{eq})(X_c' + X_{eq})}{(R_{s2} + R_1)^2 + (X_c' + X_{eq})^2}$$

Unity power factor requires that the imaginary part of the total input impedance of the induction machine equal zero, in which case

$$\text{Imag } Z_{tot} = X_{ls1} + \text{Imag } Z = 0 \tag{6}$$

or, hence

$$\text{Imag } Z = - X_{ls1} \tag{7}$$

Utilizing Eq. 7, Eq. 5 can be expressed

$$a\,(X_c')^2 + b\, X_c' + c = 0 \tag{8}$$

where

$$a = X_{eq} + X_{ls1}$$
$$b = - R_{s2}R_{eq} + X_{eq}^2 + (R_{s2} + R_l)R_{eq} + 2X_{eq} X_{ls1}$$
$$c = - X_{eq}[R_{s2}R_{eq} - (R_{s2} + R_{eq})R_{s2}] + X_{ls1}[(R_{s2} + R_{eq})^2 + X_{eq}^2]$$

and a, b, c are constants at a specific speed.

Equation 8 is a simple quadratic equation which can be readily solved by the quadratic formula. A solution for X_c' clearly exists only if $b^2 - 4\,a\,c \geq 0$ which depends on the slip of the induction machine. Figure 4 demonstrates how the imaginary part of Z_{tot} varies with X_c' for a typical machine having the parameters given in the Appendix. It can be noted that there are two values of X_c' which satisfies the condition of unity power factor for any specific slip. The smaller value of X_c' corresponds to a high current (large C) and the larger value of X_c' (smaller C) corresponds to a small value of current. Figure 5 indicates how the locus of X_c' varies with slip for both a motoring and a generating condition.

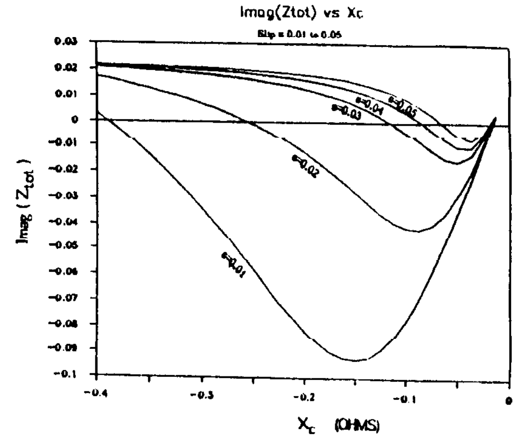

Fig. 4 Imaginary Part of Z_{tot} versus X_c' for Various Values of Slip.

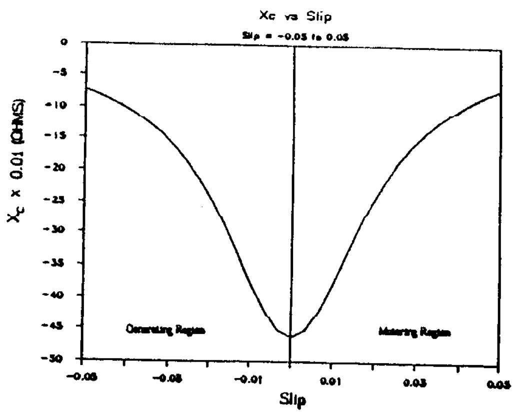

Fig. 5 Critical Value of X_c' to Produce Unity Power Factor for Motoring and Generating Conditions.

It can be seen from the equivalent circuit that with a fixed capacitor value the power factor varies with the slip. To illustrate this concept, it is useful to employ a current locus diagram. If the resistance and the leakage reactance of the main winding are neglected for simplicity and the mutual leakage is shorted ($X_{lm} \approx 0$) the simplified circuit diagram of Fig. 6 can be constructed. The admittance of the auxiliary winding branch can be written as follows

$$R_{s2} + j\,X_c' = \frac{1}{Y_{s2}} = \frac{1}{G_{s2} + jB_{s2}} \tag{9}$$

or

$$R_{s2} = \frac{G_{s2}}{G_{s2}^2 + B_{s2}^2} \tag{10}$$

so that

$$G_{s2}^2 - \frac{G_{s2}}{R_{s2}} + B_{s2}^2 = 0 \tag{11}$$

which can be written as

$$(G_{s2} - \frac{1}{2\,R_{s2}})^2 + B_{s2}^2 = (\frac{1}{2R_{s2}})^2 \tag{12}$$

Equation 12 is an expression for a circle on the G-B plane which has its center at $(1/2R_{s2}, 0)$ and for which the radius is $1/2R_{s2}$. The radius of the circle is inversely proportional to the size of the resistance R_{s2}.

Using the same approach, the equation for the rotor circuit can be represented as follows

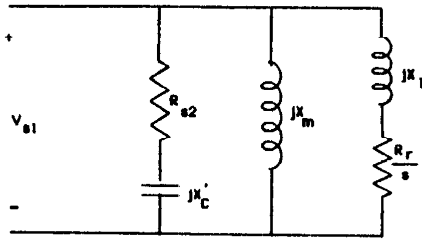

Fig. 6 Simplified Equivalent Circuit for Modelling of Current Locus Diagram.

$$G_r^2 + \left(B_r + \frac{1}{2X_{lr}}\right)^2 = \left(\frac{1}{2X_{lr}}\right)^2 \tag{13}$$

where, in this case $G_r + jB_r = Y_r$. This equation is denotes a circle whose radius and center is dictated by the inverse of the rotor leakage reactance.

Consider now the admittance diagram for the entire circuit of Fig. 6. In Fig. 7 the total admittance Y_{tot} is found by adding the admittance of the auxiliary winding Y_{s2} to the admittance of the rotor Y_r and the magnetizing branch Y_m. The total admittance becomes

$$Y_{tot} = Y_{s2} + Y_r + Y_m$$

The admittance Y_m serves to translate the admittance diagram down by $1/X_m$.

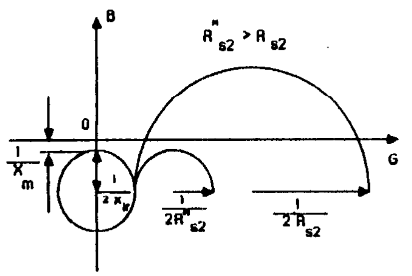

Fig. 7 Admittance Diagram as a Function of X_c' for a Fixed Value of Slip and for Two Values of Auxiliary Winding Resistance.

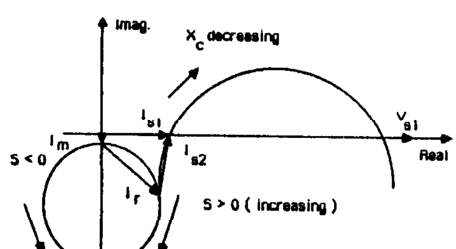

Fig. 8 Current Locus Diagram for a Fixed Slip as a Function of X_c'. Unity Power Factor Condition is Shown Explicitly.

The corresponding current locus is given in Fig. 8 in which the fixed currents I_{s2} and I_m due to the admittances Y_{s2} and Y_m are added to various values of I_r. The vector sum of the three currents results in the main stator winding current. The sketch clearly shows why there exists two values of X_c' for which the total current is in phase with V_{s1}. While the equivalent circuit of Fig. 6 is an approximation, the general behavior of the detailed circuit, Fig. 2, remains the same. In practice the larger value of X_c' is chosen since this value not only corresponds to a smaller value of equivalent inverter capacitance but also to a smaller total current.

As slip of the machine varies the semicircle locus of Y_{s2} effectively moves along the perimeter of the locus of Y_r. It can be observed that for both motoring and generating operation and for practical sized capacitors there may exist a slip limit beyond which the induction machine will not operate at unity power factor. However, for most machines this limit will occur beyond the normal operating slip region. It is also evident that there is a possibility that there may not exist a value of X_c' which corresponds to unity power factor for a specific value of Y_r since R_{s2} affects the radius of the semicircle. From Fig. 8 it can be concluded that:

1) For a given induction machine there may be a limited range of slip for which a permissible value of X_c exists.

2) To enlarge the possibility of unity power factor for an induction machine the following parameters must be considered in the machine design:

(a) R_{s2} must be made as small as possible to maximize the circle diagram of the auxiliary branch.

(b) X_m must be made as large as possible to minimize the downward shift of the Y_{s2} and Y_r loci.

(c) X_{lr} must be made as small as possible to maximize size of the circle diagram of the rotor branch.

Steady State Control Strategy

A phasor diagram of a dual three phase induction machine can be readily constructed from the equivalent circuit of Fig. 2 and is shown in Fig. 9 for the unity power factor condition. In order to simply the phasor analysis the equivalent circuit and resulting phasor diagram has been constructed by neglecting the leakage inductance in the main winding. This assumption is based on the fact that the leakage reactance will consume only a few percent of the total reactive power. The voltage $\tilde{V}_{s1}$ corresponds to the main winding stator voltage. At unity power factor the terminal voltage V_{s1} and the voltage V_{s12} are colinear and

$$V_{s12} = V_{s1} - I_{s1}R_{s1} \tag{14}$$

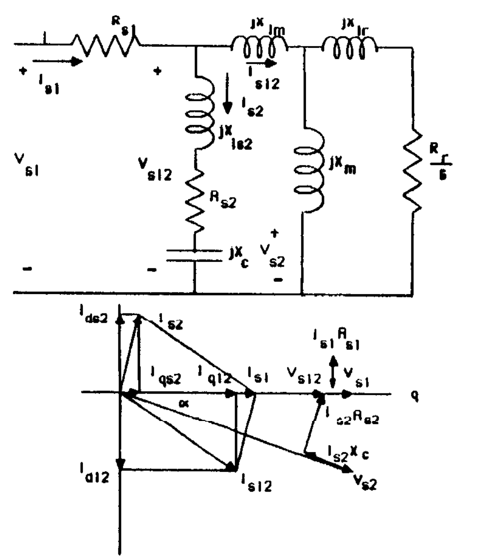

Fig. 9 Motor Equivalent Circuit and Phasor Diagram for Main Winding Unity Power Factor Operation.

The current through the auxiliary winding will be

$$\tilde{I}_{s2} = \frac{\tilde{V}_{s12}}{R_{s2} + j(X_{ls2} - X_c)} \tag{15}$$

Since R_{s2} is small the current $\tilde{I}_{s2}$ is almost perpendicular to $\tilde{V}_{s12}$. The total current into the magnetizing branch and the rotor circuit is:

$$\tilde{I}_{s12} = \tilde{I}_{s1} - \tilde{I}_{s2} \tag{16}$$

In $d-q$ notation this current can be written in terms of real variables as

$$I_{q12} = I_{qs1} - I_{qs2} \tag{17}$$

and

$$I_{d12} = I_{ds2} \tag{18}$$

The voltage output of the PWM is

$$\tilde{V}_{s2} = \tilde{I}_{s2}(-j)X_c \tag{19}$$

$$= (\tilde{I}_{qs2} + j\tilde{I}_{ds2})(-jX_c) \tag{20}$$

or

$$V_{qs2} = I_{ds2}\, X_c \tag{21}$$

and

$$V_{ds2} = -\, I_{qs2}\, X_c \tag{22}$$

The reactive power consumed by the rotor and magnetizing branch of the machine can be written as

$$Q_{s12} = V_{q12} I_{d12} + V_{d12} I_{q12} \tag{23}$$

The reactive power produced by the PWM can be written as follows

$$Q_{s2} = V_{s2}\, I_{s2} \tag{24}$$

Equation 24 can also be written in $d-q$ for as

$$Q_{s2} = V_{qs2}\, I_{ds2} + V_{ds2}\, I_{qs2} \tag{25}$$

The active power needed to compensate the losses in the auxiliary winding is

$$P_{s2} = V_{s12}\, I_{s2} \sin \alpha \tag{26}$$

where α denotes the angle between the phasors V_{s1} and V_{s2}. In terms of $d-q$ variables

$$P_{s2} = V_{q12}\, I_{qs2} \tag{27}$$

The control strategy for tentative controller can be arranged according to these equations. However, the variable to be controlled in the real circuit is different from the equivalent circuit, Fig. 2. In the equivalent circuit it is assumed there is a variable capacitor which can be controlled as desired. The variable in the actual system is the magnitude and phase of the PWM inverter and the sensed variables are the reactive power input to the main winding and the dc voltage across the dc bus. It is useful to demonstrate how the controlled variables (PWM inverter voltage amplitude and phase) affect the regulation of the sensed feedback signals (main winding power factor and dc inverter voltage).

In a conventional induction machine the stator current normally lags the stator voltage. The function of the PWM is to inject a reactive current I_{s2} into the machine so that the resultant of the two currents will be in phase with the voltage supply V_{s1}. Since the PWM used is a voltage source inverter, the only means to modulate the current I_{s2} is by modulating the voltage V_{s2} (output voltage of the PWM). The reactive power of the main winding is used to modulate the magnitude of V_{s2} or I_{s2} indirectly. The reactive power demanded by the induction machine is approximately

$$Q \approx -V_{q12}\, I_{d12} = V_{q12}\, I_{ds2} \tag{28}$$

From the phasor diagram it can be seen that the angle α is small which makes V_{ds2} and I_{qs2} small, so the product of the two $V_{ds2}\, I_{qs2}$ can be neglected then from Eq. 25, the reactive power produced by the PWM can be written as

$$Q_{s2} \approx V_{qs2}\, I_{ds2} \tag{29}$$

To increase the reactive power produced by the PWM circuit, the real component of auxiliary winding voltage V_{qs2} can be increased. In the equivalent circuit this means the size of effective capacitive reactance X_c must be increased. In the actual circuit this can be accomplished by adjusting the pulse width of the PWM. Since the angle α is always small then

$$I_{ds2} \approx I_{s2} \tag{30}$$

This result demonstrates that by adjusting the magnitude of V_{s2}, the magnitude of the reactive power produced by the PWM can be adjusted accordingly.

Another variable which can be controlled is the phase angle of the PWM output voltage. This angle related to the the active power flow between induction machine and PWM. From Eq. 26 it can be seen that if the angle α is not correctly adjusted there will be an interchange of active power between the main power and PWM. Assume, for example, that the angle α is too large. In this case the active power entering the auxiliary winding from the main winding is not only used to compensate the losses in R_{s2} but also to charge the dc capacitor. As a result, the dc voltage will increase (there is a charging current into the capacitor). On the other hand if the angle α is too small there will be a discharging current out of the capacitor which will reduce the dc voltage. The angle α of the PWM output voltage is therefor most convenient for use as a control variable to regulate the dc inverter voltage. Figure 10 illustrates how the auxiliary winding voltage amplitude and phase angle with respect to the main winding voltage must be varied with slip (i.e. load) to preserve unity power factor at the main winding terminals and keep the inverter dc voltage constant. It is clear that the relatively small variations in V_{s2} and α are required over a wide change in load suggesting that tight control of the PWM inverter output voltage will be required for satisfactory operation.

The use of voltage amplitude and phase angle control (α control) to simultaneously adjust the main winding reactive power and capacitor voltage is illustrated in Fig. 11. In step 1) it is assumed that the control angle α is too large so power flows into the inverter thereby charging the dc side capacitor. In order to prevent further charging the overvoltage condition is sensed and α decreased until the capacitor voltage becomes constant. Regardless of the value of dc voltage obtained, the reactive power to the main winding can now be regulated to zero by maintaining a constant α angle and adjusting the amplitude of the inverter output ac voltage by pulse width modulation. In practice the control of dc voltage and main winding reactive power control occurs simultaneously and the dc voltage is continuously regulated to a desired nominal value.

Analog Computer Simulation Results

In order to demonstrate the feasibility of the approach an analog simulation of the entire system has been carried out including detailed simulations of the dual three phase induction machine, the VSI-PWM inverter inverter and controller. The overall block diagram of the entire system is shown in Fig. 12.

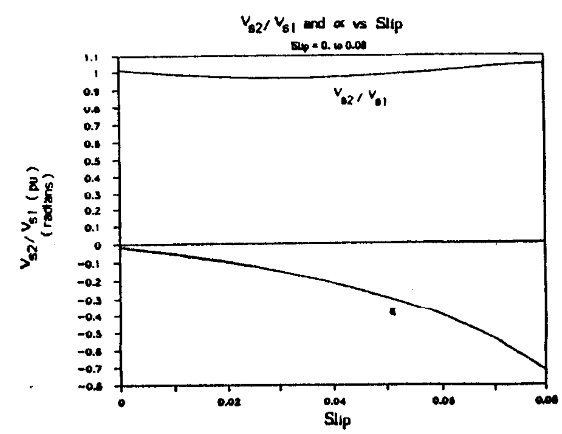

Fig. 10 Per Unit Inverter Amplitude V_{s2}/V_{s1} and Phase Angle α Required to Maintain Zero Main Winding Reactive Power and Constant dc Inverter Voltage as a Function of Slip.

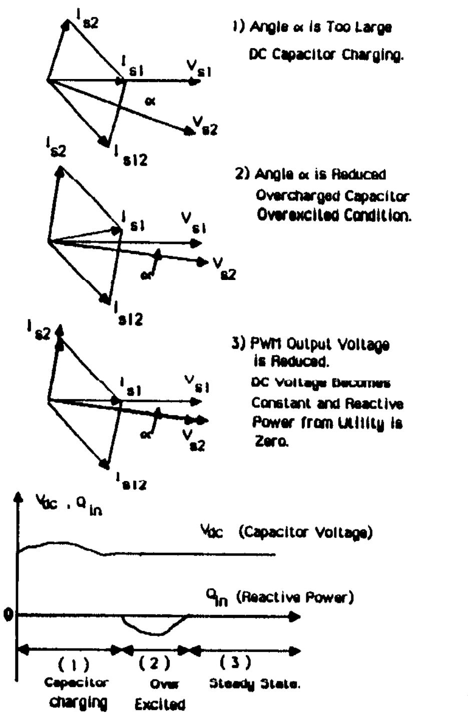

Fig. 11 Illustration of Control Philosophy Utilizing Inverter Amplitude and Phase Angle Control.

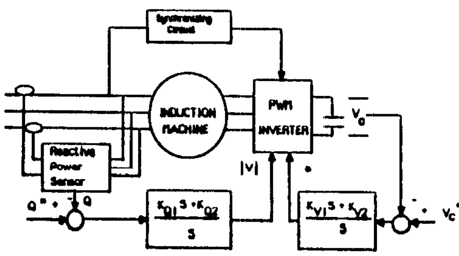

Fig. 12 Control Block Diagram of the Overall System.

The main winding is connected to the utility supply while the auxiliary winding is supplied by the PWM inverter. The PWM inverter is operated at constant frequency (same as main supply frequency) and at a constant PWM modulation frequency. Only a dc capacitor is connected to the dc side of the inverter. The pulse width is used to vary the magnitude of the inverter output voltage and therefore regulate the reactive power supplied by the main winding. The phase shift between the fundamental component of the resulting output voltage with respect to the main supply voltage is used to regulate the capacitor voltage (inverter dc voltage).

The analog traces of Figs. 13 to 16 summarize the results of a computer study which was conducted to verify the validity of the approach and to establish how the PWM switching frequency and inverter dc capacitance affect behavior of the system. It can be noted that the dc voltage (capacitor voltage) is very smooth. Operation of the system with a relatively large dc capacitor value of 70000 μF but a low chopping frequency of 600 Hz is shown in Fig. 13. It is interesting to note that the harmonic content of the main winding current is significantly less than the auxiliary winding current. It appears that while filtering action is being provided by the series leakage inductance existing between the main and auxiliary windings, substantial filtering is also derived from the rotor circuit which is effectively in parallel with the auxiliary winding impedance. In effect the rotor of the machine acts as a "zero cost rotating filter".

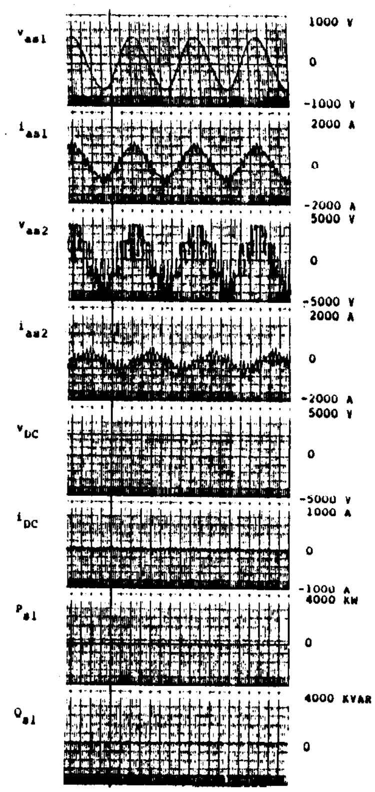

Fig. 13 Analog Simulation Result Using for Unity Power Factor Operation of the Main Winding Using a PWM Inverter with 12 Chops/Cycle (600 Hz), $C = 70000 \mu F$. Explantion of Symbols: v_{as1}, i_{as} - Main Winding a Phase to Neutral Voltage and Line Current, v_{as2}, i_{as2} - Auxiliary Winding a Phase to Neutral Voltage and Line Current, v_{DC}, i_{DC} - Inverter dc Voltage and Current, P_{s1}, Q_{s1} - Main Winding Power and Reactive Power.

For the simulation study reported in this paper the machine selected was assumed to have equal ampere turns in the main and auxiliary windings and that the windings were placed in the slots in symmetrical fashion [6]. However, the coupling between the auxiliary winding and the rotor bars can be enhanced by winding the machine so that the auxiliary winding is on the surface of the slot nearest the air gap. The filtering action of the rotating rotor bars is a new concept which has attracted little attention. Work on design of a special purpose machine is continuing and will be reported in a future paper.

For comparison with Fig. 13, the capacitor value has been reduced to only 700 μF in Fig. 14. It can be noted that the ripple on the dc voltage has increased considerably. However, the ripple in the input current to the main winding has actually decreased somewhat again suggesting the effectiveness of the rotating filter in removing unwanted harmonics from the main winding current.

The effect of changes in the PWM modulating frequency can be seen by comparing analog traces, Figs. 15 and 16. In this case the dc capacitor has been fixed at 2000 μF. The PWM modulation frequency is 1500 Hz for Fig. 15 and 3000 Hz for Fig. 16. It can be noted that the higher modulating frequencies result in a much less distorted main winding current. If the PWM chopping frequency can be raised to approximately 3000 Hz the ripple current in the main winding becomes completely negligible. It is also clear from Figs. 15 and 16 that for the same size of the ripple dc voltage, a higher modulating frequency permits the use of a smaller capacitor.

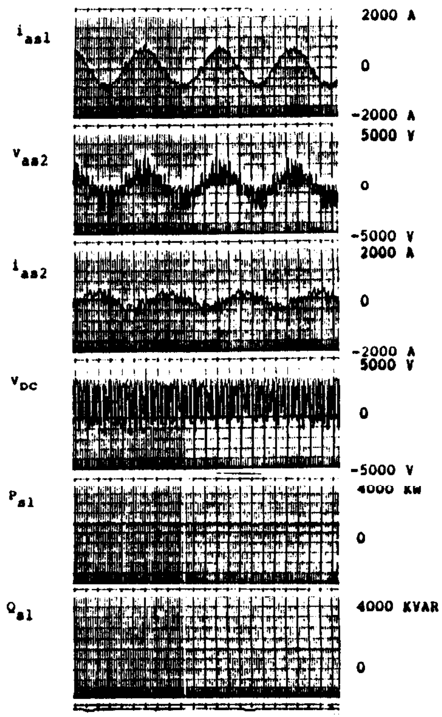

Fig. 14 Analog Computer Result for Main Winding Unity Power Factor Operation Using a PWM Inverter with 12 Chops/Cycle, $C = 700\mu F$. For Explanation of Symbols See Fig. 13.

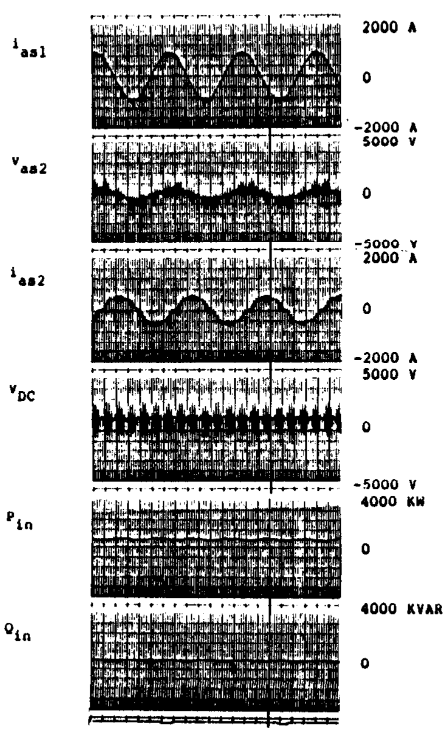

Fig. 15 Simulation Result Utilizing a PWM Inverter with 30 Chops/Cycle (1500 Hz), $C = 2000\mu F$. For Explanation of Symbols See Fig. 13.

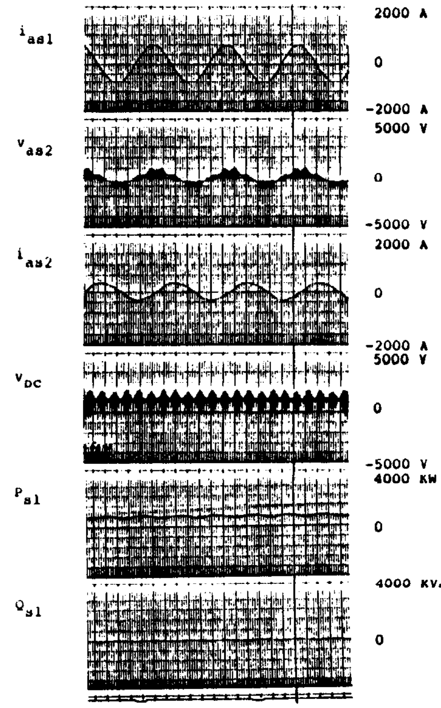

Fig. 16 Analog Trace for Main Winding Unity Power Factor Operation with a PWM Inverter having 60 Chops/Cycle (3000 Hz), $C = 2000\mu F$. For Explanation of Symbols See Fig. 13.

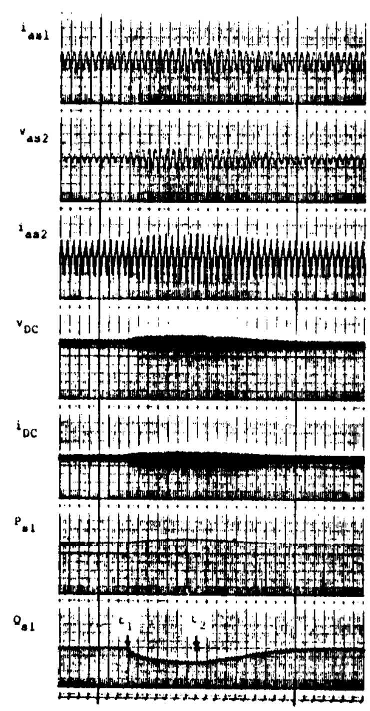

Fig. 17 Simulation Results Showing the Transient Response of the Power Factor Controller. At time t_1 the Reactive Power Command is increased to a Positive Value (Leading Power Factor). At t_2 the Command is Reduced to Zero.

Figure 17 illustrates the transient behavior of the power factor controller. In particular, the reactive power command Q^* is suddenly changed to a positive value (i.e. leading power factor at the main winding). At time t_1 the commanded value of reactive power is again reduced to zero. It can be noted that the response to the changes requires only several cycles and is well damped. The average value of the inverter dc voltage is essentially unaffected during the transient.

Conclusion

The paper has reported preliminary results of a new approach to self excitation of an induction machine. In this approach the machine is equipped with an extra three phase winding to specifically carry the reactive power required by the machine. The main winding of the machine is connected to the utility is thus able to operate at unity or even leading power factor in much the same manner as a synchronous machine. The excitation power supplied to the extra auxiliary winding is derived from a PWM inverter operating with a floating dc capacitor. Thus the ac/dc converter normally associated with power flow on the dc side of the inverter is not required. Simulation results indicate that with PWM frequencies of sufficiently large value will permit application without the need for additional filtering of the motor current seen by the utility supply.

While the work reported in this paper relates specifically to an induction motor, the principle is readily extended to an induction generator. In particular, this new concept of excitation should prove very useful for excitation of induction machines in isolated systems supplying passive $r-L$ loads. A study of this mode of operation is underway at the University of Wisconsin.

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Appendix

$R_{s1} = 0.0070\ \Omega$	$X_{ls1} = 0.00728\ \Omega$
$X_{ls2} = 0.00728\ \Omega$	$X_m = 0.4820\ \Omega$
$R_r = 0.00204\ \Omega$	$X_{lr} = 0.00697\ \Omega$

Table 1
Parameters of a 920 HP, 460 V, 6 Pole
50 Hz, 5/6 Pitch Induction Motor Wound
for Dual Three Phase Operation