INDUCTION MOTOR OVERVOLTAGE DUE TO POWER FACTOR IMPROVEMENT CAPACITOR

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ABSTRACT

For years it has been a standard practice in industry to utilize power factor correction capacitors on induction motors. When disconnecting this combination from the source, self excitation can occur and damaging overvoltages may result for an oversized capacitor. This paper will discuss this problem using digital simulation techniques and compare the results with results obtained from experiments performed on a 1.5 HP, 208 V, 3-phase motor.

INTRODUCTION

The use of a power factor improvement shunt capacitor of appropriate size at the motor terminal, to improve the steady-state performance, has been a common practice in the industry. Satisfactory compensation over the entire load range would necessitate slow speed switched capacitor banks. These capacitors act as a "VAR" generators and provide VARs required by the motor to varying degrees depending on the capacitor size. These capacitors while connected to the motor, however, may not perform optimally during motor starting or during fast and sudden load fluctuation periods. Therefore, design considerations of these banks during transient performance would be helpful. This paper reviews and analyzes the overvoltage problem due to fixed shunt compensation using digital simulation techniques and applies this to a present day design.

COMPUTER MODEL DEVELOPMENT

Induction motors can generally be analyzed in the steady state by an equivalent circuit. However, in the transient state, induction motors are better represented by a set of differential equations based on either the "abc" three-phase quantities directly or a transformed "qdo" two-axes model. For a balanced three-phase system, it is much more convenient to use the "qdo" two-axes model.

Fig. 1 shows the complete system model used in this study. To simulate no capacitor condition, the capacitors are simply removed from the circuit.

The induction motor model for transient performance calculations is developed with and without capacitors. The effects of rotor dynamics and saturation are also considered for a complete simulation.

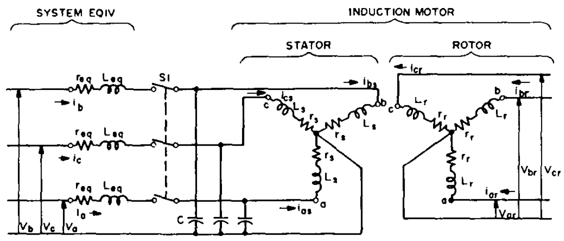

Fig. 1. Complete System Model with Capacitors

A. Induction Motor Windings

The concept of reference frame transformation is adopted in the model development. This reduces the time varying quantities, such as stator winding inductances in the "abc" windings which are dependent on the rotor position, to constant inductances in the "qdo" two-axes reference frame. The complete discussion is beyond the scope of this paper and has been discussed in detail in reference [1].

It is important to write the equations that describe the motor winding circuits in state variable form so that the system of first order differential equations can be solved using standard programs.

There are four cases that must be solved for complete simulation and to compare the effects of the capacitor.

Case 1 : No capacitor

(a) Switch S1 closed (Normal operation)
(b) Switch S1 open

Case 2 : With capacitor

(a) Switch S1 closed (Normal operation)
(b) Switch S1 open

Neglecting no-load rotational losses, saturation effects, and space harmonics, the following set of equations can be derived [1] for Case 1(a). It is also assumed that the induction motor has symmetrical stator and rotor windings.

The symbols appearing in this paper are described in the nomenclature.

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$$p\psi_{qs} = \omega_b\left[V_{qs} - \left(\frac{r_s}{X_{ls}}\right)\left(\psi_{qs} - \psi_{mq}\right) - \left(\frac{\omega_e}{\omega_b}\right)\psi_{ds}\right] \quad (1)$$

$$p\psi_{ds} = \omega_b\left[V_{ds} - \left(\frac{r_s}{X_{ls}}\right)\left(\psi_{ds} - \psi_{md}\right) + \left(\frac{\omega_e}{\omega_b}\right)\psi_{qs}\right] \quad (2)$$

$$p\psi_{os} = \omega_b\left[V_{os} - \left(\frac{r_s}{X_{ls}}\right)\psi_{os}\right] \quad (3)$$

$$p\psi_{qr} = \omega_b\left[V_{qr} - \left(\frac{r_r}{X_{lr}}\right)\left(\psi_{qr}-\psi_{mq}\right) - \left(\frac{\omega_e-\omega_r}{\omega_b}\right)\psi_{dr}\right] \quad (4)$$

$$p\psi_{dr} = \omega_b\left[V_{dr} - \left(\frac{r_r}{X_{lr}}\right)\left(\psi_{dr}-\psi_{md}\right) + \left(\frac{\omega_e-\omega_r}{\omega_b}\right)\psi_{qr}\right] \quad (5)$$

$$p\psi_{or} = \omega_b\left[V_{or} - \left(\frac{r_r}{X_{lr}}\right)\psi_{or}\right] \quad (6)$$

$$pI_{qs} = \frac{1}{L_{eq}}\left[V_q - V_{qs} - r_{eq}I_{qs} - L_{eq}\omega_e I_{ds}\right] \quad (7)$$

$$pI_{ds} = \frac{1}{L_{eq}}\left[V_d - V_{ds} - r_{eq}I_{ds} + L_{eq}\omega_e I_{qs}\right] \quad (8)$$

$$pI_{os} = \frac{1}{L_{eq}}\left[V_o - V_{os} - r_{eq}I_{os}\right] \quad (9)$$

The first set of three equations represents the rate of change of flux linkages in the transformed stator windings (Ψqdo-s), while the second set of three equations represents the rate of change of flux linkages in the transformed rotor windings (Ψqdo-r). The last set of three equations represents the rate of change of currents in the transformed stator windings. The last set of equations is not required if there is no source impedance.

To simulate the opening of switch S1 as in Case 1(b), the stator currents are set equal to zero and the last set of three equations are removed from the model. At this point during the digital simulation, the last values .of the dependant variables before the switch opens are then passed to the new model as initial conditions and the solution continues.

It can be shown that by adding shunt capacitors as shown in Fig. 1, there will be a set of three more equations added to the state model of the machine. The equations are:

$$pV_{qs} = -\omega_e V_{ds} + \frac{1}{C} I_q - \frac{1}{CX_{ls}}\left(\psi_{qs}-\psi_{mq}\right) \quad (10)$$

$$pV_{ds} = \omega_e V_{qs} + \frac{1}{C} I_d - \frac{1}{CX_{ls}}\left(\psi_{ds}-\psi_{md}\right) \quad (11)$$

$$pV_{os} = \frac{1}{C} I_o - \frac{1}{CX_{ls}} \psi_{os} \quad (12)$$

where, Iq, Id and Io are transformed currents drawn from the source and equations (7), (8) and (9) will be rewritten as:

$$pI_q = \frac{1}{L_{eq}}\left[V_q - V_{qs} - r_{eq}I_q - L_{eq}\omega_e I_d\right] \quad (13)$$

$$pI_d = \frac{1}{L_{eq}}\left[V_d - V_{ds} - r_{eq}I_d + L_{eq}\omega_e I_q\right] \quad (14)$$

$$pI_o = \frac{1}{L_{eq}}\left[V_o - V_{os} - r_{eq}I_o\right] \quad (15)$$

Equations (10) - (15) combined with equations (1) thru (6) are used to describe Case 2(a), the machine with the capacitors. To simulate Case 2(b) when switch S1 opens, equations (13), (14) and (15) are removed from the model and the values of the line currents (Iq, Id and Io) in equations (10), (11) and (12) are set equal to zero.

The above equations form the basis for the digital simulation to this problem. There are nine first order linear differential equations for Case 1(a), six for Case 1(b), twelve for Case 2(a), and nine for the Case 2(b), all of which are in state variable form. These equations are solved using fourth/fifth order Runge-Kutta method of solving differential equations[2].

B. Rotor Dynamics

In order to incorporate the effects of load, rotor dynamics must be taken into account. The rotor speed wr is not constant. An expression for rotor speed wr is needed as a function of torque.

Neglecting the damping, the rotor dynamics can be expressed by:

$$\frac{dw_r}{dt} = \frac{P}{2J}T_a = \frac{P}{2J}(\ T_e\ -\ T_1\ ) \quad (16)$$

where, Ta is the accelerating torque and equals the difference between the electro-magnetic torque (Te) and the load torque (Tl). The load torque (Tl) is assumed to be constant in this simulation. The electromagnetic torque is given by [1],

$$T_1 = (3/2)(P/2)(1/w_b)(\Psi_{qr}\ I_{dr} - \Psi_{dr}\ I_{qr}) \quad (17)$$

In order to solve this equation using the system of equations previously given, stator and rotor currents must be calculated in terms of flux linkages. The equations can be derived [1] and are given by,

$$I_{qs} = \frac{1}{X_{ls}}\left[\psi_{qs}-\psi_{mq}\right] \quad (18)$$

$$I_{ds} = \frac{1}{X_{ls}}\left[\psi_{ds}-\psi_{md}\right] \quad (19)$$

$$I_{os} = \frac{1}{X_{ls}}\psi_{os} \quad (20)$$

$$I_{qr} = \frac{1}{X_{lr}}\left[\psi_{qr}-\psi_{mq}\right] \quad (21)$$

$$I_{dr} = \frac{1}{X_{lr}}\left[\psi_{dr}-\psi_{md}\right] \quad (22)$$

$$I_{or} = \frac{1}{X_{lr}}\left[\psi_{or}\right] \quad (23)$$

where,

$$\psi_{mq} = X_m\left[I_{qs}+I_{qr}\right] \quad (24)$$

$$\psi_{md} = X_m\left[I_{ds}+I_{dr}\right] \quad (25)$$

Using simple algebraic manipulation of the above equations, the rotor currents can be calculated as,

$$I_{qr} = \left[\frac{1}{X_{lr}}\right]\left[\psi_{qr}-X_{aq}\left[\frac{\psi_{qs}}{X_{ls}}+\frac{\psi_{qr}}{X_{lr}}\right]\right] \quad (26)$$

$$I_{dr} = \left[\frac{1}{X_{lr}}\right]\left[\psi_{dr}-X_{ad}\left[\frac{\psi_{ds}}{X_{ls}}+\frac{\psi_{dr}}{X_{lr}}\right]\right] \quad (27)$$

$$I_{or} = \left[\frac{1}{X_{lr}}\right]\psi_{or} \quad (28)$$

$$\text{where: } X_{aq} = X_{ad} = \left[\frac{1}{X_m}+\frac{1}{X_{ls}}+\frac{1}{X_{lr}}\right]^{-1} \quad (29)$$

The machine terminal voltages for Case 1(a) are calculated using the following equations. This is necessary, since the machine terminal voltages are not state variables.

$$V_{qs} = r_sI_{qs} + \frac{\omega}{\omega_b}\psi_{ds} + \frac{1}{\omega_b}p\psi_{qs} \quad (30)$$

$$V_{ds} = r_sI_{ds} - \frac{\omega}{\omega_b}\psi_{qs} + \frac{1}{\omega_b}p\psi_{ds} \quad (31)$$

$$V_{os} = r_sI_{os} + \frac{1}{\omega_b}p\psi_{os} \quad (32)$$

C. Saturation Effects

In order to obtain a realistic model of the induction motor, the effects of saturation must be included in the simulation. The terms given by mq and md in equations (24) and (25) are the magnetizing flux. The normalized saturation characteristic derived from the actual machine curve is modeled by an exponential equation using the methods outlined in reference [5].

In the computer solution, the values of mq and md are updated on each iteration using the equations (24) and (25) and the saturation curve.

DIGITAL SIMULATION AND EXPERIMENTAL RESULTS

A. Digital Simulation

Pascal programs were written for the digital simulation in this study. Reference [6] should be consulted for the complete programming code. The following flow chart gives the basic steps in the simulation. The motor load torque and whether or not to include the effects of saturation are two inputs. The input voltages have been assumed to be balanced 3-phase sinusoidal voltage source.

These programs were run on a VAX 8700. To obtain the plots, a VAX-based MATLAB [7] program was used.

The equivalent circuit parameters used in the computer simulation are shown below. These parameters were obtained from the laboratory tests and were verified from the manufacturer's data.

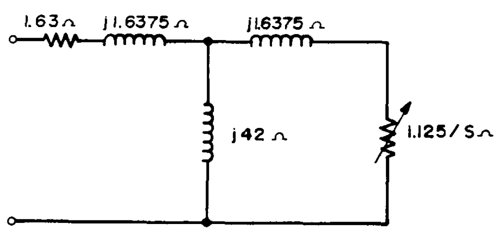


Fig. 3. Equivalent Circuit Parameters For 1.5 HP, 208 V, 3-Phase Motor

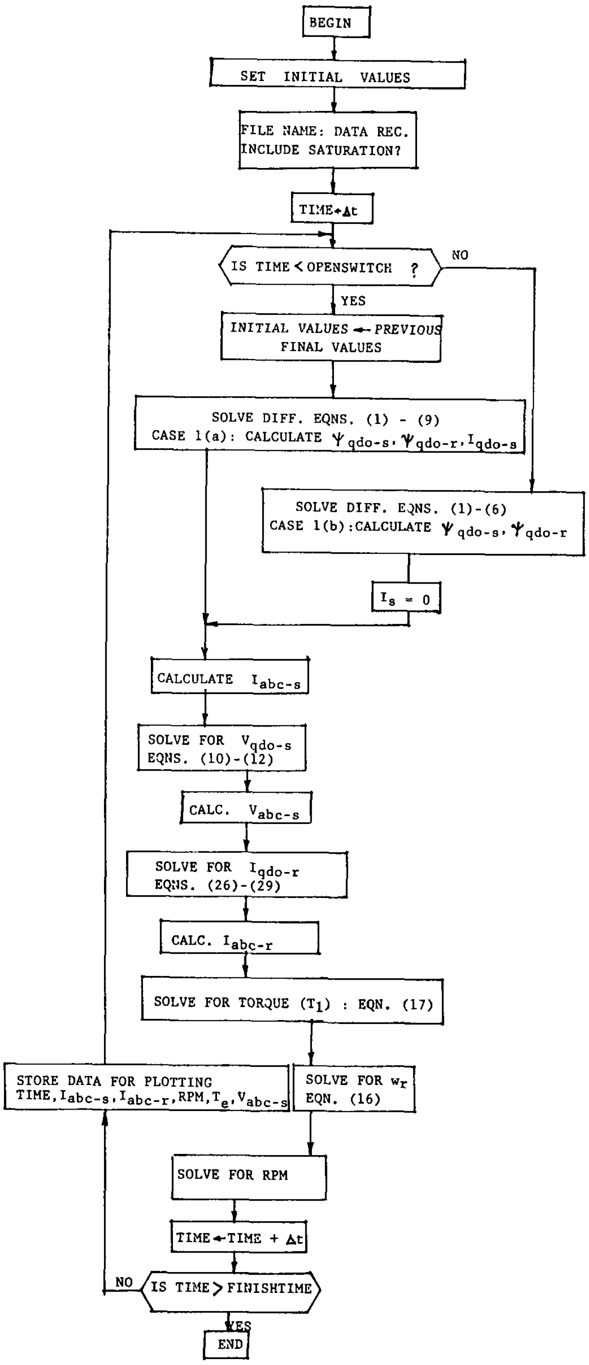


Fig. 2. Digital Simulation Flow Chart

One per unit capacitor would be (in ohms) equal to the magnetizing reactance Xm. Assuming the effects of the leakage reactance to be negligible, one per unit capacitor would raise the power factor approximately to unity at no load. For the motor in this study, the value of the capacitor C is approximately equal to 65 micro-farads and would supply 1.3 kVAR of reactive power.

Figs. 4(a) - 4(c) shows the motor terminal voltage plots for the 1.5 HP motor at no-load for varying degree of compensation and at no saturation. Figs. 5(a) - 5(c) shows the same motor terminal voltages with saturation. Figs. 6(a) - 6(c) compares the motor terminal voltages with load and saturation. For all cases studied, the switch S1 was opened at 0.6 sec at no load and 0.8 sec for full load.

In addition to the 1.5 HP motor, motor parameters were also obtained [1] for a 3 HP and a 50 HP motor. For the purposes of comparison these values were plugged into the programs and the results were plotted. These plots are shown in Figs. 7(a) - 7(b) for 3 HP motor and Figs. 8(a) - 8(b) for the 50 HP motor at no-load and no saturation.

B. Experimental Investigation

In order to verify the accuracy of the digital simulation, an "event" recording type oscilloscope (HP 54501A) was connected to the 1.5 HP motor terminals in a laboratory set up. The motor terminal voltages were recorded at no load and varying degree of shunt capacitors of 0, 1 and 2 per unit capacitors. The waveforms are shown in Figs. 9(a) - 9(c) for comparison.

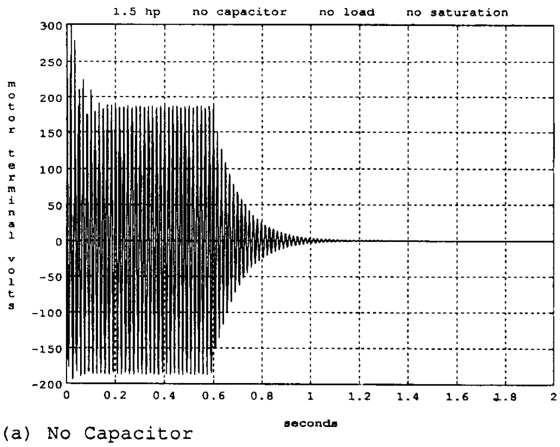
ANALYSES AND CONCLUSIONS

From the digitally simulated plots of motor terminal voltage, with saturation neglected, the voltage does rise after the switch is opened for higher values of capacitance. This effect is especially high for the 3 HP and 50 HP motors.

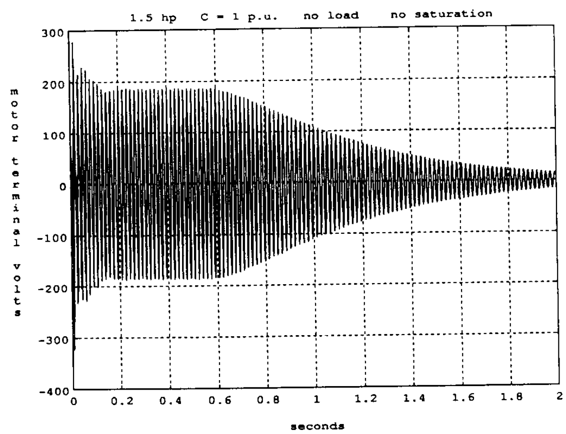
By comparing the saturated case with no saturation, it is observed that the effects of saturation tend to limit the post switching voltage transients. This is in close agreement with the results obtained by Walsh and deMello [4]. Their results predicted that for capacitor values of 1, 2, and 3 per unit, peak voltages of approximately 0.95, 1.2 and 1.3 per unit would be seen at the motor terminals. Comparison of the no load vs. full load case indicates that the no load case is the worst case situation. The effect of motor loads is to dampen any post switching transients.

The indication provided by the computer plots and experimental results is that no problem is encountered with the correction up to 100% or less. The major hazardous effect of these capacitors at no load is that the terminal voltage is sustained for several seconds.

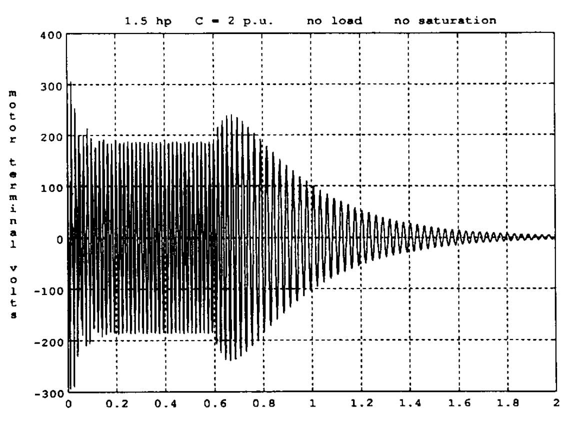
It is clear from the simulation results that while the problem of overvoltage may have been significant in the machines constructed 40 or 50 years back, it is probably no longer concern in the modern machine design. This can be attributed to the fact that newer machines are constructed with less steel and hence, operate deep into the saturation region.



(a) No Capacitor

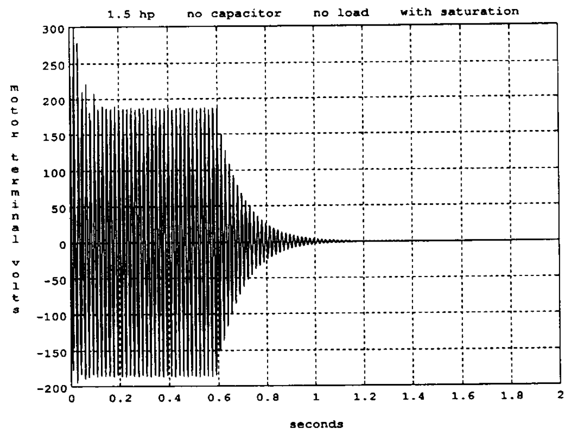


(b) 1 Per Unit Capacitor

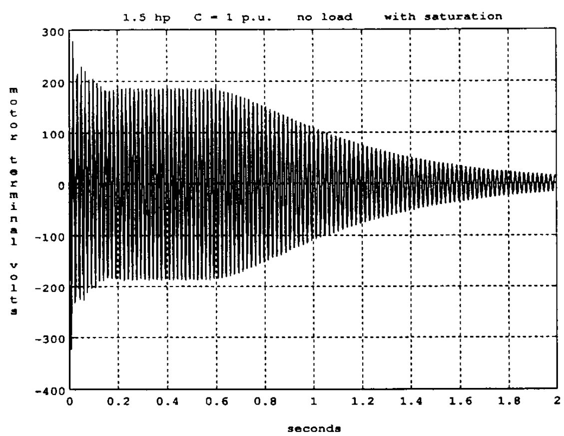


(c) 2 Per Unit Capacitor

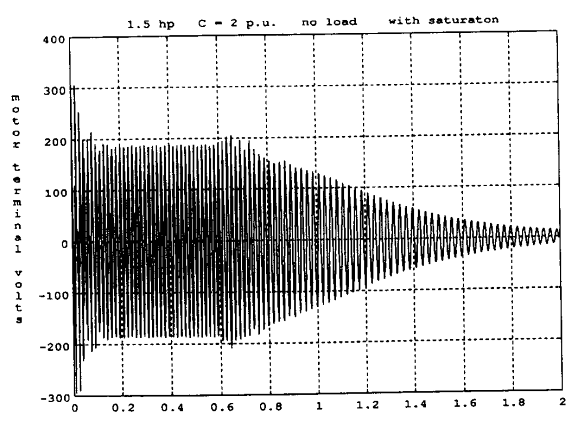
Fig. 4. Computer Simulated Plots of Motor Terminal Voltage vs. Time for 1.5 HP Motor at No-Load and No Saturation



(a) No Capacitor

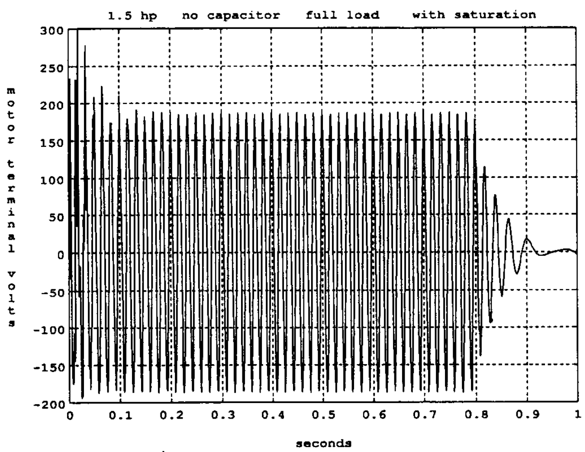


(b) 1 Per Unit Capacitor

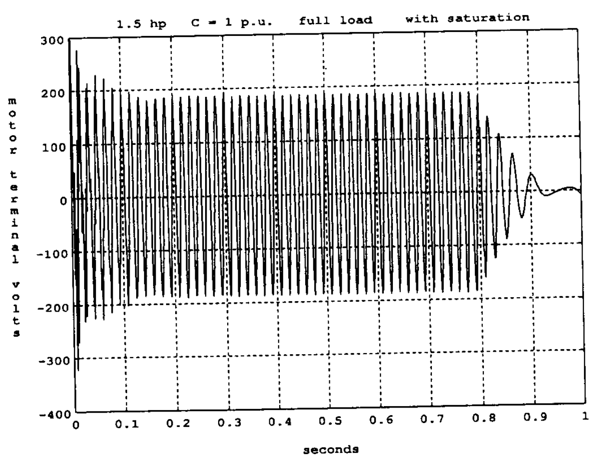


(c) 2 Per Unit Capacitor

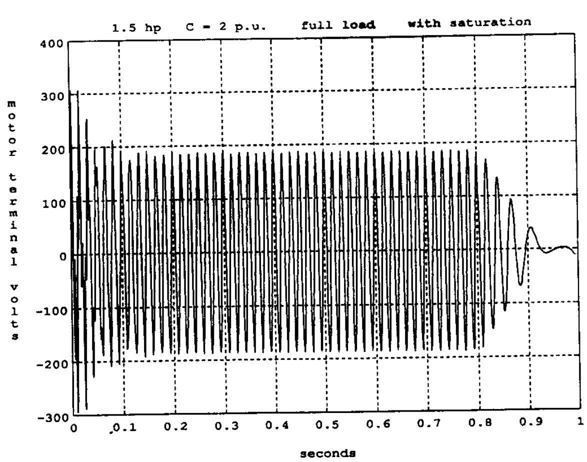
Fig. 5. Computer Simulated Plots of Motor Terminal Voltage vs. Time for 1.5 HP Motor at No-Load and With Saturation



(a) No Capacitor

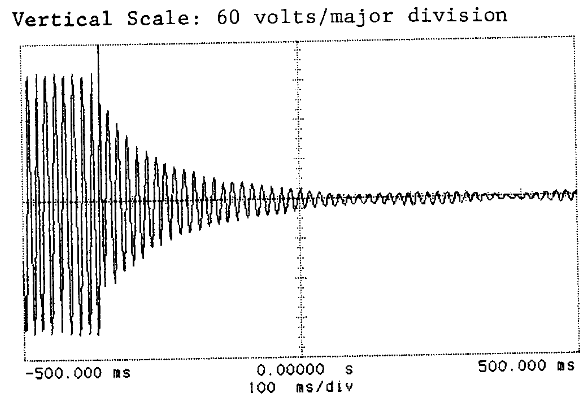


(b) 1 Per Unit Capacitor

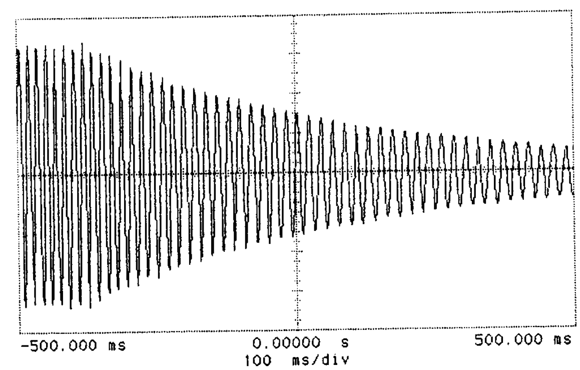


(c) 2 Per Unit Capacitor

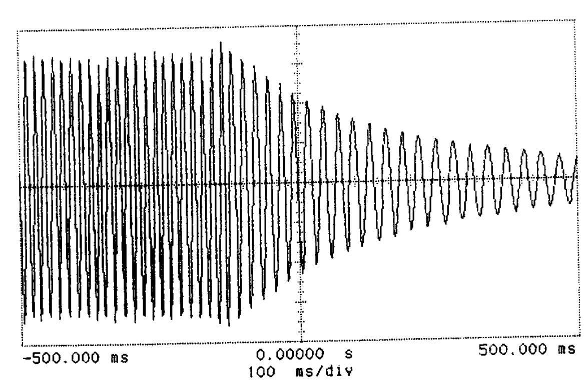
Fig. 6. Computer Simulated Plots of Motor Terminal Voltage vs. Time for 1.5 HP Motor at Full-Load and With Saturation



(a) No Capacitor

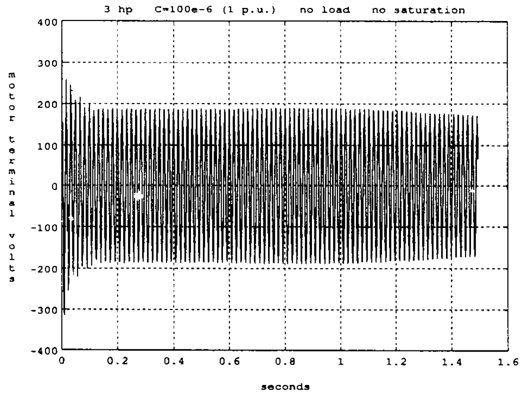


(b) 1 Per Unit Capacitor

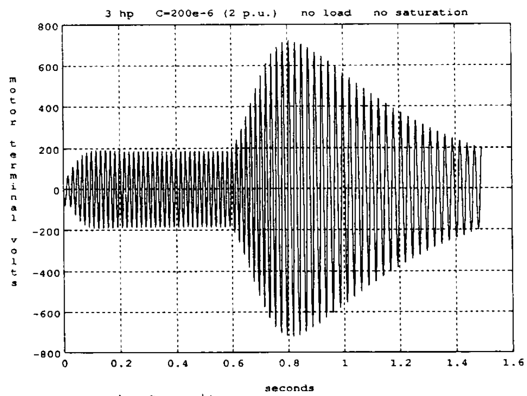


(c) 2 Per Unit Capacitor

Fig. 7. Actual Waveforms of Motor Terminal Voltage vs. Time for 1.5 HP Motor at No-Load

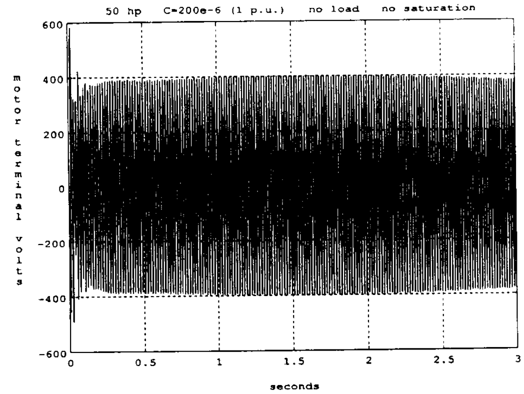


(a) 1 Per Unit Capacitor

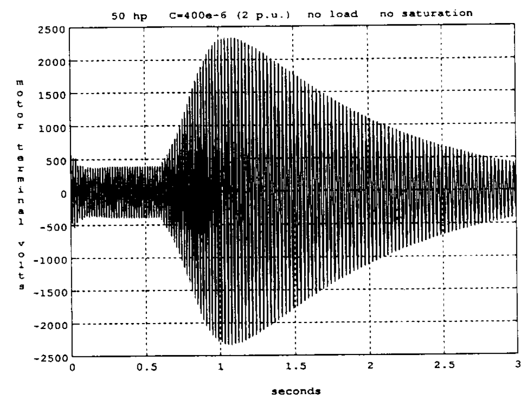


(b) 2 Per Unit Capacitor

Fig. 8. Computer Simulated Plots of Motor Terminal Voltage vs. Time for 3 HP Motor at No-Load and No Saturation



(a) 1 Per Unit Capacitor



(b) 2 Per Unit Capacitor

Fig. 9. Computer Simulated Plots of Motor Terminal Voltage vs. Time for 50 HP Motor at No-Load and No Saturation

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[3] Walsh, G. W. and DeMello, F. P., "Reclosing Transients in Induction Motors with Terminal Capacitors", IEEE Transactions on Power Apparatus and Systems, Vol. 74, Feb. 1961, pp. 1206 - 1213.

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[5] MacFayden, W. K., "Representation of Magnetization Curves by Exponential Series", Proc. IEE, Vol. 120, No. 8, Aug. 1973.

[6] Burleson, L. J.,"Switching Transients On Induction Motors With Power Factor Correction Capacitors", M.S. Thesis, University of Colorado at Denver, Denver, Colorado, 1989.

[7] MATLAB Program, Copyright The Mathworks, Inc., Version 3.34, March 1988.

NOMENCLATURE

s,r	suffixes denoting stator and rotor, respectively
d,q	suffixes denoting axes rotating synchronously with supply frequency
m	suffix used to denote mutual
eq	suffix used to denote system equivalent
p	differential operator, d/dt
r	resistance
L	inductance
Te	electrically developed torque
a,b,c	first, second, and third phases of three-phase system
ψ	instantaneous flux linkage
I	instantaneous current
P	number of poles
Ta	accelerating torque
Tl	load torque
t	time in secs
J	inertia of motor and connected load
V	instantaneous voltages
wb	base angular frequency
we	angular frequency of the synchronously rotating reference frame
Xl	leakage reactance