Motor starting with shunt capacitors: An alternate approach to voltage dip control

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MOTOR STARTING WITH SHUNT CAPACITORS: AN ALTERNATE APPROACH TO VOLTAGE DIP CONTROL

by

Ravi A. Managuli

A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science in

Electrical and Computer Engineering

Department of Electrical and Computer Engineering
University of Nevada, Las Vegas
December, 1996

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ABSTRACT

Induction motors are known to cause undesirable voltage dip because of high inrush current during starting, especially when fed from weak AC systems. For this reason, large motors are often started with reduced voltage. This thesis proposes full-voltage motor starting with shunt capacitors. Two types of capacitors are used: power factor correction capacitor and start capacitor. The start capacitor is determined to maximize the input impedance during starting in order to reduce the initial inrush current. The analysis shows that shunt capacitors improve the voltage dip and the motor acceleration significantly but introduce some level of waveform distortion during each starting period. The start capacitor is found to be very effective in voltage control, but additional components such as damping resistor must be added to effectively reduce the waveform distortion. A centrifugal switch is used to replace the start capacitor and damping resistor by a power factor correction capacitor as the motor reaches a predetermined speed. The feasibility of the proposed scheme is proven through a mathematical model and associated computer simulations. The simulation results are verified by laboratory experiments.
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Chapter 1

INTRODUCTION

Field measurements show that the most common type of power quality disturbance is the voltage sag [1]. This type of disturbance, also referred to as "voltage dip", is defined as a momentary decrease in rms or peak voltage for a short duration, i.e., few cycles to few seconds. Voltage dip does not cause any damage to loads, but with significant magnitude and duration it can cause computer systems to crash [2], electromechanical devices to malfunction, and adjustable speed drives to trip [3]. A common source of voltage dip is the starting of large induction motors with a rated voltage across the stator terminals. These motors draw large inrush currents which are typically 500%-800% larger than full load currents. This surge of high current can cause an appreciable voltage drop across the distribution transformer and feeder impedance. Because of the heavy voltage drop, the motor may not develop sufficient torque to accelerate the load. As a result, the motor may draw excessive rotor and stator currents resulting in the increased voltage dip.

A remedy to the above problem is to reduce the motor inrush current by starting the motor with a lower voltage, a method often referred to as soft start. This practice is accomplished by using any one of the following methods [4]-[7]: (a) A step-down autotransformer where taps are provided on the transformer to vary the applied voltage. (b)
Part-winding starter where only part of the stator winding is used during starting (c) Wye-delta starter where motor is started with stator in wye and then changed to delta, and (d) Solid-state voltage controller starter where reduced voltage is applied to the stator by chopping the line voltage during starting. Reducing the voltage results in reduced stator current. However, since the starting torque is proportional to square of the stator terminal voltage, the reduction in the motor line current is achieved at the cost of a reduction in starting torque. Hence, caution should be exercised with loads other than fan-type.

It is worth considering an alternative method to reduce voltage dip caused by motor starting without voltage reduction. The heavy inrush current is mainly inductive. A shunt capacitor can be a potential solution since it can compensate for the inductive part of the current. The subject of voltage dip improvement with power factor correction capacitor was investigated in Ref. [8] along with a series capacitor, but the reported theoretical results were not verified by actual experiments. Furthermore, the additional form of power quality introduced by capacitor installation, namely waveform distortion, was not fully explained. Switching of capacitors on a three-phase system is the source of several significant problems. The voltage disturbances associated with large current transients at the instant of capacitor switching are severe [9]. These transient overvoltages, if large enough, can damage sensitive power electronic devices. Shunt capacitors can also create parallel or series resonance with the system inductance [10], increasing the harmonic distortion of the voltage and current waveforms. This thesis extends the analysis performed in Ref. [8] with voltage dip and waveform distortion being the primary concern.

The analysis shows that when properly sized and simultaneously switched with the induction motor, shunt capacitors can improve both the motor acceleration and voltage dip. The power factor correction capacitor is found to improve the voltage dip and motor acceleration significantly. However, this capacitor is not optimum, because it is determined based upon the steady state power factor of the motor and does not take in to account
the initial reactive inrush current. Voltage dip is further improved by starting the motor with a start capacitor. The start capacitor is designed to maximize the impedance during starting so that the inrush current is minimized. In the remainder of this thesis the term “RC circuit” will describe “start capacitor and damping resistor” and “PFCC” will describe “power factor correction capacitor”. The analysis shows that a start capacitor reduces the fundamental current but increases waveform distortion during starting. These distortions appear to be effectively damped by a properly sized damping resistor. When the motor started with an RC circuit reaches a predetermined speed, a centrifugal switch is used to disconnect RC circuit and connect PFCC. The presence of a shunt capacitor improves the voltage dip during starting without reducing the starting torque. The feasibility of the proposed scheme is proven through the development of a mathematical model and associated computer simulations. Laboratory experiments are conducted to verify the accuracy of the proposed starting method.
Chapter 2

METHODS OF REDUCING MOTOR INRUSH CURRENT

This chapter outlines existing starting methods of induction motors to reduce voltage dip. The advantages and disadvantages associated with each starting method are pointed out.

The induction motor draws six to eight times its rated current when full voltage is applied to its stator terminal during starting. At the instant of starting, the stator current is determined by the motor locked-rotor impedance. Thus, if the stator voltage were reduced by one-half of its value, the motor starting current would be reduced by half. Therefore, desirable reduction in motor line current can be achieved by reducing the line voltage applied to the stator terminals. Auto-transformer starting, wye-delta starting, part-winding starting and solid-state voltage controller starting are the frequently-used starting methods for induction motors to reduce the inrush current.
2.1 Autotransformer Starting

Three phase induction motors are started at reduced voltage by using a single three-phase autotransformer or three single-phase auto-transformers as shown in Fig. 2.1. The taps are provided on the auto-transformer to vary the voltage from 50% to 80% of the rated voltage [4]. If the motor fails to accelerate the load at the lowest voltage, higher voltage taps may be tried until the proper and desired starting torque is obtained. The triple-pole-double-throw (TPDT) switch is thrown to the “start” position during starting, and remains there until the motor accelerates to full load speed. At full load speed, the TPDT switch is thrown to the “run” position, directly connecting the motor across the 3-φ supply. This type of starting method has an inherent disadvantage: low starting torque.

2.2 Part-Winding Starting

Some polyphase induction motors are designed with part-winding, i.e., two identical phase windings, each of which produces the same number of poles and the same amount of rotating magnetic field [4]. The stator circuit with part-winding is shown in Fig. 2.2.
During starting, the voltage is applied to only one circuit of each phase. This is done by closing the “start” section of each wye-connected winding. When the motor reaches full load speed, the “run” section of wye-connected winding is connected in parallel. The resulting starting current is about 65% of the normal starting current and the starting torque is about 45% of the normal starting torque [4]. However, during starting there is a pronounced dip in torque-slip curve. Hence, the manufacturer of the induction motor usually recommends that this type of starting should be employed where the motor is started under light-load or no-load conditions.

2.3 Wye-Delta Starting

Most large three-phase induction motors have their stator terminals brought out so that they may be connected to the line either in wye or delta. The per unit line voltage applied to each phase is \(1/\sqrt{3}\), or 57.8% when started in wye so that the line current is approximately 58% of the normal starting current. When the motor reaches full load speed,
the stator is connected in delta by moving the position of the switch from "wye" to "delta". As Fig. 2.3 indicates, this method of starting requires three double-throw switches, and it has the disadvantage of a high reclosing current [5]. Since developed torque varies with the square of the impressed stator voltage, the reduction in torque when wye connected is about one-third of the normal full-voltage starting torque. Because of these reasons, this method of starting is employed only in applications where low starting torque is permissible, with starting current of approximately 58% of the normal starting current.

2.4 Solid-State Voltage Controller Starting

The circuit in Fig. 2.4 is used in variable-speed drives to reduce the motor voltage at start-up, thereby reducing the starting currents. The reduced voltage is obtained by chopping the line voltage using thyristors. If the torque developed due to reduced voltage is sufficient to overcome the load, the motor accelerates and the motor current decreases. During the steady-state operation, each thyristor conducts for an entire half-cycle. When the motor reaches full load speed, these thyristors are shorted out to eliminate the power losses [6]. The main advantage of this voltage controller is smooth starting. However, this method of starting introduces distortion in the line current apart from reducing the starting torque.
Figure 2.4: Solid State Voltage Controller Motor Starting.

Hence all of the existing induction motor starting methods associated with reduced-voltage have an inherent disadvantage of low starting torque [7]. So caution should be exercised when the motor is started with load other than the fan-type.
Chapter 3

MOTOR STARTING WITH SHUNT CAPACITOR

In view of the disadvantages associated with existing motor starting methods, it is worth considering an alternative starting method to reduce the voltage dip without reducing the motor starting torque. In the proposed method, the induction motor is started with a shunt capacitor bank connected across the stator terminals. The shunt capacitor decreases the reactive inrush current during starting, thus reducing the voltage dip. Since the motor is started with full-line voltage across stator terminals, the starting torque is not affected by this method. In this chapter, a mathematical model is developed to simulate the induction motor. A motor-feeder-capacitor model is developed to study the effects of motor starting with PFCC on distribution feeder. Capacitor switching in distribution feeder causes waveform distortion. An approximate equivalent circuit is developed to predict the waveform distortion. The PFCC is not optimal for voltage dip improvement. A mathematical equation is derived to obtain an optimum start capacitor to minimize the inrush current. The start capacitor reduces the fundamental inrush current but increases the waveform distortion. Mathematical equations are developed to determine the optimum damping resistor.
Finally, a mathematical model is formulated to predetermine the speed at which the RC circuit should be replaced by PFCC.

3.1 Induction Motor Model

The induction motor dynamics are accurately represented by a set of nonlinear differential equations using direct three-phase $a-b-c$ quantities. But with the assumption of a balanced and symmetrical condition, it is convenient to use Parks' $d-q$ axis model. The flux linkages are selected as state variables since they tend to change more slowly than currents and provide more computational stability [11]. When expressed in the synchronously rotating reference frame, the $d-q$ flux linkage equations of the stator and rotor circuits, and the rotor slip are given by [12]:

\begin{align}
\dot{\psi}_q &= \psi_{qs} - \psi_{ds} + a_2 \psi_{qr} - a_1 \psi_{qs}, \\
\dot{\psi}_d &= \psi_{ds} + \psi_{qs} + a_2 \psi_{dr} - a_1 \psi_{ds}, \\
\dot{\psi}_{qr} &= a_3 \psi_{qs} - a_4 \psi_{qr} - (1 - \omega_r) \psi_{dr}, \\
\dot{\psi}_{dr} &= a_3 \psi_{ds} - a_4 \psi_{dr} + (1 - \omega_r) \psi_{qr}, \\
\dot{\omega}_r &= a_5 [(\psi_{qs}\psi_{dr} - \psi_{ds}\psi_{qr}) - a_6 T_i],
\end{align}

where,

\begin{align}
a_1 &= \frac{R_sX_{tt}}{X_{sr}}, a_2 = \frac{R_sX_m}{X_{sr}}, a_3 = \frac{R_rX_m}{X_{sr}}, \\
a_4 &= \frac{R_sX_{ss}}{X_{sr}}, a_5 = \frac{X_m}{2H X_{sr}}, a_6 = \frac{X_{sr}}{X_m},
\end{align}
with

\[ X_{ss} = X_{ls} + X_m, \]
\[ X_{rr} = X_{lr} + X_m, \]
\[ X_{sr} = X_{ls}X_{lr} + X_m(X_{ls} + X_{lr}). \]

\( R_s, R_r \): resistance of stator and rotor winding.
\( \psi_{ds}, \psi_{qs} \): flux linkages of d-q stator winding.
\( \psi_{dr}, \psi_{qr} \): flux linkages of d-q rotor winding.
\( V_{ds}, V_{qs} \): terminal voltages of d-q stator winding.
\( v_d, v_q \): d-q substation voltages.
\( X_{ls}, X_{lr} \): leakage reactance of stator rotor winding.
\( \omega_r \): rotor speed.
\( X_m \): magnetizing reactance.
\( X_l \): sum of stator and rotor reactance.
\( T_l \): load torque.
\( L_M \): sum of rotor and stator leakage inductance.
\( R_M \): sum of rotor and stator resistance.
\( L_f \): feeder inductance.
\( R_f \): feeder resistance.
\( V \): supply peak voltage.
\( H \): inertia constant of motor.

The d–q stator currents are expressed in terms of flux linkages by

\[ i_{qs} = \frac{1}{X_{ls}}(\psi_{qs} - X_m(\psi_{qs} + \psi_{qr})), \quad (3.6) \]
\[ i_{ds} = \frac{1}{X_{ls}}(\psi_{ds} - X_m(\psi_{ds} + \psi_{dr})), \quad (3.7) \]
Finally, the $d-q$ voltages and currents are related to the actual $a-b-c$ phase values by Parks' transformation:

\[
\begin{bmatrix}
v_{qs} \\
v_{ds}
\end{bmatrix} = \frac{2}{3} \begin{bmatrix}
\cos \theta & \cos(\theta - \beta) & \cos(\theta + \beta) \\
\sin \theta & \sin(\theta - \beta) & \sin(\theta + \beta)
\end{bmatrix} \begin{bmatrix}
v_a \\
v_b \\
v_c
\end{bmatrix},
\]

(3.10)

where $\theta$ is the angular displacement of the $q$-axis with respect to the $a$-axis and $\beta = 2\pi/3$.

### 3.2 Motor Starting with Power Factor Correction Capacitor

In this section a mathematical model to improve the voltage dip using power factor correction capacitor is presented. A bank of PFCC is connected across the induction motor as shown in Fig. 3.1. Note that the motor and capacitor are switched simultaneously with a single switch.
3.2.1 Feeder and Capacitor Model

The feeder-transformer impedance causes the substation voltage to be different from the voltage at the motor terminals. In addition, the shunt capacitor bank modifies the feeder current from the motor stator current. Mathematically, these facts are represented by four differential equations in the \( d - q \) frame of reference: the feeder current expressions

\[
\begin{align*}
\dot{i}_d &= (v_d - v_{ds} - R_i d_i)/L, \\
\dot{i}_q &= (v_q - v_{qs} - R_i q_i)/L,
\end{align*}
\]

and the capacitor voltage expressions

\[
\begin{align*}
\dot{v}_{ds} &= (i_{dl} - i_{ds})/C, \\
\dot{v}_{qs} &= (i_{ql} - i_{qs})/C.
\end{align*}
\]

Equations (3.11)-(3.14) together with those of the motor (3.1)-(3.5) represent the full model of the circuit under consideration.

3.2.2 Waveform Distortion During Starting

The capacitor switching in distribution feeders causes momentary transients in the line [9]-[10]. The same would be expected when PFCC is switched simultaneously with an induction motor. The resulting electrical distortion that occurs can be predicted by considering an approximate circuit of the motor. During the first few electrical cycles after switching, the rotor speed is nearly zero; hence, the motor can be represented by its blocked rotor circuit during this short time window. If the magnetizing and core loss impedances
are ignored, the motor equivalent circuit will consist of the sum of the stator and rotor impedances. The network can then be approximated by the circuit in Fig. 3.2 where \( R_m = R_s + R_r, \ L_m = L_s + L_r \). The natural frequencies of the circuit as well as the time constants can be determined by applying the Laplace Transform and deriving the equation for the feeder current \( i(t) \). The solution of the following third-order equation provides such information:

\[
A_3 S^3 + A_2 S^2 + A_1 S + A_0 = 0, \tag{3.15}
\]

where,

\[
A_3 = L_m L_l C,
A_2 = C R_m L_l + C L_m R_l,
A_1 = L_m + L_l + C R_m R_l,
A_0 = R_l + R_m.
\]

Note that both natural frequencies and rate of decay depend upon the motor and feeder parameters in addition to the capacitor.

The equation for the natural response of the instantaneous feeder current \( i(t) \) in Fig. 3.2 is of the form [13]:

\[
i_n(t) = B_1 e^{-\lambda_1 t} + B_2 e^{-\lambda_2 t} \cos(\omega_0 t + \theta) \tag{3.16}
\]
where $\lambda_1$ and $\lambda_2$ are time constants and $\omega_0$ is the natural frequency of distortion. The time constants and natural frequency are determined from Eqn. (3.15), while constants $B_1$ and $B_2$ are calculated from the initial conditions at time $t = 0$:

$$i(t) = 0,$$

$$\frac{di}{dt} = \frac{V - V_c}{L_1},$$

where,

$V_c$ : Initial voltage across capacitor.

$V_m$ : Peak value of the source voltage.

$V$ : $V_m \sin(\omega t)$.

Then, constants $B_1$ and $B_2$ determined from Eqn. (3.16) are,

$$B_1 = \frac{V - V_c}{L_1(\lambda_1 + \lambda_2)}, \quad (3.17)$$

$$B_2 = -\frac{\sqrt{2}(V - V_c)}{L_1(\lambda_1 + \lambda_2)}. \quad (3.18)$$

The last two equations indicate that the transient components of the circuit are due to the voltage across the capacitor at the instant of switching. If the capacitor bank is switched when the line voltage is equal to the capacitor voltage, in other words, when the voltage is crossing the zero reference with the initial voltage across capacitor being zero, the magnitude of the transient component will be minimum. When distortions are severe they can be reduced by switching the capacitor when the corresponding instantaneous phase voltage becomes equal to capacitor voltage [13] or by increasing the time constants of the circuit with damping resistor [8].
3.3 Further Improvement in Voltage Dip

The power factor correction capacitor is not optimal for voltage dip improvement because it is determined based on steady-state operating conditions. Since the inrush current is mainly inductive, introducing a larger capacitor will further compensate the inductive inrush current and improve the voltage dip. The large capacitor however, increases the waveform distortion during the first few cycles of the motor starting. Thus a suitable damping resistor to dampen these distortions is required. The resulting RC Circuit is replaced by PFCC when the motor reaches a predetermined speed. The material that follows provides a mathematical model to determine the start capacitor, damping resistor and the switching speed.

3.3.1 Selection of Optimal Starting Capacitor

The starting inrush current of the induction motor depends upon the impedance seen across the input terminals. Thus the inrush current is reduced by maximizing the input impedance. The magnitude of input impedance \( Z_i \) with shunt capacitor across the induction motor terminal is expressed in Eqn. (3.19):

\[
Z_i = \left( \frac{D_1 X_i^2 + D_2 X_c + D_3}{X_c^2 + X_i^2 - 2X_cX_i + R_m^2} \right)^{1/2}
\]  

(3.19)

where,

\[
D_1 = R_f^2 + R_m^2 + X_i^2 + 2X_iX_t + 2R_tR_m - 2X_i^2X_t + X_i^2,
\]

\[
D_2 = -2X_i^2X_t - 2X_iX_t^2 - 2X_iR_m^2 - 2R_t^2X_t,
\]

\[
D_3 = R_f^2X_i^2 + X_f^2X_t^2 + R_f^2R_m^2 + X_f^2R_m^2.
\]

The start capacitor reactance \( X_c \), is the only variable parameter in \( Z_i \) because all other parameters depend upon the feeder and the induction motor and are thus fixed. The capacitor corresponding to maximum impedance is evaluated by differentiating \( Z_i \) with

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respect to $X_c$. The differential equation

$$\frac{\partial Z_i}{\partial X_c} = 0$$

yields

$$E_1 X_c^2 + E_2 X_c + E_3 = 0, \quad (3.20)$$

where,

$$E_1 = X_i^2 - X_i R_m^2 + X_i X_i^2 + 2 R_i X_i R_m + R_m^2 X_i,$$

$$E_2 = - R_m^2 - 2 R_m X_i^2 - X_i^4 - 2 X_i X_i R_m^2,$$

$$E_3 = -2 R_m^2 X_i^3 - 2 X_i X_i^3 - 2 R_i R_m^3.$$

The solution of Eqn. (3.20) leads two values of $X_c$, and the required starting capacitor is the real positive value. The start capacitor reduces the fundamental current thus providing further improvement in voltage dip.

### 3.3.2 Selection of Optimal Damping Resistor

The start capacitor determined in section 3.3.1 decreases the fundamental inrush current but increases the waveform distortions during the first few cycles of starting. These distortions can be successfully damped by a suitable damping resistor $R_c$ placed in series with the capacitor. However this damping resistor decreases the input impedance, in effect increasing the inrush current as the motor picks up speed. An optimum damping resistor is calculated using the natural response of the instantaneous current.

The approximate model for determining the natural response is shown in Fig. 3.3 with switch $S$ in position 1. The natural response of the current $i(t)$ in Fig. 3.3 is of the form

$$i_n(t) = H_1 e^{-\alpha t} + H_2 e^{-\beta t} \cos(\omega_1 t + \theta_2) \quad (3.21)$$
where, $\alpha$ and $\beta$ are time constants, and $\omega_1$ is the natural frequency of distortion.

The natural frequencies of the circuit as well as time constants can be determined by using the method similar to that employed in section 3.2.2. The solution of the following third-order equation provides this information:

$$G_3 S^3 + G_2 S^2 + G_1 S + G_0 = 0 \quad (3.22)$$

where,

$G_3 = L_m L_t C,$

$G_2 = R_c + L_m + R_t L_m C + L_t C R_m + L_t C R_m,$

$G_1 = R_m R_c C + L_m + R_t R_m C + L_t,$

$G_0 = R_t + R_m.$

The solution of Eqn. (3.22) yields

$$\alpha = p_1^{1/3} - \frac{1}{9} P_2 - \frac{G_2}{3G_3}, \quad (3.23)$$

$$\beta = \frac{1}{2} p_1^{1/3} + \frac{1}{18} P_2 - \frac{G_2}{3G_3}, \quad (3.24)$$
\[
\omega_0 = \frac{\sqrt{3}}{2} \left( P_1^{1/3} + \frac{1}{9} P_2 \right), \text{ and } \tag{3.25}
\]

\[
\theta_2 = \frac{\pi}{4}
\]

where,

\[
P_1 = \frac{1}{54} \left( -9G_1G_2G_3 + 27G_6G_5^2 + 2G_5^3 \right),
\]

\[
P_2 = \frac{3G_1G_3 - G_3^2}{G_3^2 K^{1/3}},
\]

and the constants \( H_1 \) and \( H_2 \) are determined using the same initial conditions as in section 3.2.2 and are expressed in Eqn. (3.26), and (3.27):

\[
H_1 = \frac{V - V_c}{L_i(\alpha + \beta)}, \tag{3.26}
\]

\[
H_2 = -\frac{\sqrt{2}(V - V_c)}{L_i(\alpha + \beta)}. \tag{3.27}
\]

The last two expressions indicate that the amplitudes of distortion depend upon the initial voltage across the capacitor and time constants.

Eqn. (3.24) indicates that the time constants of distortion depend upon the damping resistor \( R_c \), which can be increased to increase the time constants. But there exists a trade-off between time constants and system impedance. The increase of \( R_c \) decreases the input impedance \( Z_s \) according to Eqn. (3.28), which in effect increases the inrush current.

\[
Z_s = \left( \frac{F_1^2 + F_2^2}{(R_m + R_c)^2 + (X_t - X_s)^2} \right)^{1/2} \tag{3.28}
\]

where,

\[
F_1 = R_l R_m + R_l R_c + R_m R_c + X_t (X_t - X_s) + X_s X_t,
\]

\[
F_2 = X_t R_m + X_t R_c + R_l (X_t - X_c) + X_t R_c - X_s R_c,
\]

\[
X_s = \text{Reactance of the start capacitor.}
\]
Therefor $R_c$ should be evaluated from Eqn. (3.24) and (3.28) so that it satisfies the system requirement of waveform distortion as well as inrush current.

### 3.3.3 Feeder-Capacitor-Damping Resistor Model

The feeder-transformer model with RC circuit is similar to the model with PFCC discussed in section 3.2.2. The damping resistor modifies only the capacitor voltage expressions and are expressed in Eqn. (3.29) and (3.30):

\[
\dot{v}_{ds} = \frac{(i_{dl} - i_{ds})}{C} + R_c(\dot{i}_{dl} - \dot{i}_{ds}),
\]

\[
\dot{v}_{qs} = \frac{(i_{ql} - i_{qs})}{C} + R_c(\dot{i}_{ql} - \dot{i}_{qs}),
\]

where $i_{dl}$, $i_{ds}$, $i_{ql}$, $i_{qs}$ and their derivatives can be obtained in terms of flux linkages from Eqn. (3.6) through (3.9) and Eqn. (3.1) through (3.5).

### 3.3.4 Switching from RC Circuit to PFCC

The approximate impedance of the induction motor during starting when the speed is increasing is given by Eqn. (3.31). The impedance increases as the motor picks up speed.

\[
Z_T = \left(\left(R_s + \frac{R_T}{s}\right)^2 + (X_t)^2\right)^{1/2}
\]

When the induction motor is started with PFCC, the input impedance at the source terminal increases as the motor picks up speed. However, when a value RC circuit is used for starting, the input impedance decreases as the motor picks up speed. Thus the inrush current decreases as the motor picks up speed with the PFCC while the inrush current increases with the RC circuit. So the speed of the motor can be determined at which impedance at the source terminal with PFCC and with RC circuit becomes equal. When the motor
started with RC circuit reaches this speed, RC circuit is replaced by PFCC.

The input impedance at the source terminal with the induction motor, feeder and PFCC is given by Eqn. (3.32):

\[ Z_p = \left( \frac{J_1^2 + J_2^2}{R_t^2 + (X_t - X_p)^2} \right)^{1/2} \]  \hspace{1cm} (3.32)

where,

\[ R_t = R_s + \frac{R_c}{s}, \]

\[ X_p = \text{reactance of the power factor correction capacitor}, \]

\[ J_1 = R_t R_t - X_t X_t + X_p X_2 + X_p X_t, \]

\[ J_2 = X_t R_t + X_t R_t - X_p R_t + X_p R_t. \]

Similarly, the input impedance at the source terminal with induction motor, feeder and RC circuit is given by Eqn. (3.33):

\[ Z_s = \left( \frac{M_1^2 + M_2^2}{(R_t + R_c)^2 + (X_t - X_s)^2} \right)^{1/2} \]  \hspace{1cm} (3.33)

where,

\[ M_1 = R_t R_t + R_t R_c + R_t R_c + X_t (X_t - X_s) + X_s X_t, \]

\[ M_2 = X_t R_t + X_t R_c + R_t (X_t - X_c) + X_t R_c - X_s R_c, \]

\[ X_s = \text{Reactance of the start capacitor}. \]

The speed at which the two impedances \( Z_s \) and \( Z_p \) are equal can be determined by either one of the following method:

- By equating Eqn. (3.32) and Eqn. (3.33) and solving Eqn. (3.34) for slip \( s \).

\[ Z_p = Z_s. \]  \hspace{1cm} (3.34)

- By Plotting impedance\((Z_s \text{ and } Z_p)\) speed curve and determining the intersection of
In the first method, speed is obtained directly by solving Eqn. (3.34) for slip \( s \), where as in the second method, the intersection point of \( Z_s \) and \( Z_p \) indicate the speed. A centrifugal switch is used to disconnect RC circuit and connect PFCC when the motor reaches \( N(1 - s) \) speed. The working principle of this centrifugal switch which replaces RC circuit by PFCC when the motor reaches predetermined speed is explained below [14].

The centrifugal switch has two distinct parts, the switch and actuator. The switch is mounted in the end plate, and the actuator is mounted on the rotor shaft so that it will come in contact with the end switch when the motor reaches the desired speed. The actuator has a weight built in to its outer edges. These weights are hinged on the inside near the rotor and allowed to move or swing at the outer edge. These weights are adjusted to move or swing at the desired speed of the rotor. Since the outer edge is heavier, the centrifugal force caused by the shaft rotation will cause them to move away from the shaft. Since the actuator is hinged to the the inside, this action will cause the actuator to move along the length of the shaft slightly in the direction of the switch. The movement is only \( \frac{1}{4} \) to \( \frac{1}{2} \) inch, but it is sufficient to actuate the switch to the open position.

The end switch is made of spring wheel, which provides tension to keep the switch in position 1. Whenever the centrifugal actuator is not pressing on the switch, the end switch will remain in the position 1. When the actuator moves along the shaft slightly, it will provide enough force to cause the end switch to move from position 1 to position 2. The end switch of the centrifugal switch is shown if Fig. 3.3. So this centrifugal switch mechanically senses the speed of the shaft, and when the motor shaft reaches the speed equal to \( N(1 - s) \), it disconnects the RC circuit and connects PFCC.
Chapter 4

SIMULATION RESULTS

Computer simulations and laboratory experiments were conducted on a three phase induction motor with shunt capacitor to verify the proposed method of starting. Simulation results are presented in this chapter.

The differential equations [1]-[5] describing the behavior of the three phase induction motor with shunt capacitor fed from a three-phase supply have been solved numerically. For this purpose, a computer program has been developed using the 4th order Runge-Kutta algorithm for numerical integration. Both starting process and dynamic behavior can be investigated by the developed program. The simulations are applied on a three-phase 220V, 1/3 Hp, 1705 rpm, delta-connected wound-rotor induction motor. The mechanical load on shaft is set at rated value. The machine parameters derived from blocked and no-load tests are as follows: $R_s = 5\, \Omega$, $X_{ls} = X_{lr} = 9.5\, \Omega$, $X_m = 125\, \Omega$, and $R_r = 6.1\, \Omega$. A weak source is modeled using a short circuit capacity of twenty times the full load motor current. This is accomplished by inserting an inductor $L_l = 5.6mH$ with resistance $R_l = 0.05\, \Omega$ in each phase between the source and the motor terminals.
4.1 Motor Starting with Power Factor Correction Capacitor

A wye-connected capacitor bank with $10\mu F$ in each phase was selected to improve the full load motor power factor from 85% to 95% at steady state. Simulation results both with and without shunt capacitors follow.

The induction motor current during the period of starting with and without shunt capacitor are shown in Fig. 4.1. One can see from Fig. 4.1 that PFCC reduced the magnitude of the inrush current approximately from 8 times the rated full load current to 5 times the rated full load current. Fig. 4.2 shows the calculated voltage dip, i.e., the difference between the peak values of the nominal voltage and the motor terminal voltage. Note that

Figure 4.1: Simulated Feeder Current (a) without Capacitor (b) with PFCC.
a severe voltage sag of 16% of rated voltage takes place without power factor correction capacitors and lasts for 0.9 seconds. The magnitude and duration of this dip is considered unacceptable and will likely interfere with electronic loads as it falls outside the CEBEMA curves [2]. The capacitor bank improved the magnitude of the voltage sag by 45% and the resulting dip is considered acceptable since it falls within the recommended tolerance curves for electronic business machines. The capacitor banks also improved acceleration time by 50% as shown in Fig. 4.3. These results agree with those found in Ref. [8].
during the first few cycles. The solution of Eqn. (3.15) indicate that the circuit's natural frequency is near the 21st harmonic order and lasts approximately 8 cycles of the 60 Hz supply, or 0.13 seconds. Its magnitude, however depends upon the time at which switching takes place. To verify the above prediction, the first 6 cycles of simulated feeder current are displayed in Fig. 4.4. The distortion level and its rate of decay can best be seen at the several peak values of the waveform.

![Figure 4.4: Simulated Feeder Current During First Few Cycles with PFCC.](image)

### 4.2 Motor Starting with RC Circuit

Further improvement in the voltage dip is obtained by using a start capacitor instead of PFCC and the results are presented in this section. The induction motor draws heavy reactive inrush current during starting without the shunt capacitor as shown in Fig. 4.1. Using Eqn. (3.20), a start capacitor of $94 \mu F$ is determined to minimize the fundamental inrush current during starting. However, a start capacitor increases the waveform distortions during the first few cycles. The Solution of Eqn. (3.22) indicates that the circuit's natural frequency is near the 4th harmonic order for this capacitor size. To verify the above prediction, the first few cycles of simulated feeder current are displayed in Fig. 4.5(a). The plot shows that the fundamental component of the inrush current is about 4 amps., but the
distortion is severe which offsets the advantage gained by the reduction of the fundamental current. To dampen these distortions, a damping resistor of 1.53Ω is used. The damping resistor is determined from Eqn. (3.24) and (3.28) by constraining the fundamental current to 4.5 amps., and decay constant to one 60 Hz cycle. These constraints are placed to improve the voltage dip to a desired level of 10V and to limit the distortions to one cycle so that the amplitude and duration of voltage dip fall inside the CEBEMA curves [2].

![Feeder Current Graph](a)

![Feeder Current Graph](b)

Figure 4.5: Simulated Feeder Current for First Few Cycles with (a) Start Capacitor (b) RC Circuit.

The first few cycles of the feeder current with damping resistor of 1.53Ω and start capacitor of 94µF in each phase is shown in Fig. 4.5(b). The resulting distortion and
decay rate can again be obtained from Eqn. (3.22). Comparison of Fig. 4.5(a) and 4.5(b), indicate that the distortion decayed in only one cycle and the fundamental current increased approximately to 4.5 amps. The line current, however, starts to increase due to the large shunt capacitor (discussed in section 3.3.4) as the motor picks up speed. Therefore the RC circuit should be replaced by PFCC when the motor reaches a predetermined speed. The speed of the motor at which the input impedance $Z_p$ (Eqn. 3.29) and $Z_s$ (Eqn. 3.30) due to the PFCC and the RC circuit respectively, become equal is determined by plotting impedance speed curve and obtaining the intersection point. The plot in Fig. 4.6 shows that the impedances become equal when the speed is 775 rpm. The RC circuit should be replaced by PFCC when the speed of the motor reaches this value. The resulting simulated feeder current is displayed in Fig. 4.7.

The calculated voltage dip, i.e., the difference between the peak values of the nominal voltage and the motor terminal voltage for all three cases is shown in Fig. 4.8. One can see from Fig. 4.8 that the RC circuit improved the voltage dip considerably as compared to other methods of starting. The severe voltage sag that takes place when the induction motor is started without shunt capacitor is improved by 66% with RC the circuit. The motor acceleration, shown in Fig. 4.9, starts decreasing as the motor picks up speed because of increased voltage dip. Therefore, the motor acceleration begins to increase again when

![Figure 4.6: Plot of Impedance Versus Speed.](image-url)
the RC circuit is replaced by PFCC at the predetermined speed. The proposed method improves the acceleration by nearly 50% as shown in Fig. 4.9.

Figure 4.7: Simulated Feeder Current with RC Circuit and PFCC.

Figure 4.8: Calculated Voltage Dip with RC Circuit and PFCC.
Figure 4.9: Simulated Machine Acceleration with RC Circuit and PFCC.
Chapter 5

EXPERIMENTAL RESULTS

The feasibility of the proposed starting method and the validity of the mathematical model developed in chapter 3 have been verified experimentally. Experimental results are presented in this chapter.

A delta connected three phase laboratory induction motor is used for experimental purpose. The rating and parameters of the motor are identical to the simulated motor in the previous chapter. Furthermore, source supplying power to the motor is identical to the source discussed in chapter 4. The experiment is conducted with a constant load of 1/3 Hp. The voltage waveform were displayed on the Textronics 2221 oscilloscope and current waveforms were obtained by using current amplifier probe Am503 in tandem with the scope.

5.1 Measurements with Power Factor Correction Capacitor

The experiment is conducted on the induction motor with and without shunt capacitor. A PFCC of 10μF is used as shunt capacitor as discussed in section 4.1. The measured feeder currents are shown in Fig. 5.1. One can see that the peak value of the inrush current due to motor starting without shunt capacitor is reduced from 8 times the rated full load current to 5 times the rated full load current with PFCC. The positive half cycle of the
Figure 5.1: Measured Feeder Current (a) without Shunt Capacitor (b) with PFCC.
measured voltage with and without shunt capacitor are shown in Fig. 5.2. The Figure shows that the average voltage dip without shunt capacitor is about 23V which corresponds to about 14% of the rated voltage and the motor start-up time is about 1 second. The volt-

Figure 5.2: Measured Voltage Dip (a) without Shunt Capacitor (b) with PFCC.

age dip and duration are not acceptable for normal operation of the electronic equipment [2]. The improved voltage dip due to PFCC is shown in Fig. 5.2(b). One can see that the average voltage dip due to PFCC is about 15V which corresponds to 9% of rated voltage
and acceleration time is 0.5 seconds. The capacitor bank improved the magnitude of voltage dip by 44% and acceleration time by 50%. This amount of voltage dip and duration are considered acceptable for the proper operation of sensitive electronic equipment [2]. The speed time curve could not be displayed because of the lack of measuring equipment in the laboratory. The corresponding simulated results of section 4.1 when the induction motor was started with a PFCC indicates a similar improvement in voltage dip and start-up time.

Capacitor switching however, introduced some level of waveform distortion in the feeder current during the first few cycles of motor starting as shown in Fig. 5.3. The distortion level and its rate of decay can best be seen at the several peak values of the waveform, similar to the simulated feeder current shown in Fig. 4.4. Hence, confirming the approximate mathematical model developed in section 3.2.2 to predict the waveform distortion.

Figure 5.3: Measured Feeder Current During First Few Cycles with PFCC.

5.2 Measurements with RC Circuit

Further improvement in voltage dip is obtained by starting the induction motor with a start capacitor bank of 94 $\mu F$ in each phase. The start capacitor is determined from Eqn.
(3.19) to maximize the input impedance across the supply terminal during starting. The start capacitor decreased the fundamental current to 4 amps, but increased the waveform distortions. A damping resistor of 1.53Ω determined from Eqn. (3.24) and Eqn. (3.28) to restrict the inrush current to 4.5 amps and electric distortion to one 60 Hz cycle, is used in series with the start capacitor to dampen these oscillations. The measured feeder currents with and without damping resistor are shown in Fig. 5.4. One can see that distortion decays in one 60 Hz cycle and feeder peak current is about 4.5 amps. The non-symmetry of the current about x-axis in Fig. 5.4 is due to dc-averaging effect of the oscilloscope. However the line current starts increasing as the motor starts picking up the speed as discussed in section 3.3.4. So when the motor started with RC circuit reaches a predetermined speed of 775 rpm, a switch is used to replace the RC circuit by a PFCC of 10μF. The resulting feeder current is shown in Fig. 5.5. The positive half cycle of the measured voltage dip with RC circuit is shown in Fig. 5.6. Comparison of voltage dip from Fig. 5.2 and 5.6 shows that the RC circuit improved the voltage dip by 66% and start-up time by 50%. The corresponding simulated results of section 4.2 when the motor was started with the RC circuit and replaced by PFCC indicate a similar improvement in voltage dip and start-up time.

It can be seen that the experimental results and simulated results (presented in section 4.1 and 4.2) are in good agreement. Thus the feasibility of the proposed starting method of induction motors with a shunt capacitor to improve the voltage dip is proved.

Discrepancies between computed and measured results can be attributed to several factors, incidentally:

1. The neglect of saturation effects in the mathematical model.
2. The approximation in measuring the motor parameters.
3. The variations of rotor parameters with frequency.
Figure 5.4: Measured Feeder Current During First Few Cycles with (a) Start Capacitor (b) RC Circuit.
Figure 5.5: Measured Feeder Current with RC Circuit and PFCC.

Figure 5.6: Measured Voltage Dip with RC Circuit and PFCC.
Chapter 6

CONCLUSIONS

This thesis proposes an improvement in voltage sag by suggesting an alternative induction motor starting method. In this method, a motor is started with a shunt capacitor. Dynamic models have been developed for feeder-capacitor induction motor using using Park's $d-q$ axis model. These models are ideally suitable for computer simulation and the transient performance can be computed using standard numerical techniques.

Two capacitors are considered for voltage dip improvement: power factor correction capacitor and start capacitor. The start capacitor is determined to maximize the input impedance during starting. The power factor correction capacitor is determined to improve the steady state operating power factor of the motor. Computer simulation and laboratory experiments are conducted on a three phase induction motor to validate the proposed starting methods. Comparison of the effects of both the PFCC and RC circuit in the laboratory experiments and computer simulation lead to the following conclusions:

- The power factor correction capacitor improves the voltage dip and motor acceleration significantly. This capacitor is not optimal for voltage dip improvement because it is selected based upon the steady state power factor.

- The start capacitor is very effective in voltage control. However, it increases the wave
form distortion during the first few cycles of motor starting. The distortion can be
damped by suitable damping resistance.

• When the induction motor is started with a start capacitor and damping resistor, the
line current starts increasing as the motor starts picks up speed. A centrifugal switch
should be used to disconnect the RC circuit and connect the PFCC when the motor
reaches a predetermined speed.

• The RC circuit and PFCC improves the start-up time of the motor.

The simulation results are found to be in agreement with the experimental results, thus val­
idating the proposed model. Therefore, it is concluded that the proposed method improves
the voltage dip considerably without affecting the starting torque of the induction motor.
Bibliography


