CHAPTER 1
INTRODUCTION

1.1 GENERAL

A recent trend in industries is the increased use of shunt capacitors for the starting, braking and power factor improvement of induction motors. Motor horsepower rating alone does not define the suitability of a motor for use in a particular application. For squirrel cage induction motors this rating defines only the continuous output capability of the motor. The starting capability is another requirement. The motor may drive the load successfully, but may not start properly. A careful selection of starting scheme for the motor is of great importance. Capacitor starting scheme of medium size motors is a well established practice with proven benefits. It is one of the few starting schemes that maintains the rated voltages at the motor terminals, resulting in ample acceleration torque, while minimizing voltage disturbances on the main bus and primary service.

The braking of induction motors is an important aspect of drive systems, when sudden stopping is demanded either due to an emergency or from an operational point of view. Development of fast braking systems for three phase induction motors used in industrial drives has been a subject of continuous study over the years. Almost instantaneous braking can be achieved by connecting suitable capacitor banks at the terminals of induction motor. A successful braking is assured by matching the motor, capacitor and the self-excitation current.

The introduction of industrial tariffs incorporating power factor penalties has made power factor correction a matter of paramount importance to the industrial consumers. This requires that the source of capacitive kilovars (kvar)
should be as close to the load terminals as possible. Shunt capacitors are being increasingly employed as a means of correcting the load power factor.

The conventional hardwired logic/control circuits when used for the above mentioned applications are quite involved and require many discrete components for their implementation thus affecting the reliability of the circuit. Further, any upgradation of the system on a later date is very difficult in hardwired logic. The hardware requirements of any scheme can be reduced by the use of a microprocessor, thereby increasing the reliability of the circuit. The microprocessor based control being completely digital in nature, is very accurate and immune to environmental changes. In the recent past only a few works related to the area of microprocessor control for the above said applications have been reported in the literature.

1.2 GENERAL PRINCIPLES OF STARTING

The following is a brief account of the general principles that govern the start of a motor. The aim of each different starting method is to minimize the voltage drop at the motor terminals and at the utility bus, or to provide a soft start for the driven equipment while still providing adequate accelerating torque to the driven equipment. Depending on the requirements and the characteristics of the utility network, criteria for selecting a starting method is chosen. The following general principles apply as per literature (W.E.Shula 1974; S.P.Schloot 1975).

* The equivalent circuit for each starting method is a series connection of a number of impedances to which the network voltage is applied. During start these impedances are mainly reactive. The voltage across each of the impedances and the motor during start is a function of their individual values.
The current drawn by the motor will also be reactive and will be reduced linearly with the voltage drop encountered in the circuit. Consequently, a reduction of current in the circuit during start will improve the available terminal voltage at the motor.

The type of motor selected affects the inrush current in the motor circuit. Induction and synchronous motors have different reactances and inrush currents. Table 1.1 indicates typical ranges for reactance and inrush current for each motor type as given in the report (Joseph Nevelsteen 1989)

Another factor in the selection of a starting method is the voltage drop permissible at a given location. The motor needs to develop sufficient starting and acceleration torque in order to successfully reach operating speed without overheating. The motor starting torque is reduced by the square of the voltage remaining across the motor during start. Adequate break away torque needs to be guaranteed to accelerate the driven equipment.

The magnitude of the voltage drop during starting of a motor is a function of the following variables:

a. inrush current of the motor
b. minimum available short circuit capacity of the utility network
c. impedance of the circuit from the network to the motor.

1.3 EXISTING CAPACITOR START INSTALLATIONS

Houston Lighting and Power Company at Texas, U.S.A. has six capacitor start installations in operation throughout the system. The first such installation was built in 1967 to serve a 400 hp, 2.4 kV, Code J motor. The distribution
<table>
<thead>
<tr>
<th>Motor Type</th>
<th>Number of Poles</th>
<th>Reactance (percent)</th>
<th>Inrush Current (p.u)</th>
</tr>
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<tbody>
<tr>
<td>Synchronous</td>
<td>2</td>
<td>14-21</td>
<td>7.1 - 4.8</td>
</tr>
<tr>
<td>Synchronous</td>
<td>10-28</td>
<td>22-26</td>
<td>4.5 - 3.8</td>
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<tr>
<td>Induction</td>
<td>2</td>
<td>20-22</td>
<td>5.0 - 4.5</td>
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<tr>
<td>Induction</td>
<td>4</td>
<td>18-23</td>
<td>5.6 - 4.3</td>
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<td>10-28</td>
<td>21-25</td>
<td>4.8 - 4.0</td>
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system serving this motor consisted of a 5 MVA substation transformer, six kilometers of 12.47 kV feeder, and three 167 kVA, 7.2 - 2.4 kV transformers as per report (John H. Stout 1978). The voltage dip was 500 V at the substation bus and 1000 V at motor site without capacitor start. The voltage dips at the above points were almost eliminated with capacitor start.

In 1978, for the above concern, another capacitor start system was installed. This system consists of 3.15 Mvar capacitor bank serving a 1500 hp motor. The distribution system serving this motor consisted of a 42 kVA substation transformer, five kilometers of 12.47 kV feeder and 3.7 MVA, 12.47 - 2.4 kV transformer. The voltage dip produced by starting without capacitors was approximately 780 V. With the capacitor start, the maximum sustained dip was 480 V.

Another example of a large horsepower installation with extremely tight voltage dip restrictions is the LOCAP Pipeline 8000 hp, 13.2 kV induction motor at Clovelly Station in U.S.A. A maximum of ± 1.5 percent voltage variation is permitted by the power company at the substation primary. The values of the three starting capacitor banks used are 11.5 Mvar, 9.9 Mvar and 9 Mvar as shown in the paper (William H Nichols 1984).

1.4 NEED FOR AN IMPROVED METHOD OF BRAKING

Most of the braking methods so far developed have not proved suitable for many present-day requirements. One of the major problems in designing modern high-speed machines is that of stopping the machine in the shortest possible time either for an emergency or in order to comply with certain prescribed limits of position for a process or product being made. Two examples are cited here as given in report (S.A. Choudhury 1964).
a. The positioning of aircraft on test in a wind tunnel: The platform supporting the aircraft was not only to be movable in various directions but also was to be capable of stopping suddenly when a predetermined position had been reached. The mobile platforms were driven by a selsyns. Plugging was tried out and proved to be too severe for the system, causing the selsyns to pull out of synchronism. There was no space for a mechanical brake.

b. The operation of a motor driving a saw for cutting logs: It was necessary to stop the motor frequently and d.c. injection braking was applied. Considerable overheating was produced in the motor by this method of braking.

These examples highlight the need for an improved method, which can be applied easily and used frequently and produces almost instantaneous braking. In the improved method, terminal capacitors are used to provide high self-excitation and the regenerated energy is dissipated within the motor itself as ohmic loss, core loss and mechanical losses as per literature (E.D.Basset 1935; A.Srinivasan 1947; T.V.Sreenivasan 1959).

1.5 SUCCESSFUL APPLICATIONS OF CAPACITIVE BRAKING

Among many successful applications of capacitive braking the following examples as given in the paper (S.A.Choudhury 1964) are of interest:

(a) an emergency stop has been achieved, within 3.81cm peripheral movement of 40.64 cm diameter rollers weighing 12 tonnes, driven by 40 hp motor and revolving once in three seconds.

(b) a small motor has been stopped within 0.75 revolution (0.1 sec from a speed of 1500 rpm).

(c) a multi-motor drilling machine has been stopped every 5 seconds.
(d) an accuracy of positioning of ± 2.5 mm has been obtained on a machine tool which must be stopped within 25.4 mm.

(e) a conveyor being stopped every eight seconds showed a fourfold improvement in positional accuracy compared with mechanical braking.

(f) a 600 Hz motor running at 36,000 rpm was stopped in only 3½ seconds.

The above applications highlight very well, the efficiency and scope of capacitive braking.

1.6 CONTROLS FOR SWITCHED CAPACITORS

1.6.1 Different ways of sensing circuit conditions

Though industries are less likely to employ switched capacitor banks than utilities, increasing emphasis on maintaining a high plant power factor to achieve minimum purchased power cost may lead to increased application of switching controls as presented in the literature (N.E.Dillow 1952; J.A.Sainz 1958).

There are a variety of ways by which circuit conditions can be sensed and switching actions initiated. Time, voltage, current, kilovars can be utilized in order to add or remove capacitors from the system to meet varying conditions. To utilize the capacitors most effectively and to select the most suitable control, the daily and weekly variations in the circuit conditions should be known. This also includes the time of the day when change can be expected and the magnitude of change in terms of current, voltage, and kilovars. Some of the most commonly encountered controls and some of the factors in their selection and application are discussed in the following section.
1.6.2 Time-switch control

Time-switch or time-clock control is one of the most common types of control used with switched capacitor banks. The control simply switches the capacitor bank on at a certain time of the day and takes it off at a later time. Its greatest application is with small single-step banks where the daily load cycle is known and consistent.

A carry-over device is required for each time-clock to keep the clock running at the time of temporary power outages. Most carry-over devices are of the mechanical spring type and can keep the clock running for up to 36 hours. The spring is continually kept in a wound position by the small electric motor which runs the clock. During a power outage, the spring begins to unwind. If power is restored before the carry-over period has passed, the motor restores the spring to its wound position. If a carry-over device is not used, a manual reset is necessary at each capacitor location affected by a power outage.

An omitting device is also required for each time-clock to omit switching the capacitors on or off on Sundays and holidays. On some feeders there may be a definite reduction in feeder loading on these days. If the capacitors were switched on, overvoltage could result as per reports (W.C. Bloomquist 1945; R.E. Marbury 1949).

1.6.3 Voltage control

Voltage can be used as a source of intelligence, only when the switched capacitors are applied at a point where the circuit voltage decreases as the load increases. Voltage is the most common type of intelligence used in substation applications. It has the advantage of initiating a switching operation only when the circuit voltage conditions request an operation, and is independent of the load cycle.
1.6.4 Current control

Current control is used when voltage is not a satisfactory signal. Such applications would be at locations where the voltage reduction with increase in load, is not enough for effective relaying.

The important applications of current control are with single-step capacitor banks applied on feeders or in substations where large intermittent loads occur as per reports (W.C. Bloomquist 1950; N.L. Kuster 1980).

Current control relays are similar to voltage control relays and can be either of the solenoid type or of the induction-disc type. The solenoid type is most often used with large substation capacitor banks, while the induction-disc type is used with smaller single-step capacitor banks. The current transformer should always be connected on the load side of the capacitor bank in order to measure load current, excluding the capacitor current.

When using current control, no recognition is given to the voltage conditions of the circuit. Therefore, circuit voltage conditions throughout the load cycle must be known in order to make sure that the capacitors are not switched on, if overvoltage conditions occur.

1.6.5 Kilovar control

Kilovar sensitive controls are utilized at locations where the voltage level is closely regulated and not available as a control variable. This can occur on an industrial bus which is served by an on-load tap-changing transformer or a generator system with automatic voltage regulators. In these cases, the capacitors can be switched to respond to decreasing power factor as a result of change in system loading. This type of control can also be used to avoid a utility power factor penalty clause, by adding capacitors, when the system power factor begins to lag.
Since the kilovar control requires two inputs, both current and voltage, it will have a higher cost than a single-input control. Thus, if a single step of switching is all that is required, the needs may be met satisfactorily by a current sensitive control. If power factor needs to be more accurately controlled, particularly if several steps are involved, then the kilovar control will be used as given in papers (N.E.Dillow 1952; L.Gyugyi 1976).

1.7 CAPACITORS AT LOADS

The sizing and control of capacitors that are sought by many users have been fostered in part by the historical development as given in reports (I.B.Johnson 1955, H.M. EL-Bolok 1990).

* 1930's : In the early days of capacitor switching with motors, the aim was to get maximum power factor at full load. Capacitor kvars were matched with the demands, but incidents of motor damage led the AIEE and NEC to recognize that these were caused by overvoltage.

Motors driving high-inertia loads, when taken off the line, would generate voltage several times the normal value if excited by large capacitors. In those days, motors did not protect themselves by saturation. In order to protect them, National Electrical Code states: 'The total kvar rating of capacitors which are connected to a motor should not exceed the value required to raise the no-load power factor of the motor to unity'.

Although this rule drastically reduced the amount of capacitance applied to many motors, the practice was still quite economical as indicated by the increased acceptance of the concept. Power factor was typically brought to 90-95 percent at full load.
Tables were published, by NEC showing "permissible" value of capacitance for various horsepower and speed ratings. They were adopted "wholesale" in some industries such as machine tools, process equipment, and many building factory drives. The economisation was welcomed.

* 1950's: Further economisation came from the decrease in cost of small capacitors. It enhanced the applications of small capacitors for individual motors instead of whole plant correction with large capacitor banks.
* 1960's: The concept of adding capacitance was at first overlooked when U-frame and then T-frame motors became prevalent. These motors used materials which saturated at low enough levels, so that the voltage developed by the induction machine was usually acceptable.
* 1980's: Widespread use of "metallized" capacitors was in sight. This resulted in some improved features; smaller power losses, less weight, lower cost and greater volumetric efficiency.
* 1990's: Increased use of microcomputers for better flexibility and reliability is in progress.

1.8 LITERATURE REVIEW

Self-excitation of induction motor is regarded as a resonance phenomenon in the oscillatory system consisting of the shunt capacitor and equivalent inductance of the motor. In most practical circumstances, such self-excitation is undesirable as it can cause severe overvoltages stressing the insulation of the machine as shown in papers (J.Nanda 1977; Bhim Singh 1982; Edward L. Owen 1983; N.H. Malik 1990). Development of effective protection system against self-excitation has been a subject of continuous study over the years. Use of zinc oxide limiters as given in literature (William H. Nichols 1984), series resistance as adopted in literature (C.F. Desience 1965, C. Chellamuthu 1991) and U-frame and T-frame motors instead of Pre-U-frame motors as
pointed out in literature (Myron Zucker 1985) are some of the protection methods being employed.

H.W. Cory and T.F. Bellinger (1955) have advocated full voltage starting of induction motors, when the line and load conditions allow. Reduced-voltage motor starters are used only when the distribution system cannot maintain its voltage, during the motor starting or when the driven load cannot stand the shock of a sudden start. Conveyors, elevators, hoists, feeders and certain machine tools frequently fall into the latter group of loads as shown in paper (S.K.Sen 1976).

Joseph Nevelsteen and Humberto Aragon (1989) have evaluated the available starting methods for ac motors, focusing on technical and economic aspects. They have claimed that a capacitor start provides a capability to cancel out a large portion of the reactive current drawn by the motor during acceleration. This can reduce the circuit current during start with improved terminal voltage at the motor. But they have not mentioned anything about the stepped capacitor starting scheme. It is very essential to have stepped capacitor scheme because it is not possible to remove all the capacitors in one step and stay within the required voltage limits.

John H. Stout (1978) has presented the basic requirements of a capacitor starting system to reduce voltage flicker during start-up of ac motors. He has given the test results from the several existing capacitor start installations at the HOUSTON LIGHTING AND POWER COMPANY in TEXAS, USA, but he has not mentioned anything about the stepped capacitors during starting.

Three-step capacitor starting has been attempted as per paper (William H. Nichols 1984) to keep the primary voltage fluctuation within the allowed ± 1.5 percent in the 8000 hp, motor starting scheme at the LOCAP PIPELINE CLOVELLY STATION in USA. Of the three possible variables (current, speed and voltage), William H. Nichols (1984) has sensed the motor
current in order to get the time for switching off the capacitors. He has also recommended the speed parameter as the most accurate variable which can be used to switch off the capacitors.

Any starter scheme should have built-in-protective features, like overload protection, singlephasing protection and phase sequence protection. But the papers (H.W.Cory 1955; John H.Stout 1978; and Joseph Nevelsteen 1989) have not reported any such protection schemes.

William H. Nichols (1984) has attempted to have protection features with costly schemes. For example, a phase failure relay may cost 20 percent or more as that of a 100 hp motor and may even be costlier than a 10 hp motor as given in the literature (Warded Garry 1975).

The present downward trend in the cost of large scale integrated circuits is encouraging the use of microprocessor in the application of protection of motors. Apart from low cost, the advantages of microprocessor based protective relaying also include flexibility and small size. Many authors (Badri Ram 1986; M.A. Al-Nema 1986; and Mahmoud A.Manzoul 1990) have attempted only the microprocessor based overcurrent relays for protection. But it is possible to develop a single multifunction unit to provide total integrated motor protection as per literature (A.J.Kellogg 1982).

For the capacitor starting scheme, improved speed measurement is needed. Conventional analog control methods suffer on several accounts, including nonlinearity in the analog speed transducer and difficulty in accurately transmitting the analog signal after it has been obtained from the transducer as per report (Timothy J. Maloney 1976). Also, while manipulating the signal to effect control action on the motor, errors are incurred which are related to temperature, component ageing, and extraneous disturbances as given in paper (John Hawkins 1972). R.R.Sule (1985) has reported that a digital speed control system is superior because there is no nonlinearity in the speed
transducer and the digital signal representing speed can be transmitted over long distances with no degradation of the original accuracy. Also the digital control signal is not subject to temperature variations, component changes, or noise.

Two digital methods to measure rotational speed are generally reported in the literature. The first method involves the measurement of time between successive slots of a disc attached to the shaft under study as given in papers (A. Dunworth 1969; Carlos F. Christiansen 1989). In this case, the sampling period varies with speed; the time information must be processed in order to obtain speed information and the low speed readings become too slow. The second method involves the count of number of pulses, over fixed intervals of time provided by a uniformly spaced slotted disc attached to the shaft under test as shown in report (C.Chellamuthu 1991).

S.A. Choudhury and S.P. Hastings (1964) have given examples for many successful applications of capacitive braking. But they have not tried any analytical procedure to predetermine the braking performance.

The general theory, the price and the various methods of braking of ac machines have been compared by J.C. Gosling (1967).

The machine behaviour under capacitive braking has been analyzed in reports (S.Sreenivasaamurthy 1984, Ajay K. Tandon 1984) using instantaneous symmetrical components and the associated operational equivalent circuits. R.Perryman (1971) has avoided this long and tedious method of analysis by selecting the equivalent circuit as suggested by N.N. Hancock (1967). But he has advocated a better solution to avoid the ambiguity faced by him. Hence improved method of analysis is needed to obtain the solution without any ambiguity as per literature (C.Chellamuthu 1990).
To improve the power factors of induction motors, different schemes have been developed time-to-time by many investigators. Frank J. Nola (1984) has developed at USA, a three phase power factor controller using phase controlled antiparallel thyristors. In this scheme reduced voltage is applied under light load conditions to reduce magnetising current in order to improve the light load power factor. Obviously, this scheme is not suitable for full load conditions.

Another method of power factor correction of induction motors has been designed as given in the paper (Eduard Muljadi 1989) using specially wound induction motor equipped with two electrically isolated but magnetically coupled stator windings. The auxiliary winding with a pulse width modulated (PWM) inverter will supply excitation power to the machine. The main winding of the induction machine can be controlled to carry only the active power while the auxiliary winding carries only the reactive component. Here the PWM inverter with dc capacitor is modelled as an equivalent ac capacitor. The main shortcoming of this scheme is that it requires specially wound induction motors. Also, the large harmonic content in the inverter currents will result in pulsating torques as per reports (Raj C. Yalamanchili 1990; T.Choudhury 1991).

In 1914, fixed shunt capacitor banks were first used for the improvement of power factor. But fixed capacitor banks yield constant reactive power and is therefore only suitable for plants having a relatively constant reactive power consumption. The authors (Timothy R. Feldman 1984; S.A. Nasar 1987) feel that these fixed capacitor banks can cause problem at light load conditions. To meet the variable reactive power consumptions, N.S.Saxena (1982) has developed a switched capacitor scheme with hardwired logic. But this scheme does not provide any control for over compensation. To have the control for over compensation S.B.Dewan (1980) has suggested thyristor controlled reactors along with switched capacitors. S.E.Haque, N.H.Malik and W.Shepherd (1985) have developed a scheme with fixed capacitors and thyristor controlled reactors.
They have calculated the change in power factor as a change in load voltage. This is not a faithful representation, hence the correction is not very accurate as per report (H.M. El-Bolok 1990). A recent method (R.P. Gupta 1990) uses a quite involved technique to compensate reactive power. This method requires many discrete components for the implementation.

In the papers (M.F. McGranaghan 1982, L. Zhaohui 1990, S.E. Zocholl 1990 and K.E. Addoweesh 1990), it has been proclaimed that the digital control using microprocessor is preferable over the analog scheme when more versatile, flexible and on-line controls are required.

1.9 OBJECTIVE OF THE THESIS

The above survey of literature brings out the need for the present work. The objectives of the thesis are:

* Development of a full voltage starting scheme for induction motor with switched capacitors. Speed variable has been selected to switch off the capacitors instead of current variable in order to improve accuracy. It is also aimed to provide economical and total integrated motor protection. It is also aimed to propose a simple protection scheme to avoid overvoltage due to self-excitation.

* Presentation of a simple and effective analytical method to predetermine the performance of braking of induction motor using shunt capacitors.

* Development of an accurate power factor controller using switched capacitors and three phase thyristorised inductance for induction motor with minimum hardware.
1.10 ORGANIZATION OF THE THESIS

The research work carried out are presented in six chapters in this thesis and is delineated in the approach flow diagram as in Figure 1.1. The first chapter briefly reports the review of literature which necessitated the scope of the present work.

The second chapter deals with overvoltage due to self-excitation and inrush current due to capacitor switching. Self-excitation is a condition, which if not adequately considered, adds complexity to the installation and negates the simplicity concept on which the selection of machine type has been based. It is important to understand the conditions under which self-excitation can occur so that protective measures can be taken to avoid either self-excitation or the possible overvoltage consequences should it occur with self-excitation. This high voltage across the capacitors may drive large currents in the machine windings, though for a short time, which may contribute towards winding failure. Different protection schemes are listed in this chapter to limit overvoltage due to self-excitation. A simple protection scheme using series resistance is also proposed. This chapter discusses the ability of a switch gear to interrupt short circuit currents and its ability to switch capacitance current. Introduction of series inductances limit the inrush currents due to capacitor switchings.

Development of capacitor starting with necessary protection schemes forms the main theme of the third chapter. Digital speed sensor has been developed for cutting off capacitors at required speeds. The capability of capacitor starter to cancel out a large portion of the reactive current drawn by the motor during acceleration, thereby limiting the voltage dip at main bus has been studied. An economical protection scheme with minimum components has also been developed to provide protection against overload, single phasing and incorrect phase sequence.
An analytical procedure is outlined in chapter four to get solution without any ambiguity to predetermine the braking performance of induction machine using capacitors. Experimental results are compared with analytical results. Experimental procedure is also given to select capacitor values for braking.

The automation of any modern power system is inevitable due to the increase in its complexity and sophistication. The control of power factor plays a vital role in determining the regulation and the efficiency of electrical system. The control design objective is to get capacitors on and off the line as and when needed. In chapter five, an automatic power factor controller using microprocessor for induction motor is developed with minimum hardware. The microprocessor with switched capacitor banks along with thyristorised phase controlled inductance controls the power factor accurately.

A comprehensive summary of conclusions obtained from this research work is presented in the sixth chapter.