The College of Engineering
University of Wisconsin-Madison

Wisconsin Electric Machines and Power Electronics Consortium

RESEARCH REPORT
91-18

Adjustable AC Capacitor for a Single Phase Induction Motor

Y. Zhao, T. H. Liu, T. A. Lipo
Dept. of Electrical and Computer Engineering
University of Wisconsin-Madison
1415 Johnson Drive
Madison, Wisconsin 53706

E. Muljadi
Dept. of Electrical Engr.
California State University
Fresno, California 94730

WEMPEC

Department of Electrical and Computer Engineering
1415 Johnson Drive
Madison, Wisconsin 53706

ADJUSTABLE AC CAPACITOR FOR A SINGLE PHASE INDUCTION MOTOR

E. MULJADI
California State University - Fresno
Department of Electrical Eng.
Fresno, CA

Y. ZHAO and T. H. LIU and T.A. LIPO
University of Wisconsin
Department of Electrical and Computer Eng.
Madison, WI

ABSTRACT—The most common practice for starting a single phase induction machine (SPIM) is to install a starting capacitor in series with the auxiliary winding. In some applications two capacitors are used; one is used during starting period to help creating the starting torque and the other one is used during the running condition to improve efficiency. This paper discuss the possibility of using an electronic switch in parallel with the running capacitor thereby providing the equivalent of a starting capacitor. The capacitor is shorted during each cycle to vary the effective size of the AC capacitor. By using this method, only one capacitor is used for both the starting and running condition and a similar starting performance can be obtained when compared with the conventional method of using two capacitors.

1. INTRODUCTION

The single phase induction machine (SPIM) is the most widely used type of ac machine in the world. Despite all its good merits, the SPIM has disadvantages when it comes to realizing the beauty of the smoothly rotating flux found in three phase machines. One of the major problems associated with the design of SPIM is that, unlike a three phase power system, a single phase does not produce a rotating magnetic field. Instead, the magnetic field produced by a single phase remains stationary in position and pulsates with time. Since there is no net rotating magnetic field, single phase induction motors can not start without modification. The most common type of starting aid used to start a SPIM is the starting capacitor installed in series with the auxiliary winding. Typical applications for such motors are compressors, pumps, air conditioners, and other pieces of equipment that must start under load.

The function of the capacitor is to realize another phase from supply source to feed a second, auxiliary winding so that the motor can operate as a balanced two phase machine. For this purpose the capacitor size must be carefully determined according to the terminal impedance of the auxiliary winding. Unfortunately this impedance changes dramatically from starting to running condition. Hence, it is impossible to use only one fixed value capacitor for both starting and running. If both the largest starting torque and the best running conditions are needed, at least two capacitors must be used with the auxiliary winding. Motors with two capacitors are called capacitor-start capacitor-run, or two value capacitor motors. The larger capacitor is present in the circuit only during starting when it ensures that the currents in the main and auxiliary windings are roughly balanced, yielding a relatively high starting torque. When the motor runs up to speed, the centrifugal switch opens, and the permanent capacitor is left by itself in the auxiliary winding circuit. The permanent capacitor is just large enough to balance the currents at normal motor loads, so that the motor again operates efficiently with good power factor. The permanent capacitor in such a motor is typically about 10 to 20 percent of the size of the starting capacitor which, together with the centrifugal switch, accounts for considerable portion of the cost of the motor.

In this paper it is proposed to eliminate the centrifugal switch and starting capacitor and to use a switched capacitor as shown in Fig. 1. In this case the system consists of three major elements: the induction machine, the running capacitor and an inverse/parallel set of bi-directional switches. The main winding of the SPIM is directly connected to the main supply. The apparent capacitance of the running capacitor can be made larger than its actual value if the capacitor is shorted periodically. Thus, by operating the switch on and off regularly during each cycle and by changing the length of the shorting interval γ, the effective capacitance of the capacitor can be enlarged and adjusted to an optimal value to realize the maximum possible starting torque for any rotor speed condition. By using this method, only one capacitor is used for both starting and running conditions.

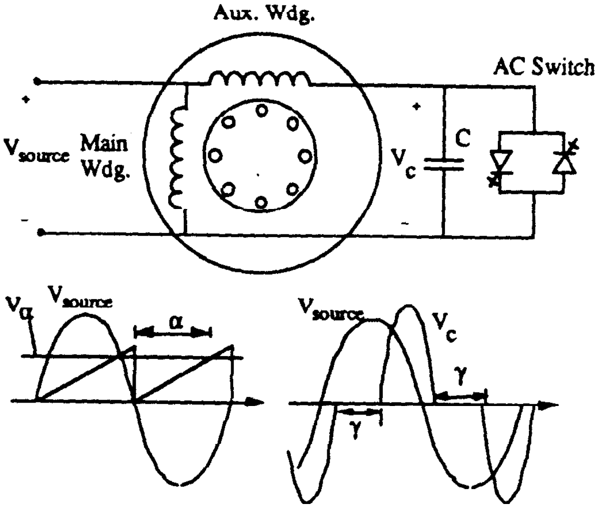


Fig. 1 Circuit layout of the proposed system and circuit operation.

2. STEADY STATE ANALYSIS AND CONTROL STRATEGY

GENERAL TORQUE ANALYSIS

Before discussing the control strategy of the system, it is necessary to investigate first the general characteristics of the SPIM running at the various speeds with different capacitor sizes.

0-7803-0453-5/91$1.00© 1991IEEE

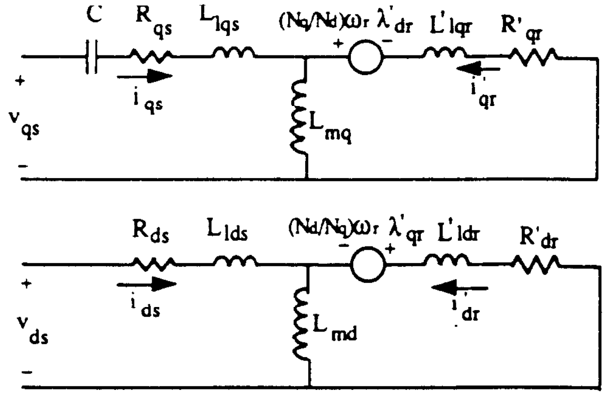


Fig. 2 Single phase induction machine equivalent circuit.

The equivalent circuit representing the SPIM is shown in Fig. 2 and the machine model can be expressed by the equations below [1]:

$$\left[\, v_{qs}^{s} \;\; v_{ds}^{s} \;\; 0 \;\; 0 \,\right]^T =$$

$$\begin{bmatrix} Rqs+\frac{p}{\omega_b}Xqs & 0 & \frac{p}{\omega_b}Xmq & 0 \\ 0 & Rds+\frac{p}{\omega_b}Xds & 0 & \frac{p}{\omega_b}Xmd \\ \frac{p}{\omega_b}Xmq & -\frac{N_q}{N_d}\frac{\omega_r}{\omega_b}Xmd & R'_{qr}+\frac{p}{\omega_b}X'_{qr} & -\frac{N_q}{N_d}\frac{\omega_r}{\omega_b}X'_{dr} \\ \frac{N_d}{N_q}\frac{\omega_r}{\omega_b}Xmq & \frac{p}{\omega_b}Xmd & \frac{N_d}{N_q}\frac{\omega_r}{\omega_b}X'_{qr} & R'_{dr}+\frac{p}{\omega_b}X'_{dr} \end{bmatrix} \cdot$$

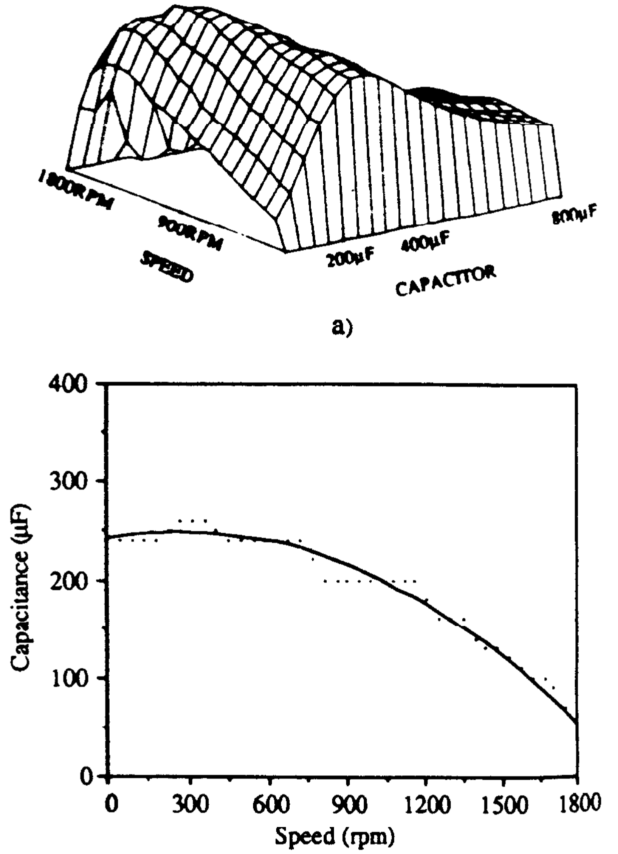
$$\left[\, i_{qs}^{s} \;\; i_{ds}^{s} \;\; i_{qr}^{\prime s} \;\; i_{dr}^{\prime s} \,\right]^T \qquad (1)$$

where, the q-axis stator resistance, r_s, stator self-inductance, x_{qs}, magnetizing reactance, x_{mq}, rotor self-inductance, x_{qr}', and rotor resistance, r_r' denote the main winding parameters and corresponding d-axis parameters denote similar quantities for the auxiliary winding. The quantity N_d/N_q denotes the turns ratio between the main and auxiliary windings.

Initially, it can be assumed that a real adjustable capacitor is used. In this case, for the purpose of obtaining equations for steady state analysis, the terms $\frac{p}{\omega_b}$ are simply replaced by the complex operator j. The average electromagnetic torque can be expressed as,

$$T_e = \frac{P}{2}\frac{N_d}{N_q}\frac{X_{mq}}{\omega_b} Re\left(i_{qs}^{s*} i_{dr}^{\prime s} - i_{ds}^{s*} i_{qr}^{\prime s} \right) \qquad (2)$$

From the resulting equations it is possible to generate a contour graph of torque as function of slip and the capacitance as shown in Fig. 3a. As can be seen from this graph, the significant characteristic is that the starting torque reaches its maximum value at a certain capacitance when the motor is at standstill. After this point the capacitance related to the maximum torque begins to decrease as the speed increases. The optimal starting curve of capacitance as a function of speed can be obtained by connecting all the tangent points of the equal torque curves and the constant speed lines on the graph as shown in Fig. 3b.



a)

b)

Fig. 3 a.) Contour graph of torque as a function of capacitor size and motor speed. b.) Optimal starting curve of capacitance as a function of motor speed.

Based on the torque variation available from the contour graph of Fig. 3, it is clear that one can choose an optimal path to control the capacitance to achieve an optimized starting performance. However, due to the difficulty in realizing an adjustable capacitor and the need for a speed sensor for realizing optimal starting, the most common practice has been to choose the starting capacitor to satisfy the zero speed torque requirements and to keep the capacitance constant from zero speed to a speed near rated speed at which point the centrifugal switch opens. It can be seen from Fig. 3 that the starting performance resulting from the use of a fixed starting capacitor is far from optimal. Another problem raised from this approach is the unavoidable use of a mechanical centrifugal switch.

3. SWITCHED CAPACITOR START PRINCIPLE

The concept of a switched capacitor provides an effective means to solve the problems associated with the need for a variable capacitor. The switched capacitor consists of an AC capacitor in parallel with an electronic switch and the switch is allowed to periodically turn on and off during each cycle. When the switch is open, current flows though the capacitor which is placed in series with the auxiliary winding. The current bypasses the capacitor when the switch is closed. The switch is closed at the instant the voltage across the capacitor reaches zero. Thus, a zero voltage switching operation is performed and the switch remains closed until it is opened by the command signal. The effective value of the AC capacitor can be adjusted if the magnitude of the fundamental component of the voltage across the switch is adjusted independent of the current flowing through it. Hence, by shorting the switch periodically, the fundamental component of the voltage across the capacitor appears to be lower than the case without a shorting period so that the effective size of the capacitor appears to be larger than its actual size. As the shorting interval γ reaches π radians the effective size of the capacitor approaches infinity because the switch is closed during entire cycle. Figure 4 shows a calculated result showing the effective size of a 40 µF running capacitor being operated as a switched capacitor for a given set of machine parameters.

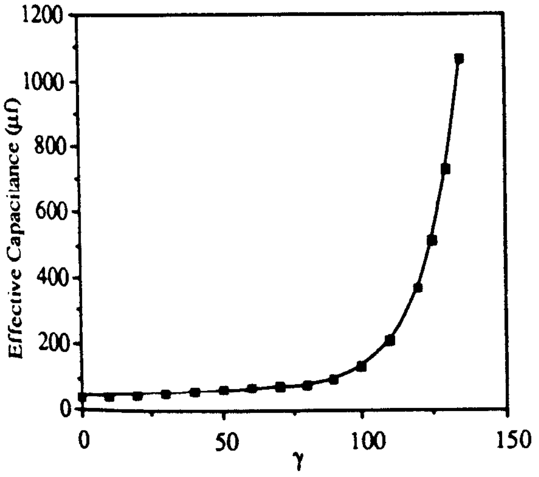


Fig. 4 Effective size of a 40µF AC capacitor operating as switched capacitor versus control angle γ.

Although one can control γ to adjust the effective capacitance, the switched capacitor can also be implemented by controlling the firing angle α of the switch. The firing angle α is controlled directly by a sawtooth waveform generator which has a frequency two times the frequency of the voltage supply and is synchronized to the supply. The sawtooth waveform is then compared to a DC bias voltage V_α which represents the firing angle and the switch is opened when the sawtooth voltage is equal to the V_α. The switch is closed at the zero crossing point of the capacitor voltage. The overall concept is again illustrated in Fig. 1. In this case γ, or the effective size of the capacitor is determined both by the angle α and the instant of the capacitor voltage zero crossing. However, since the machine impedance changes when the speed changes, the zero crossing point will also change. Hence, the effective size of the capacitor will not be maintained constant even if α is maintained constant. Figure 5 shows a simulation result demonstrating the influence of the speed changes on γ. The firing angle α in Fig. 5a and Fig. 5b is the same. However, in Fig. 5a the motor is in the standstill condition whereas in Fig. 5b the machine is running at 1700 r.p.m. It can be seen that the value of γ in Fig. 5a is much larger than that of Fig. 5b so that the effective capacitance corresponding to Fig. 5a will appear to be larger as well.

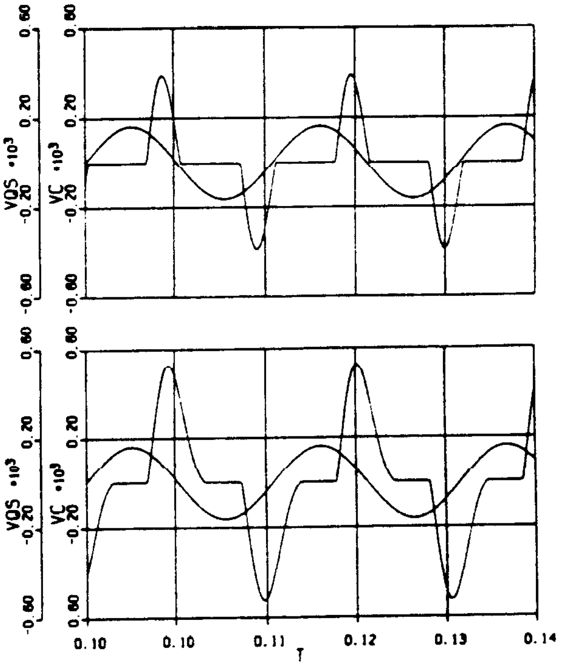


Fig. 5 The influence of speed change on shorting interval γ. a.) n=0.0 rpm, $\alpha=120^0$, $\gamma=113^0$. b.) n=1700 rpm, $\alpha=120^0$, $\gamma=69^0$.

Figure 6 shows the change of the effective capacitance versus speed for various values of the control angle α. The optimal path in Fig.3 is again drawn in Fig. 6. The advantage of using firing control method can be immediately found from Fig. 6. In particular, the inherent changing nature of the motor impedance during starting which is the major cause of using two capacitors in the conventional SPIM design becomes an advantage when a switched capacitor and firing angle control method is used for motor starting. As a result of the speed change, the effective size of the capacitor inherently becomes smaller and smaller as the motor speed increases thereby making the effective capacitor curve come closer to the optimal path compared with the use of a fixed value starting capacitor.

To provide another viewpoint concerning motor torque production with a controlled capacitor, a contour graph of the motor torque as a function of speed and firing angle has been calculated and is plotted in Fig. 7. As can be expected, the optimal path (dashed line) in Fig. 7 is very close to a constant α line. Thus, a satisfactory starting performance can be obtained by using a switched capacitor and constant α control.

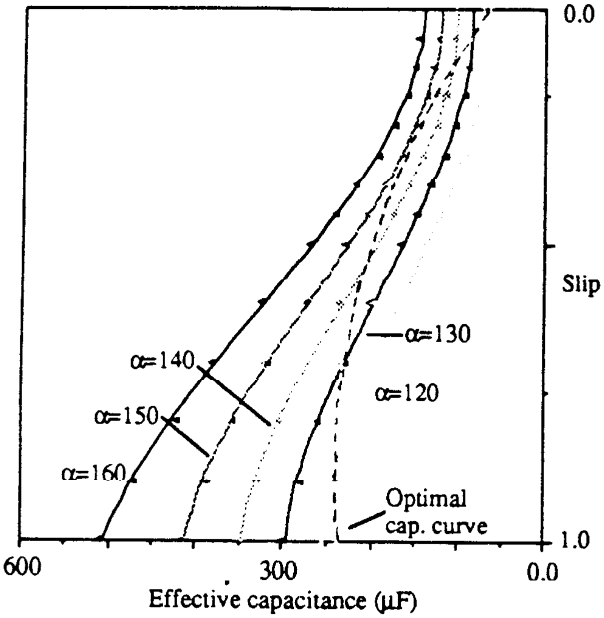


Fig. 6 Relationship between effective capacitance and speed.

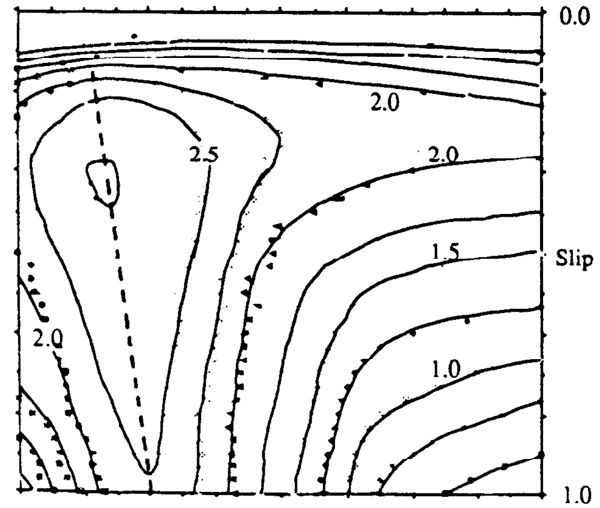


Fig. 7 Contour graph of torque (in p.u.value) as a function of speed and control angle α.

4. CONTROL STRATEGY

It is evident that the starting performance can be further improved if α is adjusted to always follow an optimal path. However the benefit obtained will not be as significant as that obtained by the constant α control compared to the fixed capacitor value and the inevitable trade off is that speed sensor must then be used. In this paper, the switched capacitor is simply controlled under constant α control. Figure 8 shows the block diagram of the control circuit which was implemented in hardware. In this control the main winding current is used to terminate the switching operation on the capacitor when the motor reaches nominal speed. Because of the orthogonality of the two windings in the SPIM, the switching action in the auxiliary winding circuit has very little influence on the amplitude of main winding current and sensitivity of the constant α controller with changes in speed greatly increases when the machine is near the running condition. Hence, the α controller is simply disabled at this point. It should be pointed out that a low cost current sensor can be used due to its simple function in the circuit.

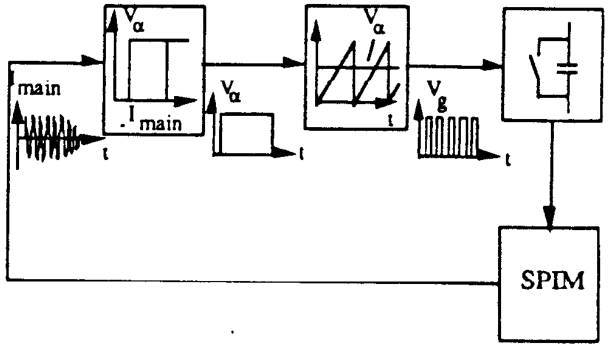


Fig. 8 Control circuit block diagram.

5. EXPERIMENTAL RESULTS

VOLTAGE AND CURRENT

The voltage applied to the auxiliary winding is the resultant of the source voltage and the capacitor voltage. The current entering the auxiliary winding, which can also be considered as the current passes through the effective capacitor (the switch and the running capacitor), is the sum of capacitor current and the switch current. The capacitor voltage and the voltage across the auxiliary winding are not smooth sinusoidal due to the existence of switching action on the capacitor. The switching applied to the capacitor generates a resonance between the inductance of SPIM and the capacitor. As a result, the current entering the auxiliary winding is also not a smooth sinusoidal. Figure 9 shows the typical waveforms of the voltages and the currents. It can be seen that if only the fundamental components are considered the voltage across the capacitor lags the auxiliary current by 90°. It is also shown that the auxiliary winding voltage is shifted by approximately 90° with respect to the main winding voltage V_S and consequently the auxiliary winding current is similarly shifted with respect to the main winding current. It is apparent that substantial loss producing harmonics are induced in the motor. However, since this condition persists only during the brief acceleration period, such additional losses can be considered as having a negligible effect on the thermal design and efficiency of the motor.

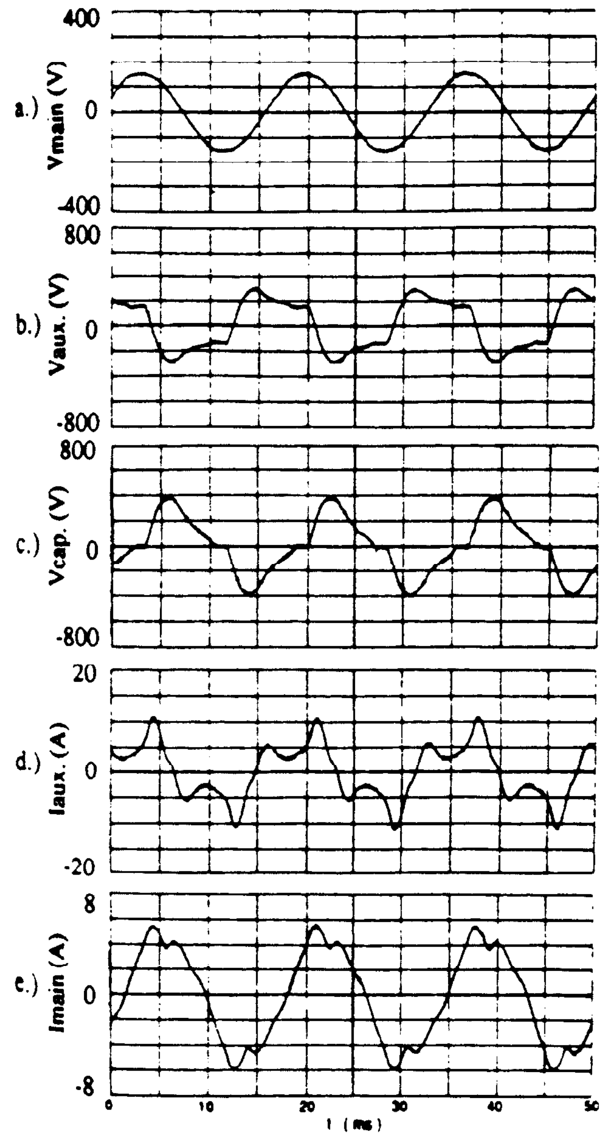


Fig. 9 Typical Voltage and Current Waveforms ($\alpha=100^0$, $T_l= 4.0$N.m, n=1725rpm). a.) Main Winding Voltage. b.) Auxiliary Winding Voltage. c.) Capacitor Voltage. d.) Auxiliary Winding Current. d.) Main Winding Current.

SPEED

Acceleration of a SPIM utilizing control of V_α *is shown in* Fig. 10 and Fig. 11. For the parameters of the SPIM summarized in the Appendix the constant value of α was selected as 130˚.

For purpose of comparison, the motor was started with its rated running capacitor (40 μf), its rated starting capacitor (250μf) and then with a switched 40 μf running capacitor under a light load torque condition. The light load condition was chosen to enable the motor to start when utilizing the relatively small running capacitor. Figure 10 shows the acceleration of the SPIM for the three cases. It can be seen that use of the starting capacitor for starting produces a very small accelerating torque. However, when the capacitor is switched in accordance with the principles of this paper, the time to accelerate to rated speed approaches very closely, the time achieved by the optimum capacitor. The fact that the start time required by the swithced starting capacitor is slightly greater than when using the starting capacitor can be attributed to the additional losses produced by switching the running capacitor. Figure 11 shows a comparison of starting performance using the optimum 250μf capacitor versus the switched 40 μf running capacitor when starting under rated load. Although an increase in starting time when using the swtiched running capacitor is now more apparent, it is still very close to the case of the optimum capacitor. When the running capacitor is used without switching, it was incapable of starting under more than 0.2 pu load.

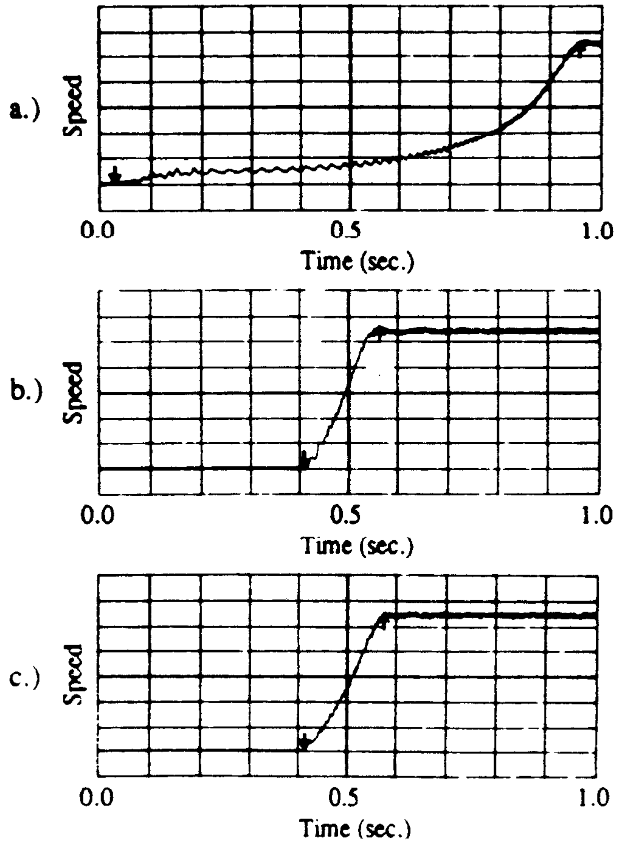


Fig. 10 Acceleration of SPIM under 0.15 load torque

a) Using Installed Running Capacitor(40μF).

b) Using Installed Starting Capacitor(250μF).

c) Using Switched Running Capacitor(40μF).

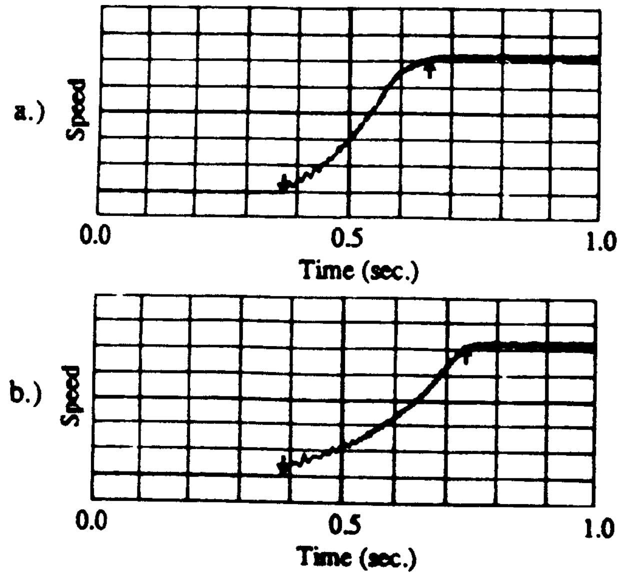


Fig. 11 Acceleration of SPIM under rated load torque.

a) Using Installed Starting Capacitor(250µF).

b) Using Switched Running Capacitor(40µF).

It should be noted in passing that for the motor tested, the starting capacitor actually supplied with the tested motor was 506 µf rather than the optimum value of 250 µf used for these tests. Hence, starting performance using the switched running capacitor actually showed a marked improvement when compared with the installed running capacitor rather than the optimally calculated 250 µf.

6. CONCLUSION

This paper has presented a new scheme for starting a single phase induction motor. By periodically and synchronously shorting the running capacitor with a solid state switch, the need for a separate starting capacitor and start/run switch can be eliminated. Since the starting capacitor can now be dynamically varied, the optimum capacitor value can be selected for any rotor speed. However, it was shown that by simply controlling as constant, the switch turn-off instant with respect to the source voltage zero crossing, good starting performance can be obtained with a minimum of complexity. Since the starting switch is one of the most failure prone components of a typical single phase motor, elimination of this device is expected to significanly improve the reliability of such machines for only a modest cost difference.

7. ACKNOWLEDGMENT

The authors wish to thank the member companies of the Wisconsin Electric Machines and Power Electronics Consortium (WEMPEC) for funds and equipment provided.

8. REFERENCES

[1] P.C. Krause and C.J. Thomas, "Simulation of Symmetrical Induction Machineary", IEEE Trans. on Power Apparatus and Systems, Vol. PAS - 84, No. 11, Nov. 1965, PP. 1038 - 1053.

[2] P.C. Krause, "Analysis of Eletric Machinery", McGraw - Hill Book Company, 1986.

[3] Fitzgerald, Kingsley, and Umans, "Electric Machinery", McGraw - Hill Book Company, 1984.

9. APPENDIX

Motor Nameplate Data:

HZ.	60	HP.	1
RPM.	1725	VOLT.	115/230
FLA.	8.6/4.3	SF.	1.15

Motor Parameters:

R_{qs}=3.52 Ohm R_{ds}=0.785 Ohm

R'_{qs}= 4.746 Ohm R'_{ds}=1.614 Ohm

L_{lqs}=0.00902 H L_{lds}=0.00327 H

L'_{lqs}=0.00876 H L'_{lds}=0.00318 H

L_{mq}=0.199 H L_{md}=0.0722 H

N_q/N_d=1.66

Running Capacitor = 40µF

Starting Capacitor = 506µF