

THE APPLICATION OF SERIES CAPACITORS TO REDUCE MOMENTARY
VOLTAGE DROP DUE TO INDUCTION MOTOR STARTING
ON A THREE PHASE RADIAL FEEDER

by

Alonso Rodriguez Peña

A Thesis Submitted to the Faculty of the
DEPARTMENT OF ELECTRICAL ENGINEERING
In Partial Fulfillment of the Requirements
For the Degree of
MASTER OF SCIENCE
In the Graduate College
THE UNIVERSITY OF ARIZONA

1 9 7 7

STATEMENT BY AUTHOR

This thesis has been submitted in partial fulfillment of requirements for an advanced degree at The University of Arizona and is deposited in the University Library to be made available to borrowers under rules of the Library.

Brief quotations from this thesis are allowable without special permission, provided that accurate acknowledgment of source is made. Requests for permission for extended quotation from or reproduction of this manuscript in whole or in part may be granted by the head of the major department or the Dean of the Graduate College when in his judgment the proposed use of the material is in the interests of scholarship. In all other instances, however, permission must be obtained from the author.

SIGNED: _____

Gloria Rodriguez Leiva

APPROVAL BY THESIS DIRECTOR

This thesis has been approved on the date shown below:

R. N. Carlile

R. N. CARLILE

Professor of Electrical Engineering

SEP. 30, 1977

Date

To my family

ACKNOWLEDGMENTS

I am indebted to the Institute of Electrical Research in Cuernavaca, Morelos, Mexico, for permitting me to perform this study at their facilities. In particular, I am grateful to Dr. Carlos Treviño and Dr. Fernando Schutz for all their helpful suggestions and encouragement. No less important in helping me complete this project was Dr. R. N. Carlile, my adviser and friend.

TABLE OF CONTENTS

	Page
LIST OF TABLES	vi
LIST OF ILLUSTRATIONS	vii
ABSTRACT	viii
1. INTRODUCTION	1
2. OTHER SOLUTIONS	10
3. BASIC APPLICATION THEORY OF SERIES CAPACITORS	16
4. DESCRIPTION OF THE MATHEMATICAL MODEL USED	25
5. USE OF THE COMPUTER PROGRAM SRCP	37
6. PROTECTION OF THE CAPACITOR BANK	46
7. CONCLUSIONS	57
APPENDIX A: BANK FORMING EXAMPLES	59
APPENDIX B: SAMPLE COMPUTER RUN	61
NOMENCLATURE	69
LIST OF REFERENCES	71

LIST OF TABLES

Table		Page
1.	Rated Voltages	2
2.	Voltage Limits	3
3.	Voltage Variation Limits for Motors	4
4.	Effects of Voltage Variation on Motors	5
5.	Effect of Motor Starters on Voltage, Torque, and Current . .	13
6.	Shunt Capacitor Ratings (Individual Units)	42
7.	Capacitor Equipment for 60 Cycle Operation	43

LIST OF ILLUSTRATIONS

Figure		Page
1.	E'_S Becomes Smaller than E_S as IX_C Increases	18
2.	Error of Approximate Voltage Drop Formula	19
3.	Overcompensation with Series Capacitors during Motor Starting	21
4.	Use of Series Capacitors with a Leading Power Factor	22
5.	Information Transfer Block Diagram	27
6.	General Radial Circuit	28
7.	Equivalent Form of Radial Circuit and Motor Being Studied	30
8.	Simplified Flow Diagram	32
9.	Effect on Motor Terminal Voltage of Increasing Series Capacitive Reactance	34
10.	Typical Protective Scheme	48
11.	Protective Scheme with Motor Operated Switch	48
12.	Protective Scheme Employing the Feeder's Breaker	50

ABSTRACT

This is a study conducted to arrive at the necessary application engineering information and data to be able to successfully apply series capacitors at the distribution level as an alternative solution to reduce flicker caused by motor starting. The problem is usually seen at installations where squirrel-cage induction motors are started across-the-line, and upon starting the power supply is oversized by the normal loads plus the inrush current. Guidelines and recommendations are given to calculate and apply series capacitors, including a computer program which improves efficiency and accuracy.

CHAPTER 1

INTRODUCTION

One of the standards of the quality of service of a distribution power system is the ability to maintain a nominal voltage at the terminals of all connected power-consuming devices with a minimum of variation and at the lowest possible cost. Modern equipment and processes require that this voltage be kept within acceptable limits of the equipment's rated voltage. This is one of the principal problems in practical power systems and several methods for the design and operation of the system have been developed to reduce such variations.

To discuss voltage regulation, a review of the terminology involved in voltage identification at various points in the system is helpful to avoid confusion. Historically, system voltages have been incremented as needed to compensate for voltage drop, resulting in slightly higher voltage ratings for equipment at the source end of the system. When referring to equipment, the rated voltage is used; and within a system, several different voltage ratings for different equipment may be found. For the system or circuit voltage, the voltage class is designated by the nominal system voltage identification. These terms do not guarantee that a device in a particular voltage class will have the same voltage rating. The following table summarizes the system and equipment voltage identification scheme generally accepted and used in distribution systems (Table 1).

Table 1. Rated Voltages.

Nominal System Voltage	Generator Rated Voltage	Transformer Secondary Rated Voltage	Transformer Primary Rated Voltage	Motor and Control Rated Voltage*
<u>Single-Phase Systems</u>				
120 or 120/240	120 or 120/240	120 or 120/240	120	115
240 or 120/240	240 or 120/240	240 or 120/240	240	230
208Y/120	208Y/120	208Y/120	120	115

<u>Three-Phase Systems</u>				
208Y/120	208Y/120	208Y/120	208 or 120	220 or 208
240	240	240	240	220
480	480	480	480	440
600	600	600	600	550
2,400	2,400	2,400	2,400	2,300
4,160	4,160	4,160	4,160	4,000
4,800	4,800	4,800	4,800	4,600
6,900	6,900	6,900	6,900	6,600
12,000	12,500	12,000	12,000	11,000
13,200	13,800	13,200	13,200	13,200
13,800	13,800	13,800	13,800	13,200
23,000	-	-	22,900	-
34,500	-	-	34,400	-
46,000	-	-	43,800	-
69,000	-	-	67,000	-
115,000	-	-	110,000	-

*Motor-control equipment should have the same voltage rating as the associated motor.

Voltage drops can occur either in a gradual varying manner or in a sudden momentary change of a transitory nature. Associated with the first type of voltage variation is a maximum and a minimum voltage value at any point in a distribution system under normal operating conditions. This voltage spread is caused by current flow through the feeder components such as transformers, conductors, buses, loads, etc., and/or by variations in the primary voltage supply which might be caused by voltage drops or regulation in the primary system. Tables 2 and 3 show the NEMA recommended limits of voltage spread at the terminals of a utilization device.

Table 2. Voltage Limits.

Nominal System Voltage	Commonly Used Utilization Device Voltage Ratings	Recommended Limit of Voltage at Terminals of Utilization Devices
208Y/120	115 or 120-1 phase 208 or 220-3 phase	197Y/114-217Y/125
240	220, 230	210-240
480	440, 460	420-480
600	550, 575	525-600

Table 3. Voltage Variation Limits for Motors.

Nominal System Voltage	Motor-Nameplate Voltage Rating	Recommended Limits of Voltage at Terminals of High-Voltage Motors	
		Minimum (-2%)	Maximum (+8% approx.)
2400	2200	2160	2380
2400	2300	2250	2480
4160	4000	3920	4320
4800	4600	4500	5000
6900	6600	6470	7130

The consequences of exceeding the above-given limits depend upon the characteristics of the device and its operation. In certain cases, more or less spread can be tolerated, i.e., a balance has to be reached between the effects of voltage variation on the life of the equipment and its performance. Table 4 summarizes the changes which typically occur in induction-motor performance as terminal voltage is varied $\pm 10\%$ of rated.

Since torque is proportional to the square of the voltage, a small voltage drop could be significant in the acceleration time of large loads. With low voltage, starting current will decrease; but the full load current increases, increasing temperature rise and thus shortening insulation life. On the other hand, high voltage increases torque which demands higher starting current, which in turn produces higher voltage drops in the system.

Table 4. Effects of Voltage Variation on Motors. -- From Beeman (1955, p. 206).

	Voltage Variation		
	90% Voltage	Function/Voltage	110% Voltage
Starting and maximum running torque	Decrease 19%	(Voltage) ²	Increase 21%
Synchronous speed	No change	Constant	No change
Percent slip	Increase 23%	1 (Voltage) ²	Decrease 17%
Full load slip	Decrease 1-1/2%	(Synchronous speed slip)	Increase 1%
Efficiency:			
Full load	Decrease 2 pts.	-	Small increase
3/4 load	Practically no change	-	Practically no change
1/2 load	Increase 1-2 pts.	-	Decrease 1-2 pts.
Power factor:			
Full load	Increase 1 pt.	-	Decrease 3 pts.
3/4 load	Increase 2-3 pts.	-	Decrease 4 pts.
1/2 load	Increase 4-5 pts.	-	Decrease 5-6 pts.
Full-load current	Increase 11%	-	Decrease 7%
Starting current	Decrease 10-12%	Voltage	Increase 10-12%
Temperature rise, full load	Increase 6-7°C	-	Decrease 1-2°C
Maximum torque capacity	Decrease 19%	(Voltage) ²	Increase 21%
Magnetic noise, no load in particular	Decrease slightly	-	Increase slightly

A component which is also frequently affected as the square of the voltage (approximately) is the A-C solenoid. There is no accepted standard for the design of solenoids used in motor control equipment with regard to drop-out voltage and time. For example, drop-out range in motor-starter contactors can occur from about 30% to 85% of rated voltage. This variation depends on the manufacturer, type, size, magnetic iron used, change in armature seating and contamination conditions, and, of course, time of duration of the voltage drop.

When the time of voltage variation is short, i.e., a few cycles or seconds at most, the sudden change is usually referred to as flicker, since flickering lights are one of the more noticeable and common effects of this voltage condition. In earlier days, this effect was only a nuisance due mainly to regulation in the utility's distribution system. Today the problem has greatly increased in importance because of the economic consequences involved and frequency of incidence. The majority of modern industrial equipment is electrically driven and controlled, requiring stricter voltage regulation. But, in turn, some of this equipment is connected to rapidly changing loads, which produce corresponding changes in current and voltage. In automated equipment, electronic and magnetic devices are the most sensitive to momentary dips.

Electronic components usually have some arrangement to protect it and assure normal operation during brief voltage variations. As mentioned before, this does not appear to be the case for solenoids. It has been found that most losses are due to undervoltage drop-out, which results in motor and other production equipment outage (Westinghouse

Electric Corp. 1965, p. 362). In practice, systems are sometimes designed to permit a drop as low as 22% at the terminals of a motor on starting, under the assumption that the solenoid coils will still operate satisfactorily at this voltage. A more conservative limit for drop-out voltage is considered (Beeman 1955, p. 213) to be 85% of rated (and 10% overvoltage).

Depending on the factors discussed before, drop-out will occur in a time varying from about one to twelve cycles. When the voltage dip is caused by a fault somewhere else in the system, clearance will, on the average, take about twenty cycles, so that the more conservative design tends to reduce the number of unnecessary outages due to faults, but the improvement in service continuity increases costs. Other solenoid-operated devices such as control relays, magnetic chucks, electrically operated valve, etc., will sense a voltage dip as an interruption in their voltage supply and, depending on the duration and magnitude of the change, the device might trip to its normal position since, in general, they are spring-loaded. (Since inrush current is typically about ten times normal current in a solenoid, the supply lines to these devices should be checked to see that undervoltage is not caused by lack of current-carrying capability.)

Flicker arising in the primary system may be caused by a variation in speed of engine-driven generators and by abrupt load changes in plants where sudden load increments are significant relative to the total installed generating capacity. Generator excitation will almost never

cause flicker because field time constants are usually too long to cause armature voltage to change rapidly.

Short circuits and switching will produce flicker. The design of the system as a whole will determine the magnitude of the drop, and the protection scheme will determine the duration.

Flicker originating in the generating plant or in the primary system will affect distribution regulation, and it is also at the distribution level where most flicker originates due to connected equipment. Commonly, the following equipment cause flicker: electric arc furnaces; electric welders; large electric shovels; heavy rolling mills; intermittent motor-driven loads having heavy overloads or long and irregular periods, like sawmills, coal cutters, punch presses, and shears; motor-driven reciprocating loads where the motor load varies cyclically, producing a corresponding current change, like in compressors, pumps, and refrigeration units; and motor starting, which is the origin of flicker in most cases. The effects associated with these rapid voltage fluctuations together with the voltage spread seen when load changes normally can thus limit circuit capacity before steady-rate regulation or thermal limits are reached.

It is this problem that is the subject of this study. In particular, the Instituto de Investigaciones Electricas (IIE; Electrical Research Institute) was contracted to arrive at application guidelines to use series capacitors to reduce momentary voltage drop due to induction motor starting at full voltage.

These motors are squirrel-cage type, ranging from ten to fifteen hundred HP, and are connected on three-phase radial feeders which are capable of handling normal load within allowable voltage drop, but too weak to carry the initial inrush current plus normal current successfully. Motors smaller than these usually present tolerable or no flicker, and motors larger than these are installed with adequate power supplies and lines; because of their size, they usually receive special attention. However, those in the middle range combined with other loads may outsize their power facilities. This situation is seen at out-of-the-way installations such mines, pumping stations, and industrial plants in rural or suburban locations, where lines are long or the transformers and lines were not intended to be used with loads added on at a later time.

CHAPTER 2

OTHER SOLUTIONS

Before discussing further the application of series capacitors, it makes economic sense to review briefly alternative solutions to the flicker problem, and keep them in mind when attacking a definite problem because, depending on local conditions, the technical and economic value of a solution changes.

If the origin of flicker is motor-starting, the most obvious remedy would be to install the correct starter. A-C squirrel-cage induction motors starting at full voltage may have an inrush current from about five to ten times full load, depending upon the size, speed, load, torque characteristics, and special application conditions. Starting power factor may vary from 10 to 50 percent. These conditions result in severe voltage drop when the design of the system does not allow for this type of momentary power demand. Full-voltage starting provides the most torque but applies the full-voltage starting KVA of the motor to the system which is equal to:

$$\text{KVA (Starting)} = \frac{(1.73) \times (\text{Starting amps}) \times (\text{Line-line volts})}{1000}$$

This is the least expensive method of starting.

To prevent flicker, the starter must then limit the initial high current and slowly increment it to make flicker unnoticeable. (It is

important to check that the correct size feeder lines are connected from the starter to the motor to avoid unnecessary drop there.)

Reactor starting involves connecting a reactor in series with the motor and shorting it out when full speed is neared. The current is reduced in proportion to the tap used and the torque is reduced by the square of the tap used.

When an autotransformer is used, the current is reduced approximately as the square of the tap setting plus allowance for the autotransformer magnetizing current. Tripping of instantaneous overcurrent protection may be caused by setting too low a tap, which will not permit acceleration of the motor to a speed at which current will not be excessive after switching to the running connection. Inrush current flows for a few cycles if the load torque is too high, giving rise to a voltage spike. Autotransformer starting costs more than reactor starting but may be set to provide more torque. Autotransformers are being used less because of the greater acceptance of across-the-line starting and because, in some cases, the two voltage dips caused by the autotransformer may be worse than only one larger dip starting at full voltage. Reactor starting will not create any significant transitory effects if the shorting-out operation is done when the motor is at a high enough speed.

With resistor starting, a resistor is inserted in series with the motor. The line-voltage drop is reduced a little because of an improvement in power factor, but the available torque varies the same as for reactor starting. Where electric utilities specify a maximum permissible KVA applied in one step, this type of starting is well suited, although

it is more expensive and requires more maintenance. Resistor starters have been used mainly with the smaller size motors, usually with a single-step resistor, which when shorted-out will not cause a noticeable dip. To adjust to individual cases, resistor starters should be variable. Changing from squirrel-cage to wound-rotor motors using this type of starter will also reduce flicker substantially but it is expensive.

For low-speed (514 RPM or less) motors, part-winding starting can be used at a cost comparable with autotransformer starting. The motors are provided with taps to apply power first to a portion of the winding and then in steps using increasing portions of the winding to connect the full winding to the line.

Current and torque are changed approximately in proportion to the amount of winding connected. This method provides a smoother transfer to the running connection.

A special type of starter is the increment starter, which is a combination of autotransformer and reactor starter. Switching is done without opening the circuit, increasing stator current in steps and switching out impedance remaining at full-load speed. This is a non-commercial, special purpose design. Table 5 summarizes the most commonly used starting methods.

In Mexico, there is as yet no specific regulation as to the type of starter that should be employed, nor a limitation on the maximum KVA applied per step. The Reglamento de Obras e Instalaciones Electricas (comparable to the National Electrical Code) requires reduced voltage

Table 5. Effect of Motor Starters on Voltage, Torque, and Current.

Type of Starter	Line Voltage Motor-Rated Voltage		
	Motor Voltage (Line Voltage)	Starting Torque (Full-Voltage Starting Torque)	Line Current (Full-Voltage Starting Torque)
Full-voltage starter	1.0	1.0	1.0
Autotransformer:			
80 percent tap	0.80	0.64	0.68
65 percent tap	0.65	0.42	0.46
50 percent tap	0.50	0.25	0.30
Resistor starter, single step (adjusted for motor voltage to be 80% of line voltage)	0.80	0.64	0.80
Reactor:			
50 percent tap	0.50	0.25	0.50
45 percent tap	0.45	0.20	0.45
37.5 percent tap	0.375	0.14	0.375
Part-winding starter (low-speed motor only):			
75 percent winding	1.0	0.75	0.75
50 percent winding	1.0	0.50	0.50

starting on all motors greater than 10 HP but, depending on the supply circuit, across-the-line starting can be used with any HP motor.

Besides series capacitors and motor starters, supply system changes can be an acceptable technical and economic solution. This possibility is more attractive when system capacity needs to be increased for the benefit of other loads or future growth; otherwise it could easily become the costliest method. The idea here is to stiffen the system as much as possible. One way is to separate the flicker-producing loads at the substation bus, if the customers causing the flicker can tolerate it and the dip is not large enough to show its effects through transformers, adding more transformer capacity, interconnecting to a stiffer circuit, relocating closer to the power supply, or paralleling lines.

When circuit impedance is decreased, there will be a corresponding reduction in voltage drop. The following system and process changes will aid in reducing impedance:

1. Closely spaced cables can be used instead of open, widely spaced conductors.
2. Buses can be made up of conductors of all phases instead of only one.
3. Two or more smaller size cables can be used in parallel instead of one large cable.
4. If short-circuit currents are not too high, transformer reactance can be reduced.

5. Load control is effectively impedance control. Today this method could be implemented much more easily with a load control micro-processor. Motor starting could be programmed in conjunction with load demand.

The three general alternatives given before are measures usually considered to be technically and economically acceptable in suppression of flicker due to motor starting. But local conditions always should dictate which correction method is the most appropriate for a particular case. A combination of two or more remedies might solve the problem even better and the following should also be considered: motor-generator set, synchronous condenser, flywheel, clutch, phase balancer, and compensating transformer. The setback with this equipment is that it is generally uneconomical for flicker reduction. Switched shunt capacitors and voltage regulators are too slow to minimize flicker and will only reduce voltage spread, so that combined with other equipment a corrective scheme could be devised.

CHAPTER 3

BASIC APPLICATION THEORY OF SERIES CAPACITORS

Series capacitor compensation is another method of reducing line impedance, thereby reducing voltage drop. The term "series capacitors" refers to the fact that the capacitor is connected in series with the load. There are specially built capacitors for series use, but regular shunt capacitors whose rating and protection is specified with care can be used with good results in series applications. This is what is planned for use in this project because only shunt capacitors are included in the standard inventory, they are much less expensive, and are the only type manufactured in the country. (Special series capacitors are more rugged and are rated both in continuous working current and a momentary current rating is specified in order to establish the maximum limit of operation.)

At the present time there are no series capacitor installations in Mexico at the distribution level. In the United States, their use dates back to March of 1928, on a 33 KV line to divide load equally between two branches of a loop circuit of the New York Power and Light Company (Buell 1937, p. 174). Since then, various installations to reduce flicker and to improve power factor on constant reactance loads have been put in service, but their number is relatively small. Widespread use has been limited by technical problems of a resonance nature,

although these can be eliminated with the proper engineering for each installation.

A series capacitive reactance in a line will compensate for the inductive reactance drop of the supply circuit by producing a voltage rise 180 degrees out of phase with the supply's reactive drop and in direct proportion to the line current flowing through the capacitor, leaving only a small resistance drop. The capacitive reactance can also be thought of as cancelling the inductive reactance of the supply circuit. This is shown in the vector diagram of Figure 1.

The same information can be deduced from the basic voltage drop formula for a feeder with lagging power factor:

$$E_S - E_R = (IR \cos \theta + IX \sin \theta) + j(IX \cos \theta - IR \sin \theta)$$

This equation can be simplified by neglecting the imaginary term because it represents a phase shift between the sending and receiving end voltages which is usually a negligible drop (Figure 2):

$$E_S - E_R = IR \cos \theta + IX \sin \theta$$

$$E_S - E_R = IR \cos \theta + I(X_L - X_C) \sin \theta$$

Analyzing the formula, it can be seen that when $IX_L \sin \theta$ is greater or equal to the desired voltage improvement, then the use of a series capacitor might be beneficial. With a low-power factor, $\sin \theta$ is large, as in motor starting, and in a typical distribution system X_L/R

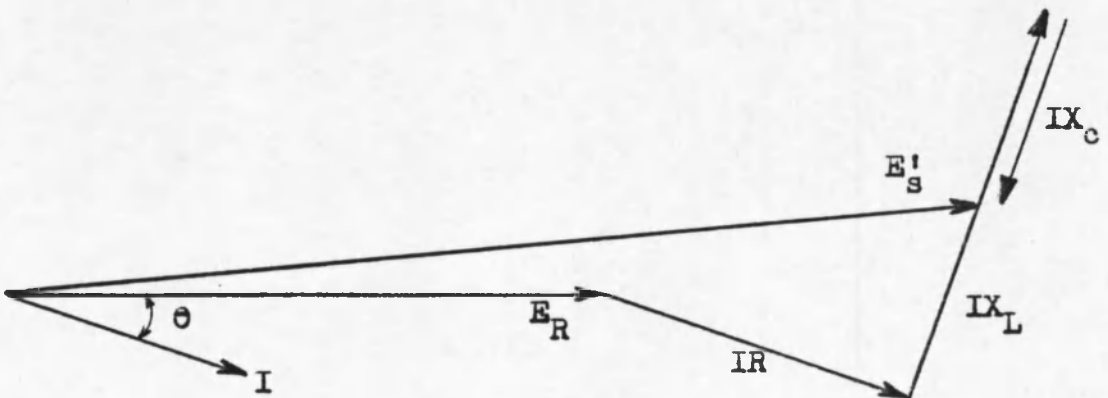
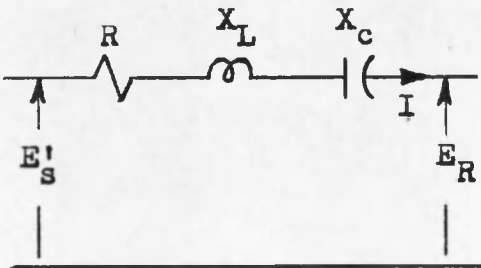
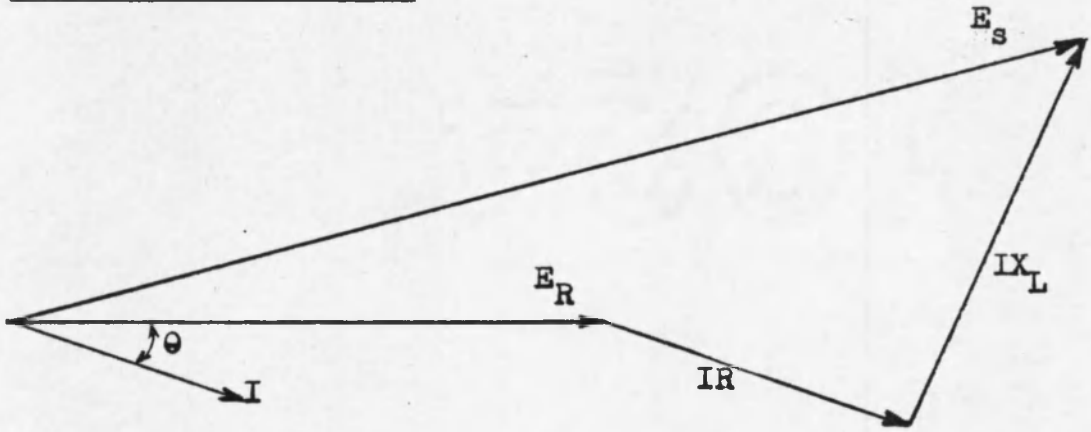
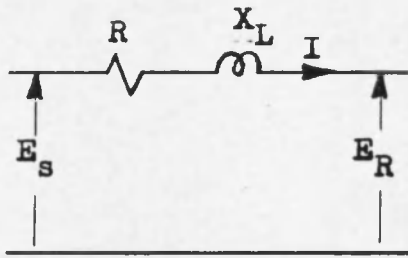


Figure 1. E'_s Becomes Smaller than E_s as IX_C Increases.

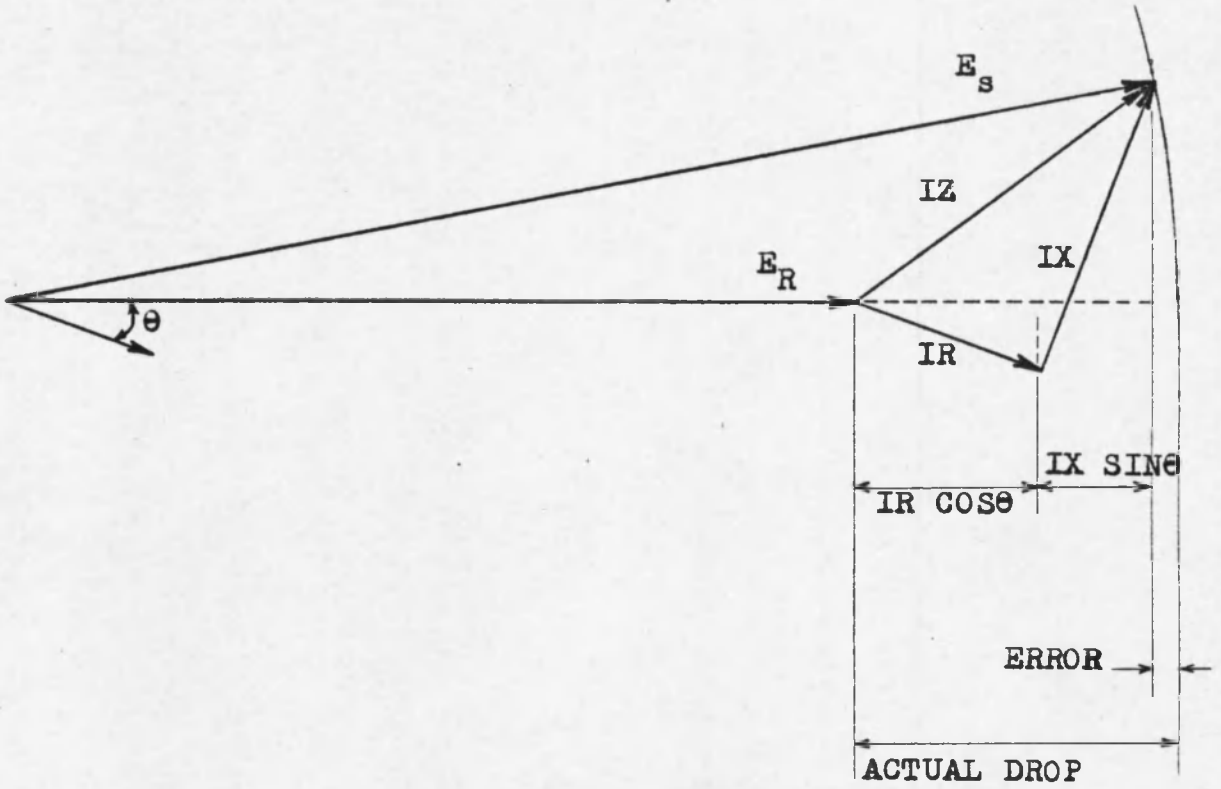


Figure 2. Error of Approximate Voltage Drop Formula.

ranges from about 3 to 10, making the second term the most significant portion of the voltage drop.

To be effective in improving voltage conditions on a general feeder, the R/X ratio should be less than one, and the power factor should be less than .90 and lagging. But it is possible to use series capacitors outside these limits by over-compensating for the line reactance. During motor starting, the lagging power factor angle and line current increase several times their normal values and the receiving end voltage might easily rise to an unsafe value (Figure 3). This is flicker, but in the opposite direction normally encountered. Over-compensation should be used with nearly constant reactance loads only or when power factor is low and its behavior can be reasonably known at all times.

If the power factor is leading, the receiving end voltage is reduced even more with the use of series capacitors (Figure 4).

A series capacitor produces a voltage rise which is proportional to the magnitude and power factor of the line current, i.e., the resulting voltage increases as load is increased. But the unique merit of the series capacitor is that its response to load changes is instantaneous, because it is in series with the load. Other types of regulating equipment will initiate corrective action when the voltage dip has appeared and then switch-in the required KVAR. There is a time lag involved which makes it impossible to correct momentary voltage drop satisfactorily. The series capacitor has no moving parts, so that it is practically maintenance-free and very reliable if applied correctly. It

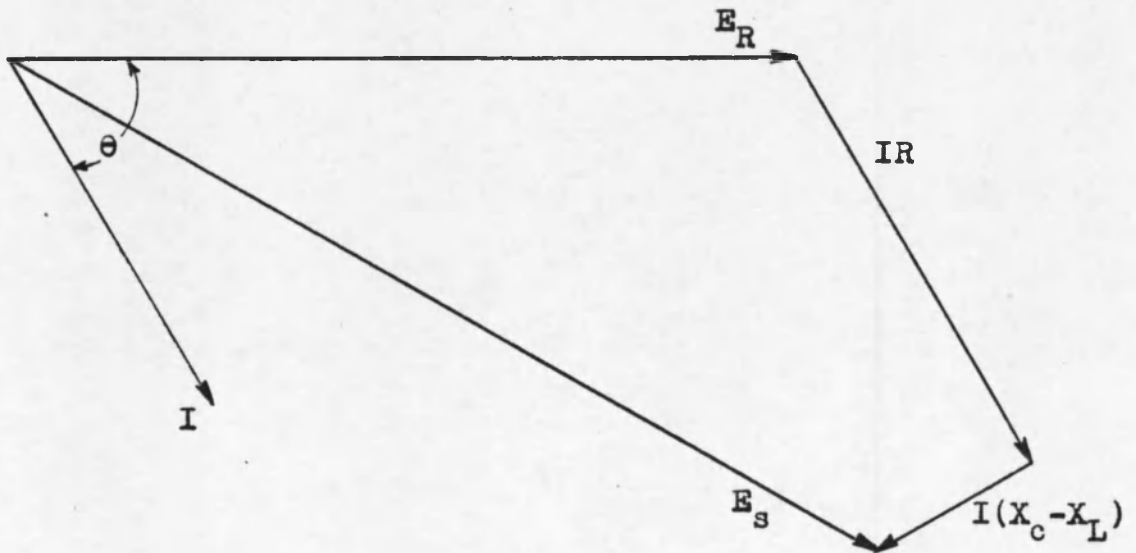
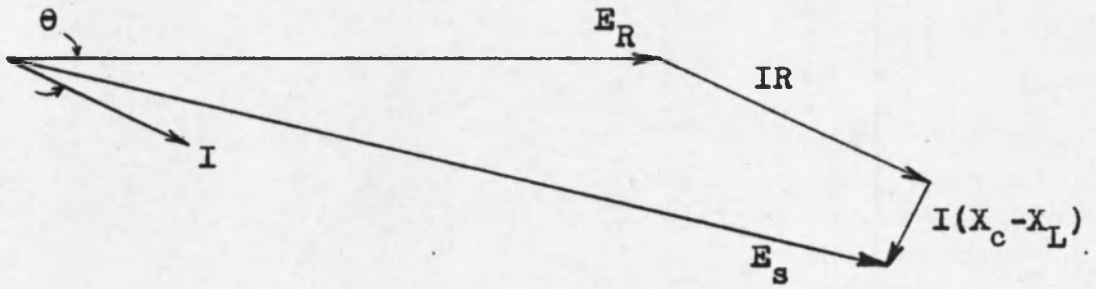


Figure 3. Overcompensation with Series Capacitors during Motor Starting.

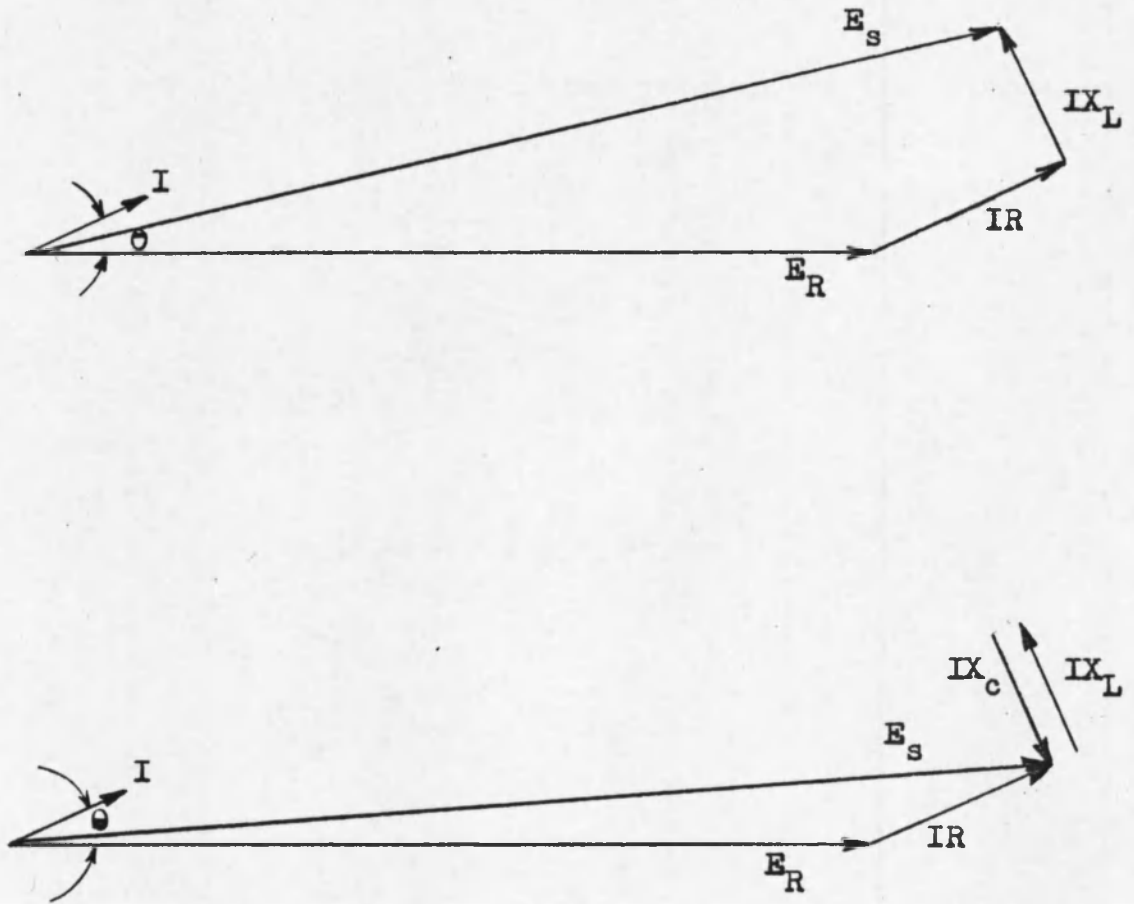


Figure 4. Use of Series Capacitors with a Leading Power Factor.

has very high operating efficiency, since losses are proportional to load. The losses are approximately 0.3% of capacitor rating at full load. Series capacitor installations take up relatively little space.

Another advantage obtained from the use of series capacitors is that, because of the rise in voltage at the receiving end, an increase in KVA capacity of the feeder will result. It is then often possible to postpone the extensive capital investment required in system equipment, such as new transmission lines, transformers, regulators, protection devices, right-of-way permits, etc., to supply additional loads. Today the savings in interest and taxes made by postponing even a moderate investment might pay, within a very short time, for the series capacitor installation. In voltages approaching the subtransmission level, such as 69 KV, the effect of allowing more power to be carried over the same circuit can be exploited even more because, when properly chosen, the series capacitor will improve stability.

The series capacitor will do a good job in correcting voltage conditions where the circuit is highly reactive relative to its resistance, the load power factor is low and lagging, and the load has rapid variations. However, the series capacitor is not an effective means of improving the power factor of the circuit because, in most applications, the series capacitor kilovar rating will be too low (one-fourth to one-half of the shunt capacitor kilovars for the same voltage change) to make a significant increment in power factor. It should also be remembered that the series capacitor will not compensate for voltage variations originating in the power supply; it will only reduce supply reactance and

cannot hold a fixed value of voltage. It may be necessary to use controlled induction or step-voltage regulators at a substation in addition to series capacitors if the voltage spread of the source is too wide.

CHAPTER 4

DESCRIPTION OF THE MATHEMATICAL MODEL USED

Some engineering must be applied at each new series capacitor installation to avoid technical problems, and in small capacity banks where the voltage improvement is small relative to the system considered, the cost of engineering per KVAR may be uneconomical. Therefore, a procedure was sought which would reduce the required engineer-hours without reducing the accuracy of the results. Briefly, the approach normally taken to calculate the necessary ohmic capacitive reactance to compensate for circuit reactance when a motor load is applied is to apply the approximate voltage drop formula for a feeder:

$$E_S - E_R = IR \cos \theta + I(X_L - X_C) \sin \theta$$

Knowing the maximum allowable voltage drop, the equation can be solved for X_C , after current and power factor are calculated. These are calculated assuming a power factor and KVA load for starting and normal running conditions to arrive at a combined KVA load and its components. The voltage rating is then selected using the motor-starting condition data, and the location of the capacitor is chosen using a voltage-profile chart based on the above equation. These steps are the first round of cut-and-try calculations. The following factors have to be accounted for and corrected: motor-starting KVA for the actual motor voltage, the

impedance values for the actual circuit voltages, the load power factor, and the voltage drops on the source side of the capacitor for the effect of the series capacitor. This is obviously a long and tedious procedure prone to calculation error and subject to estimated initial and final conditions.

The data used in the determination of X_c outlined above are basically the magnitude of the load, its power factor, and the impedance of the power supply, all evaluated at two values of load power factor. If a dynamic analysis approach is taken, knowledge of these factors as a function of time can be obtained, reducing or eliminating the uncertainty of the estimates, and improving the efficiency of the method. An analytical solution in closed form is practically impossible, but a digital representation resulted in a useful tool which satisfies the objectives of efficiency and accuracy.

A program was written to calculate the ohmic capacitive reactance required to obtain a minimum voltage deviation from a given nominal voltage and within a given voltage spread at the terminals of the motor being started. Additional output consists of RMS single-phase voltage and current of the motor, angular velocity, and time during the acceleration period of the motor with and without series capacitors (Figure 5 and Appendix B). With this information and some basic electrical engineering, the rating, protection, and location of the series capacitors which give the desired voltage regulation can be determined.

The general circuit involved in this problem is of the form shown in Figure 6. Using the steady-state equivalent circuit for the motor, it

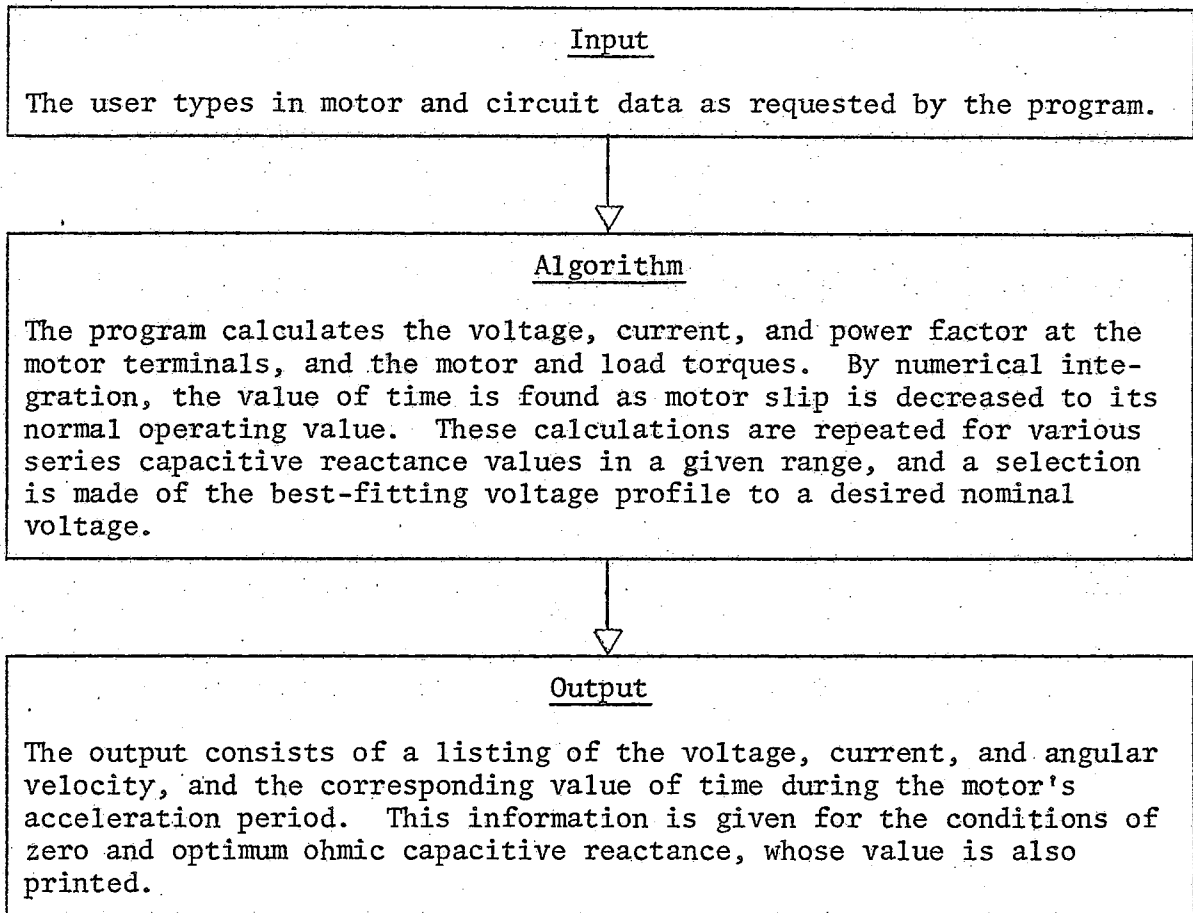


Figure 5. Information Transfer Block Diagram.

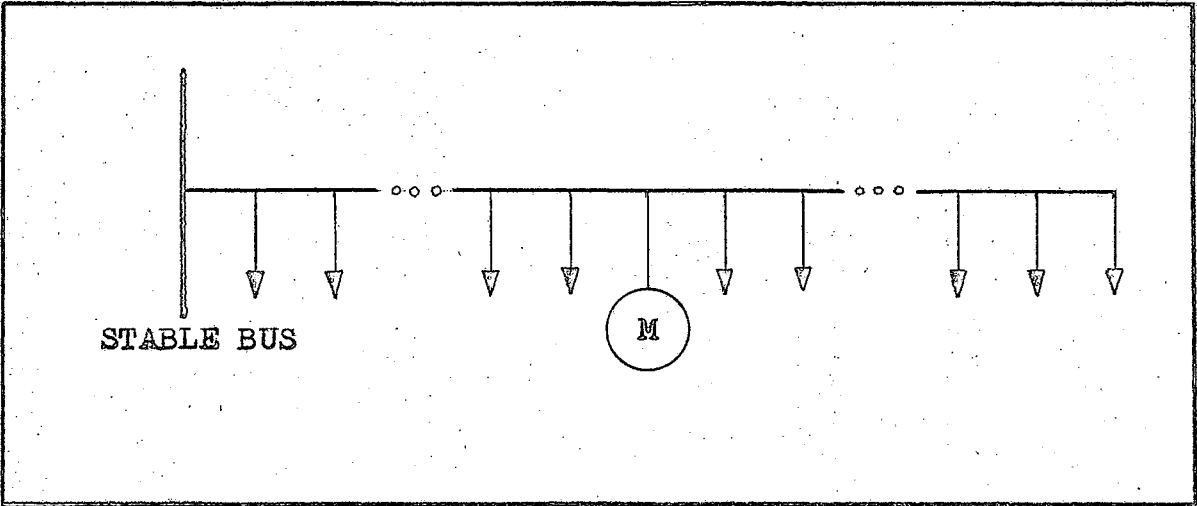


Figure 6. General Radial Circuit.

can be reduced to the form shown in Figure 7. The important point to consider in calculating the impedance of the circuit is to consider all lines, transformers, loads, and other components of the system back to some point in the system where the voltage is held practically constant, which is a point where load changes have negligible effect on voltage stability. The equivalent impedance also includes the series capacitors to be inserted at selected locations, i.e.:

$$Z_e = R_e + j(X_e - X_c)$$

The program simplifies the circuit further by calculating the equivalent impedance Z_f and summing it to the stator and circuit equivalent impedances to calculate the motor current I_1 :

$$Z_f = \frac{(r_2/s + jx_2)(jx_m)}{r_2/s + j(x_2 + x_m)}$$

$$I_1 = \frac{V_1}{Z_{tot}} = \frac{V_1}{Z_e + (r_1 + jx_1) + Z_f}$$

The torque is then calculated using the following formula where R_f is the real part of Z_f , and 8% allowance has been estimated for friction, windage, and copper losses:

$$T_m = \frac{Q_1 R_f I_1^2}{W_s} \quad (.92)$$

Then the voltage at the motor terminals, V_2 , is calculated:

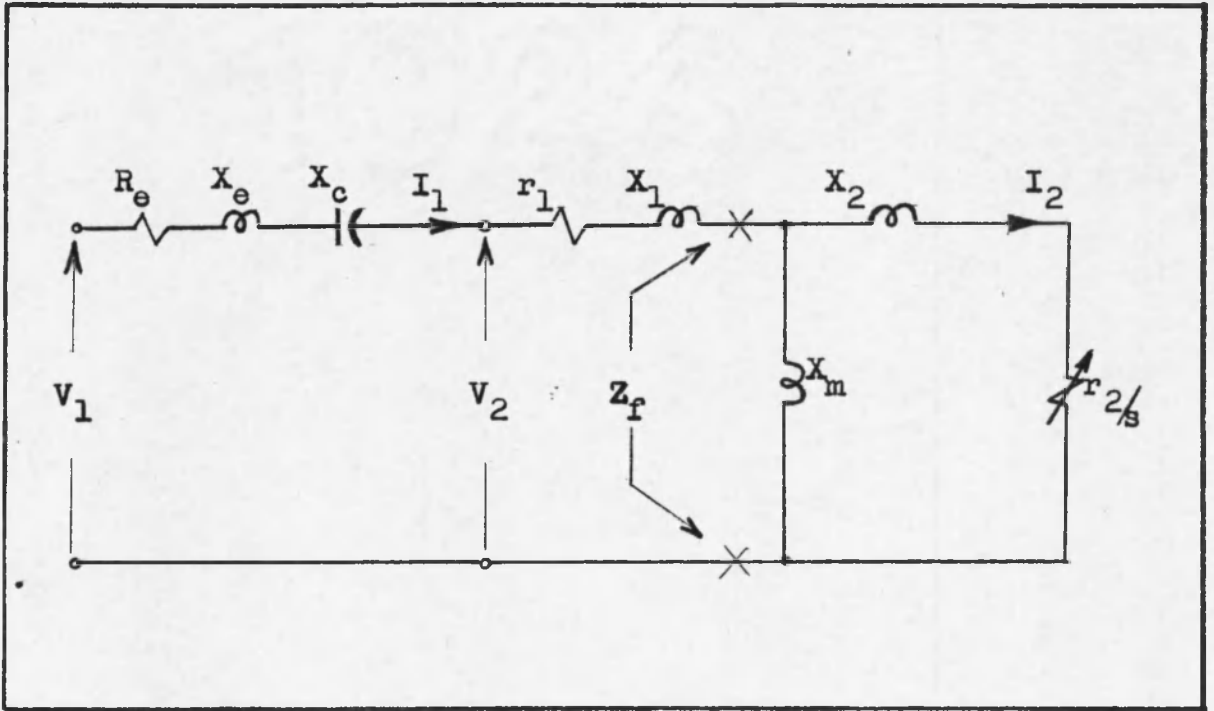


Figure 7. Equivalent Form of Radial Circuit and Motor Being Studied.

$$V_2 = V_1 - I_1 [R_e + j(X_e - X_c)]$$

A numerical (trapezoidal) integration subroutine is then used to find the corresponding value of time from:

$$t = J \int_{W_1}^{W_2} \frac{dW}{T_M - T_L}$$

The program generates the desired output data points using two principal loops (Figure 8). The outer loop assigns the value used for capacitive reactance, X_c , by calculating a reactance increment based on the given maximum capacitive reactance available and the size of the matrix used in the program. Using the value assigned to X_c , the inner loop will then calculate I_1 , T_M , V_2 , and t , as the slip-velocity varies from zero to normal operating speed.

Slip velocity is varied to simulate starting acceleration by decrementing the slip from 1.0 (standstill) to the operating slip of the motor being studied (typical range is .05 to .02):

$$W = W_s (1 - s)$$

The absolute value of the difference between the calculated motor terminal voltage, V_2 , and the given nominal voltage value is computed for all corresponding points of time (t) during the starting acceleration period and summed:

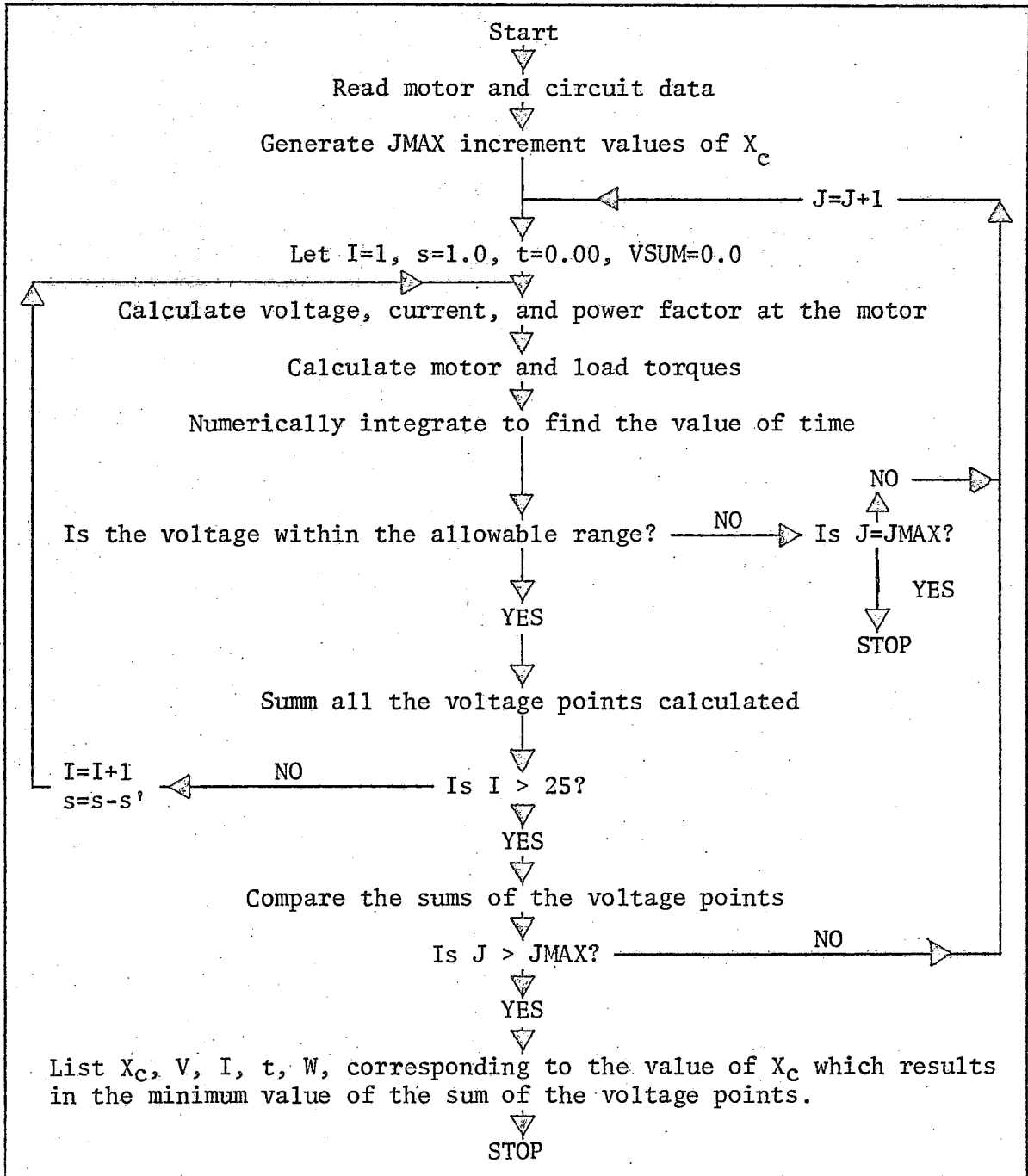
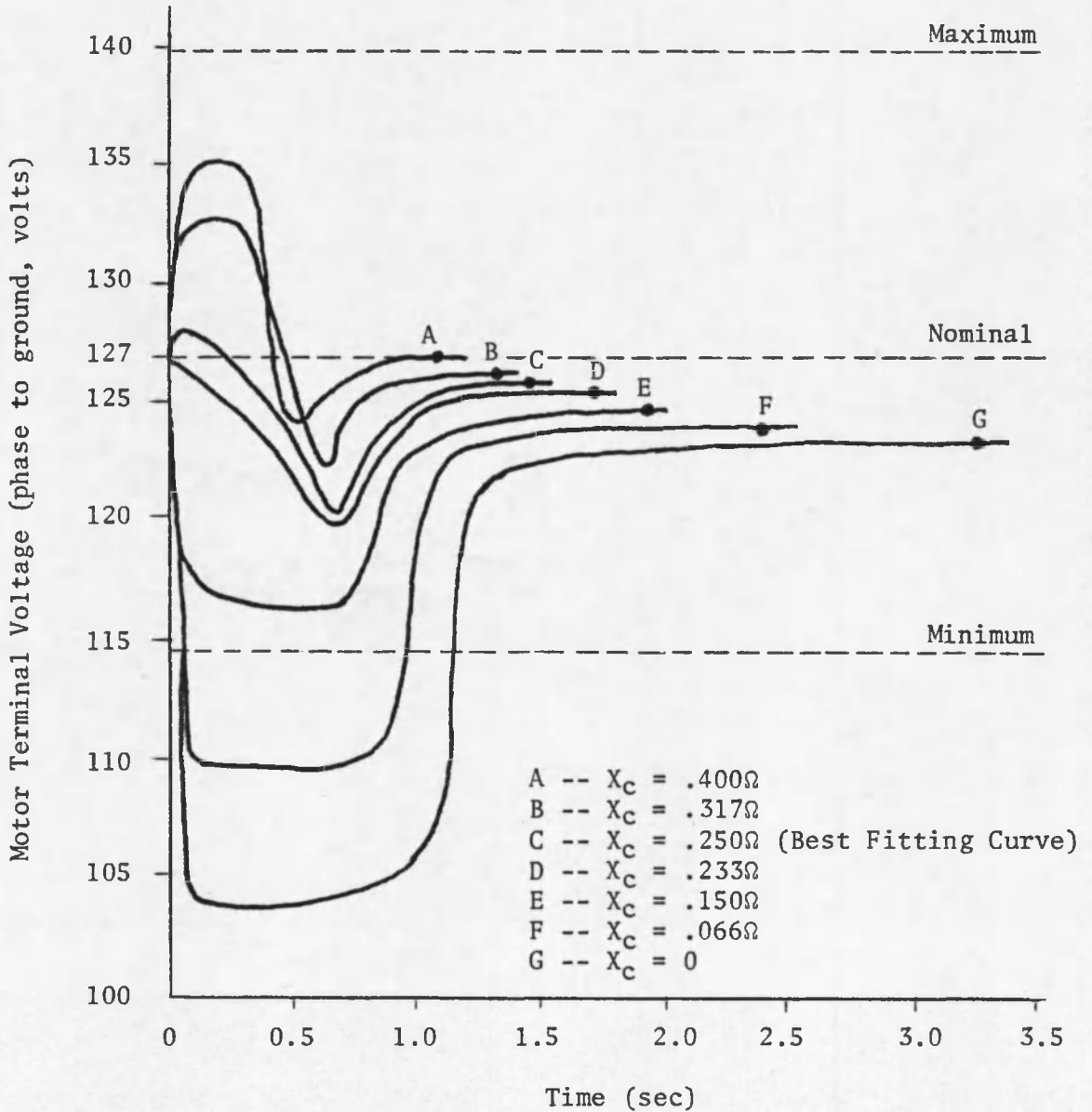


Figure 8. Simplified Flow Diagram.

$$\sum_{i=1}^{i_{\max}} \text{SUM}_i = |V_{2ij} - V_{\text{nom}}|$$

where V_{2ij} corresponds to the i th value of slip and the j th value of series capacitive reactance.

A comparison is made of all sums corresponding to all X_c values used (including $X_c = 0$). The value of X_c which corresponds to the sum with the minimum value is selected as the capacitive reactance which will give the closest fitting voltage curve with respect to the given nominal voltage during the acceleration period. The criteria used consist in considering only the acceleration time as the critical period, as opposed to giving more weighting to the voltage value reached after the acceleration period (only one such point, the final value, of the voltage curve is included in the sum used for comparison). It was chosen because the voltage fluctuation occurs during acceleration and voltage conditions before and after were given as being within the allowable spread. Using this criteria may result in an X_c value that corresponds to the minimum value sum, but there may be other X_c values which will give a closer value to the nominal voltage at normal operating speed, although their sum would be greater than the minimum because during the acceleration period there might have been over- or under-shoots with respect to the nominal, thus increasing the sum (Figure 9). How much this increase is depends on the time the over-shoot lasts. If operating normally at a voltage closer to nominal is important and the voltage dips or peaks can be tolerated during starting, a decision can be made to use or not a



Motor: 10 HP, 3 ϕ , 220 V, 60 Hz, 6 Pole, Design B, 28 Amp F.L., 2% slip

●: Normal operating speed reached at this point.

Figure 9. Effect on Motor Terminal Voltage of Increasing Series Capacitive Reactance.

capacitor which will give a closer final voltage, because both the magnitude and duration of the fluctuations is furnished. This can be easily implemented by specifying as desired higher or lower nominal and limit voltage values in the input data of the program. This has the effect of giving higher weighting to the voltage value corresponding to normal operating speed. For the more realistic case, where voltage conditions during normal operation are not within the allowable voltage limits, the same "procedure" can be applied to help correct both voltage fluctuations and spread, when the allowable spread has not been exceeded too much. To increase the voltage boost, a greater capacitive reactance is needed, which means a higher cost because the KVAR rating is proportional to the reactance of the capacitor.

The steady-state equivalent circuit was used to represent the motor during starting because it permits step-by-step calculation of the desired variables as a function of time, taking into account mechanical transients, but ignoring all electrical transients and saturation (Gabbard and Rowe 1957). The value of the effective rotor time constant of a motor depends on system and motor constants and, in most systems, it is negligible relative to the motional transients or flicker critical period. The stator transients introduce a DC component of current in the stator phase current and pulsating electrical torques. This effect is considered important only for a three-phase terminal fault study and impractical to represent elsewhere (Brereton, Lewis, and Young 1957). More simplified models are based on the assumption that the disturbance on the system caused by the motor on starting will be negligible, which

is certainly not true for the radial feeder in this problem. Saturation was also ignored since the error is small when the correct equivalent circuit constants are used.

To obtain a correct value of time, it is necessary that the model used for the motor's mechanical load be as real as possible. The program calls for the input of a list of twenty-five points from the load torque (nt-m) curve with the corresponding values of angular velocity (in radians/sec and in ascending order). This set of points is used by a subroutine to provide a piecewise linear representation of the load torque function. The value of load torque for any value of angular velocity which is not one of the given values is found by linear interpolation.

CHAPTER 5

USE OF THE COMPUTER PROGRAM SRCP

The program is interactive and written in BASIC-PLUS language. It was run on a PDP/11 machine. It uses approximately 14 K words of core memory, which makes it possible to run this program on practically almost all minicomputers with a BASIC interpreter. The procedure to run the program, whose name is SRCP, is summarized as follows:

1. By field measurement, determine which point in the circuit can be considered as a stable or infinite bus and measure the voltage at that point.
2. Reduce the circuit to the form of the one-phase equivalent circuit shown in Figure 7.
3. Obtain, preferably by field measurement or by calculation using the program's output information, the voltage profile of the circuit as a function of electrical distance at the moment when all loads are connected and the largest motor is being started (a group of similar motors started simultaneously can be considered as one large equivalent motor).
4. The following rule is applied to obtain a voltage profile as uniform as possible within the allowable limits: Locate the series capacitor at a point where voltage drop is one-third of the total voltage drop and compensate at this point for two-thirds of the total drop. Since the capacitive series reactance is

concentrated at one point while resistance and inductive reactance are distributed along a circuit, the voltage will rise sharply on the load side of the capacitor.

5. Since the program selects the value of capacitive reactance based on the voltage conditions at the motor terminals, nominal, minimum, and maximum voltage values are obtained from the voltage profile of step 4, such that, by correctly specifying these limits at the motor terminals, the general voltage profile will be within the allowable range (Figure 9).
6. Call the program by typing OLD SRCP.
7. Run SRCP by typing RUNNH. The interactive part of the program will request the following information: motor synchronous speed in RPM; resistance and reactance of the stator and rotor; magnetizing reactance; operating slip (decimal fraction); resistance and reactance of the equivalent impedance; voltage at the stable bus (from step 1); nominal, maximum, and minimum voltage values at the motor terminals (from step 5); motor full-load current; maximum series capacitive reactance available (ohms); and twenty-five load-curve data points. The load torque (nt-m) and the corresponding angular speed (rad./sec) are specified. (To reduce error, the points should be chosen so that the curve is well described where its magnitude is largest.)
 - a. The full-load current is used to calculate the moment of inertia (J) of the motor (Fitzgerald and Kingsley 1961, p. 546):

$$J = \frac{(1.73) (I_{FL}) (V_{LL}) (H)}{(5.48 \times 10^{-3}) \text{ (RPM)}}$$

- b. By maximum capacitive reactance available is meant the largest reactance value which is tried by the program in its selection process of the best reactance value.
- c. The units used are volts, amps, ohms and MKS units, unless otherwise specified.
8. The output consists of a listing first of the time, motor terminal RMS voltage magnitude, angular velocity (rad./sec) and current magnitude and angle (radians) during the period of time that the motor requires to accelerate from zero to its normal operating speed. A second listing follows with the same type of information but for conditions with the capacitive series reactance which best compensates per the program. The value of that reactance is also given (ohms).

If more capacitive reactance is needed to meet the specified voltage requirements, a message will be printed stating:

INSUFFICIENT CAP REACT AVAILABLE.

If the voltage maximum is exceeded with the smallest increment of reactive capacitance, the output will read: MAX VOLT EXCEEDED W/SMALLEST CAP REACT.

If the motor torque is less than the load torque at any point, the message will read: LOAD GREATER THAN MOTOR TORQUE.

9. With this information, a new voltage profile of the circuit should be drawn to verify that the voltage is, in fact, within

acceptable limits at all load points. This is done using the highest value of current listed. (Knowledge of duration time is valuable in this part of the analysis, since being aware of the amount of time over- or under-voltage conditions exist is essential in deciding whether this condition can be tolerated or not.)

10. If the voltage profile is not acceptable, steps 4 through 9 are repeated to locate and find a second capacitor. (More than two capacitors are not recommended because of the cost and associated resonance problems associated with too large of a capacitive reactance. In this case, a voltage regulator and a series capacitor might be a better solution.)
11. With known capacitive reactance and current, the KVAR rating can be calculated:

$$\text{KVAR} = \frac{3 I_m^2 X_c}{1000}, \quad I_m = .67(I_s + I_n)$$

This is the three-phase reactive KVA required, and I_m is the rated momentary current that will flow through the capacitor. In this case, it represents 67% of the initial starting current of the largest motor plus normal current to other loads, i.e., at the moment of largest inrush, the current at the point where the capacitor is to be located is calculated and this value is multiplied by .67 to obtain I_m for the above formula. Per NEMA (1973), the maximum total momentary current which the capacitor

can safely withstand is one-and-one-half times the rated current.

12. The minimum voltage rating is equal to the current I_m from step 11 multiplied by the capacitor reactance value given by the program:

$$VR = I_m X_c$$

13. Tables such as Tables 6 and 7 or manufacturer's tables (which might include more ratings other than standard for low-voltage units) are used to find the capacitor unit or units which, in a series parallel combination, will give a value of X_c , VR, and KVAR as close as possible to the desired and still be economical.
14. The capacitive reactance in ohms for the unit selected in step 13 is calculated from:

$$X'_c = \frac{1000 (Kv)^2}{KVAR'}$$

15. The continuous current rating for the unit selected in setp 13 is:

$$I_c = \left(\frac{1000 KVAR'}{X'_c} \right)^{1/2}$$

The corresponding momentary current is:

$$I_m = 1.5 I_c$$

Table 6. Shunt Capacitor Ratings (Individual Units).

Voltage	Kilovar Ratings			Phase
	Indoor Enclosed Units	Indoor Nonenclosed Units	Outdoor Units	
230	0.5,1,2.5, 5.5,7.5	5,7.5	2.5,5, 7.5	Single, Three
460	1,2,5,10,15	10,15	5,10,15	Single, Three
575	1,2,5,10,15	10,15	5,10,15	Single, Three
2,400	-	15,25	15,25	Single, Three
4,160	-	15,25	15,25	Single, Three
4,800	-	15,25	15,25	Single, Three
7,200	-	15,25	15,25	Single, Three
7,960	-	15,25	15,25	Single
12,470	-	15	15	Single
13,800	-	15	15	Single

Table 7. Capacitor Equipment for 60 Cycle Operation.

Capacitor Voltage Rating					
<u>230</u>	<u>460 and 575</u>	<u>2,400 and 4,160</u>		<u>4,800-13,800</u>	
Kilovar Rating of Units					
<u>7-1/2</u>	15	15	25	15	25
15	30				
		45*			
30	60				
45	90	90*	-	90*	
60	120				
		135*			
90	180	180*	-	180*	
180	360	-	600		
270	540	-	900	-	900
450	900	-	1,200	-	1,800
630	1,260	-	1,800		
			2,700	-	2,700
			3,600	-	3,600
					4,500
					5,400

*Outdoor equipment may be pole- or base-mounted.

16. The number of standard units required is (NS'):

$$NS = \frac{X'_c}{X_c}, \quad NS' = \text{Nearest whole number of NS}$$

The actual total capacitive reactance if NS' units are connected in parallel is:

$$X''_c = \frac{X'_c}{NS'}$$

The connection could also be made in series, but it is not usual at this point in distribution bank forming.

The bank of the series capacitor at this point will have a total reactance equal to X''_c ; a continuous current rating of NS' times I_c ; a momentary current rating of NS' times I_m ; and a single-phase KVAR rating of

$$\frac{(NS' I_c)^2 (X''_c)}{1000}$$

The above combination is usually the starting point in forming the series capacitor bank. Depending on the required capacitive reactance value and KVAR capacity, another group might be connected in series, or a series-parallel arrangement might be used. There are an infinite number of schemes to obtain the desired values, but in practice this will be limited by cost and available stock. The important parameter to watch and try to keep as close as possible to the calculated

value is the capacitive reactance, so that no large deviations in voltage will result. The program can be used with the resulting X_c value voltage profile. The resulting X_c value would be input as the maximum capacitive reactance available to force the program to select that value or one very close to it as the best choice and output the corresponding voltage and current data.

The current should be greater or equal to the rated current of the units and the total KVAR should be greater or equal to the calculated value, but these values should not be exceeded by much as cost will be greatly increased (Appendix A).

Capacitor cost will vary approximately as the square of the current. A sample run was made (Appendix B) using a 10 HP motor whose characteristics are given in the listing. For simplicity, only the line (750 feet, 3-1/0 ACSR) was considered and no additional loads were tapped off. Figure 9 shows voltage behavior for several X_c values. The indicated curve corresponds to the capacitive reactance value which provides the best fitting curve with respect to the nominal value during acceleration.

CHAPTER 6

PROTECTION OF THE CAPACITOR BANK

Under short-circuit conditions, the current flowing in the line and the associated voltage across a series capacitor may increase several times its value at maximum load. The economical solution in many circuits is to select capacitors for maximum load current and protect them against overvoltage by an external device. However, there are some cases where it is economical to build the capacitors with sufficient dielectric strength and eliminate the protective equipment (continuous current ratings equal to 50% of the maximum fault current would be used). For example, this could be done in circuits where the maximum short-circuit current is only a few times (3 to 6) the maximum load current. Several low-voltage installations use regular shunt capacitors with no protection of any kind because a cost analysis showed that it was less expensive (about 50% less) to operate this way even if half the installations were damaged (Bates 1968, p. 94). But these are not typical cases and common practice is to install an arcing gap which will by-pass the capacitor with enough speed to limit overvoltage to not more than 200% of the normal rating and do it within one-half cycle. The gap must then be shunted because the gap cannot carry high currents for any appreciable length of time and still be self-clearing. Also, as soon as the line current drops to a safe value, the capacitor must be reinserted. The gap

sparks over in microseconds and the system's original fault duty is re-established, so that the series capacitor stiffens the system during normal operation without really increasing faulty duty.

A typical protective scheme is shown in Figure 10. The gap is set to spark-over to protect the capacitor at about twice rated voltage across the capacitor. If the capacitor is to reduce voltage dips caused by high momentary current, it should be of a size so that the largest motor-starting current will not cause operation of the gap. This is why the current rating of the capacitor is equal to 67% of the total current as mentioned before. The voltage rise is thus limited to 150% of normal, and in the arrangement shown the contactor M relieves the gap from continuous operation. M_{sh} closes the contactor and the M_s series coil holds it as long as fault current is present. M_{tc} is a time-delayed auxiliary contact that prevents pumping action of the main contactor when closing. The Thyrite resistor by-passes some of the current to protect the M_{sh} coil. The M_s and M_{sh} coils are wound on a common core, making up a transformer whose primary voltage is determined by the loading resistor DR across the secondary winding, which is coil M_{sh} . This is the way the value of line current at which dropout of contactor M occurs is set, and consequently the capacitor is reinserted in the line.

Another protective scheme appears in Figure 11 (Westinghouse Electric Corp. 1965, p. 339). Here the solenoid trips a spring-loaded switch to by-pass the gap. When the line current returns to normal, the relay energizes the motor to open the switch and reconnect the capacitor in the line.

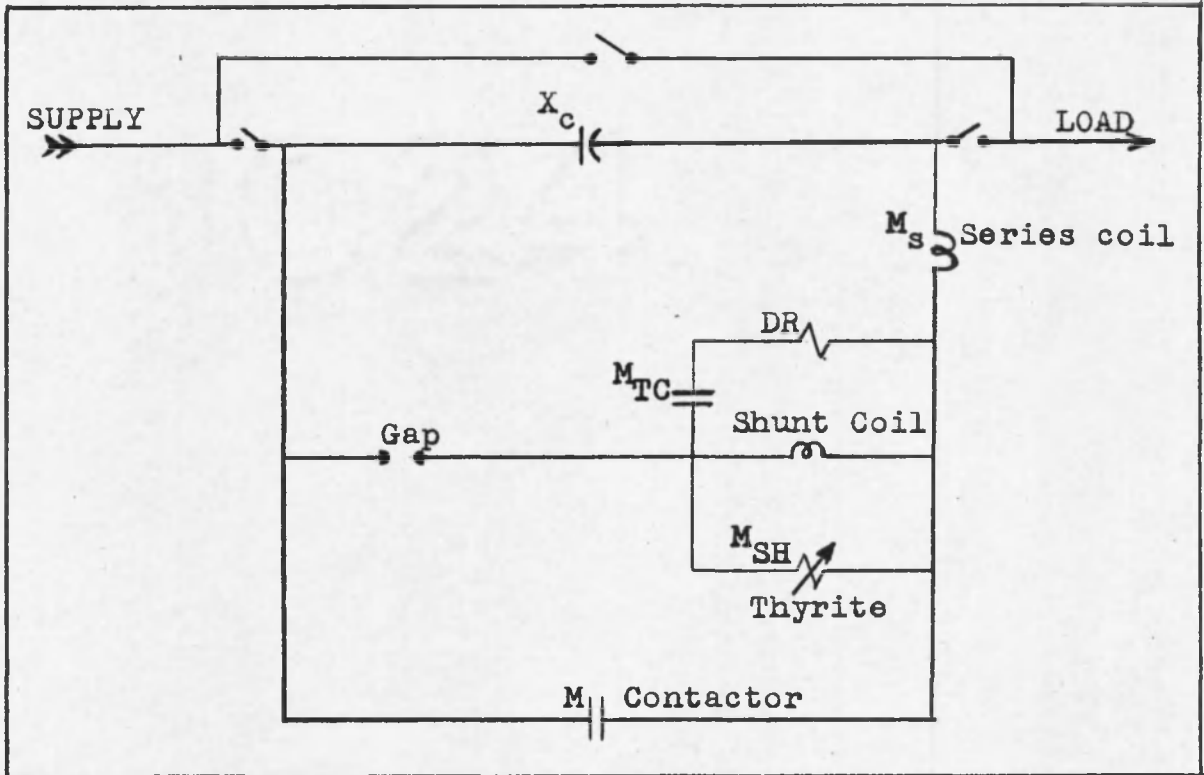


Figure 10. Typical Protective Scheme.

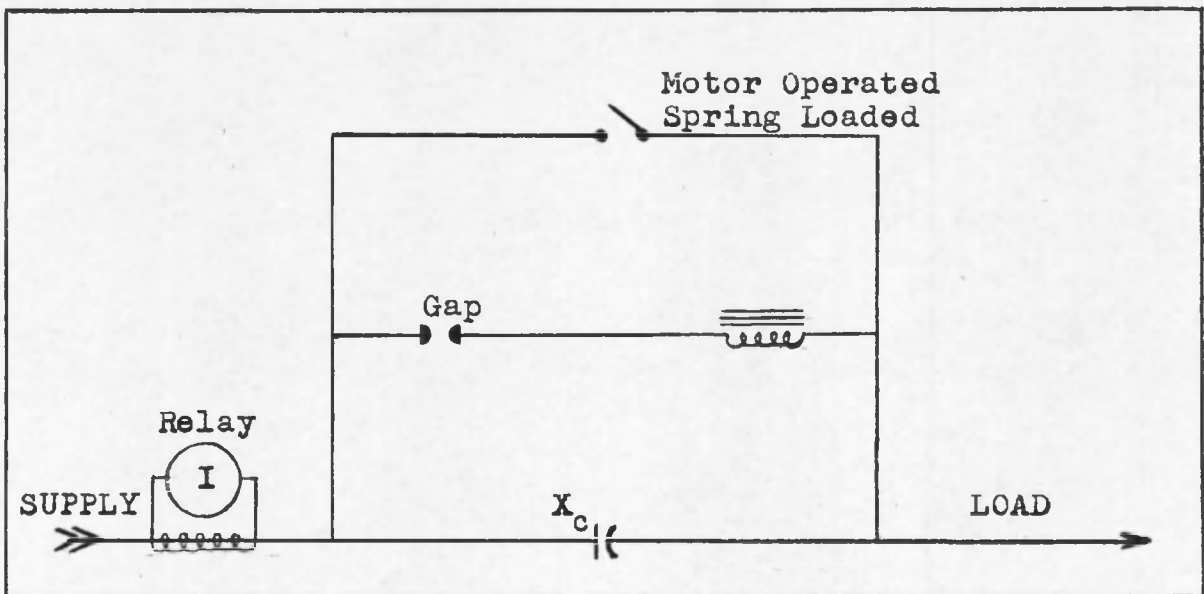


Figure 11. Protective Scheme with Motor Operated Switch.

These two schemes have an outage time of about a minute. Reinsertion can also be manual, or, at the other extreme, a compressed air circuit breaker for rapid reinsertion may be used when the capacitor is critical for system stability. Contactors are used for maximum capacitor voltages up to 7.5 KV, and power circuit breakers are used for higher voltages.

In all cases, it is recommended that the disconnect switches (which may be interlocked for safety) be used for maintenance purposes. In neither case is any auxiliary power required, which makes it possible to locate series capacitors remote from substations anywhere in the line. It is very difficult to set a gap for less than 0.020 to 0.030 inch clearance and expect reliable spark-over. This limits this method to around 2000 volts. The lowest rated voltage of a capacitor with a direct gap protective scheme is about 500 volts. This is another case where units with extra insulation may be used. Series step-up transformers have also been used to be able to use higher voltage rating capacitors. Figure 12 shows another method where a relay trips the radial feeder's circuit breaker (Bloomquist and Wilson 1950, p. 149).

To reduce costs and simplify the protective scheme, neither overload nor dielectric protection is used on some distribution-size installations, which makes it even more critical that the continuous current should not exceed 110%, nor should the average current over any 24-hour period be greater than 105% of the capacitor rating. The short-circuit protective equipment is set to function at 150 to 200% of rated voltage and provides no overload protection. If used, it must have an

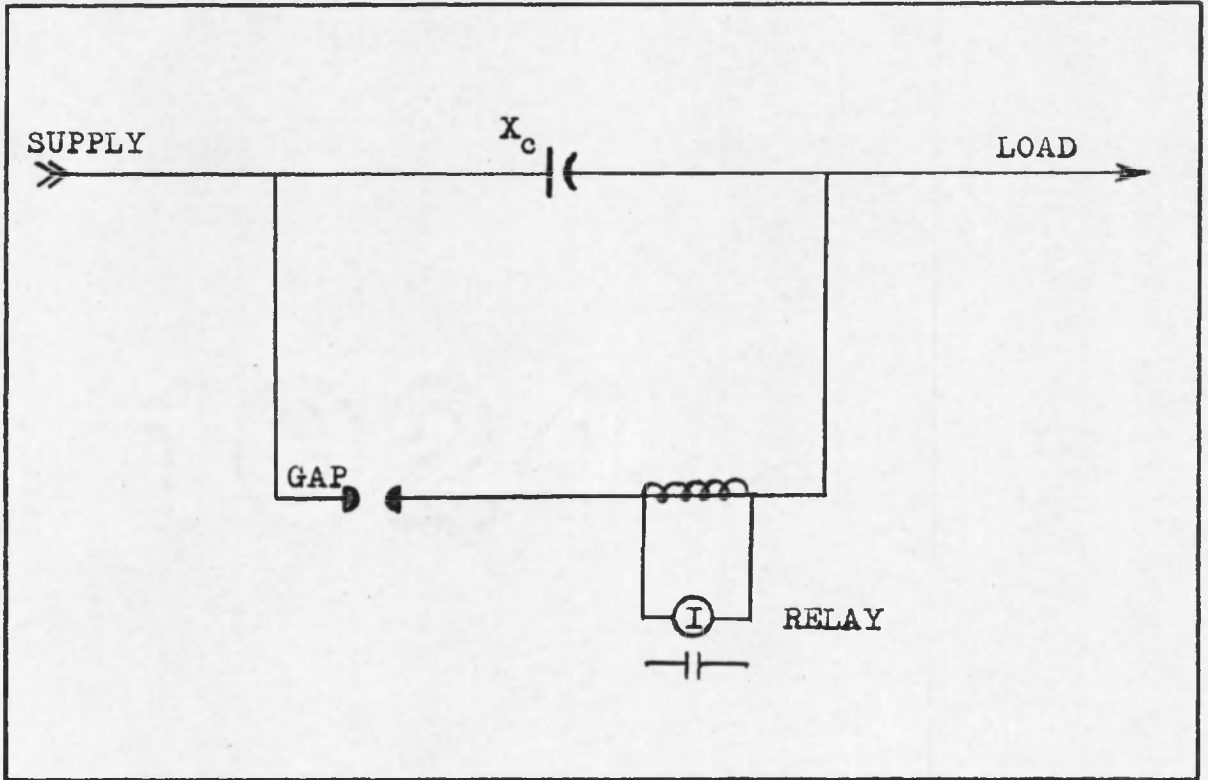


Figure 12. Protective Scheme Employing the Feeder's Breaker.

inverse time-current characteristic that can be coordinated with the capacitor to allow momentary overvoltage up to 150%. Specially built series capacitors have a 30-minute rating of 1.35 times rated current and a 5-minute rating of 1.5 times rated current.

On large banks where the units are individually fused, dielectric protection is usually implemented by means of a differential relay scheme. After a fuse blows to remove a shorted unit, the reactance of the bank increases, causing an overvoltage on the remaining units. The current will be unbalanced, causing the relay to operate and capacitor bank will be by-passed.

For voltages above 4 KV, it is generally uneconomical to use series capacitors (and protective equipment) insulated for the circuit line-to-ground voltage level (Bloomquist and Wilson 1950, p. 152). The series capacitor can be considered a part of the line conductor and needs the same level of insulation to ground and between phases, which may be many times the rated voltage between its terminals. If additional insulation to ground is provided, capacitors insulated for a lower voltage may be connected in series with a line of higher voltage. When the additional insulation is added external to the capacitor tank or case, standard shunt units may be used as series capacitors, provided the insulation to ground is adequate. The capacitor banks and protective equipment are then internally insulated only for the actual capacitor voltage and are rack-mounted on pedestal-type insulators. With this set-up, lightning arresters may be omitted; but with special series capacitors, arresters should be placed on both the source and load sides

of the capacitors on all phases. In practice, either single- or three-phase equipment is used up to 15 KV, and above this voltage mostly single-phase equipment is installed. The capacitor must be short-circuited and solidly grounded before working on it or its protection. The complete assembly should also be physically separated so that humans, animals, or objects cannot come in contact with it.

Circuit breaker operation is not affected by the installation of series capacitors because the gap will arc much faster than relay and breaker operation. A series capacitor will not change much the value of neutral current, so that line-to-ground fault relaying is not affected either. However, tie line relaying can be greatly influenced by the presence of series capacitors.

The principal reason why distribution series capacitor installations are not numerous is because there is always the potential for inductive-capacitive resonance. Being aware of these problems and their nature, the engineer can take the necessary precautions and, in most cases, avoid the difficulties. There are two major resonance phenomena involved with the use of series capacitors and induction motors.

The first is self-excitation or sub-synchronous resonance of induction motors during starting. When voltage is applied to the rotor, it rotates but will only come up to partial speed and will continue to rotate at this reduced speed below synchronous. The capacitor, in combination with the stator, sets up a resonant circuit at a frequency lower than line frequency. Because this resonant condition exists, impedance is at a minimum and a large current easily flows, which may heat up the

motor or cause pulsating torques. The resonant frequency is related to the relative ratings of the motor, capacitor, and feeder. For a motor whose input KVA is about half the circuit rating, the resonant frequency will be about 20 to 30 cycles (Johnson 1948, p. 106). As the relative motor rating decreases, its reactance increases and as capacitive reactance increases, the frequency decreases. This means that the smaller the motor relative to the feeder the lower the subsynchronous frequency.

Current during resonance flows in accordance with the natural frequency of the circuit and gradually decays to zero. The rate of decay depends to a large extent upon resistance and advantage is taken of this to damp out the subsynchronous frequency by placing a resistor in parallel with the capacitor. To reduce losses, the resistance is chosen as high as possible. If the ohmic value is too low, the resistor can be by-passed when the motor has attained normal operating speed. There are methods of calculating the resistance values, as shown by Butler and Concordia (1937), and also Wagner (1941), but the real values used are usually two to ten times what the calculations call for (Johnson 1948, p. 106). This large error is due to the inaccuracy of the circuit component values and operating conditions which are changing. Therefore, the resistors used are adjustable over a certain range. In a few cases, parallel resistors across only two phases have been used because the unbalance was acceptable. Switchable series resistors have also been employed during starting. The gap protective circuit can also stop the resonant condition, since the voltage across a capacitor increases as the frequency is decreased; i.e., for frequencies lower than rated, the

voltage might be raised enough to cause spark-over and by-pass the capacitor. If the energy stored in the capacitors is high, heavy-duty gaps and dissipating resistors might have to be used. Self-excitation is possible when the capacitive reactance is greater than half of the system's short-circuit reactance, and in systems with motors whose rating is more than 5% of the circuit rating especially when there are high-inertia loads connected.

The second type of resonance phenomena occurs when an unloaded or lightly loaded transformer in series with a capacitor is energized. If voltage is applied close to the zero point of the wave, a high magnetizing current may flow due to the high saturation caused by the rapid increase in flux. The reactance of the transformer then decreases to the equivalent air core reactance of the transformer winding. High current normally lasts only for several cycles and then reduces to a low-value exciting current, but with a series capacitor ferroresonance can be sustained. This behavior depends on the nonlinear transformer characteristics and there are no practical analytical solutions to this problem. The capacitor acts as a secondary voltage source which badly distorts the current wave, which is of a very low frequency and can have a value equal to or greater than full-load current. This kind of current causes a voltage drop across the capacitor which can break down the protective gap. When steady state is reached, the capacitor is reinserted. This abnormal condition can be remedied with the same parallel resistor applied to prevent self-excitation of motors. It has been found that the losses due to the shunting resistor are less than 10% of the normal line

loss. It makes little difference where the resistor is located or where the voltage is applied. If losses are considered too high, an automatic switch can be used to disconnect the resistor when the transient is over. Secondary loads can also prevent over-excitation, but cannot always be depended upon. If the loads are fluctuating, ferroresonance may appear in the steady state. Another alternative to prevent abnormal conditions is to change the transformer to one having a smaller exciting current.

Another operating problem which may appear with the application of series capacitors is hunting of synchronous and induction motors. The effects of hunting are seen as voltage and frequency pulsations. This situation is caused by rotor oscillations set up by system disturbances such as load changes, switching, changes in the power source, etc. Hunting is found in most cases in lightly loaded synchronous motors, although it can also occur in induction motors with pulsating loads such as reciprocating compressors or pumps. Flicker due to hunting is sometimes reinforced when the frequency of the pulsating load is a multiple of the frequency of hunting. To predetermine hunting, the ratio R/X of the feeder between the power source and the motor is evaluated. The probability of hunting is very low for positive values less than one (Johnson 1948, p. 106). This limiting condition is based on a study of the relation between system damping and hunting. Damping can either be positive, which reduces rotor oscillations, or negative, which amplifies oscillations (negative damping is due to line resistance). If a series capacitor is used, the ratio is increased or can become negative and negative damping becomes more likely. Hunting can sometimes be

eliminated by relocating the capacitors. As in the problems involving resonances, calculations can, at best, indicate tendencies, and field experience must be relied upon heavily to determine whether or not damping might occur.

CHAPTER 7

CONCLUSIONS

1. Series capacitors can be applied successfully if their benefits and technical limitations are recognized. Series capacitors are not a specialized device, but a useful alternative for correcting momentary voltage drop.
2. A careful engineering evaluation of each new installation is strongly recommended since the behavior of a series capacitor is directly dependent on other loads, and load conditions are frequently quite variable.
3. It is advisable to organize and start a test and evaluation program of a few trial installations representative of cases where series capacitors could be beneficial. This program could shorten the time necessary to acquire the experience to install and operate series capacitors, and thus reduce installation costs.
4. Regulation as to the type of starter to be used with certain sizes and type loads, as well as the maximum KVA demand applied per step, should be implemented.
5. To complement this study, a thorough familiarization of the hardware involved and installation details are deemed essential. Emphasis should be placed on protective equipment and methods used to solve resonance-type problems.

6. The benefits obtained by the use of the approach taken in this study are:
 - a. Reduction in engineering manpower employed.
 - b. Improved accuracy of the results. Initial conditions are based on measured values and during acceleration a sufficient number of points is considered so that no doubt can exist as to the behavior of the voltage between starting and running conditions.
 - c. Knowledge of over- or undervoltage duration time is valuable information in deciding when these conditions can be tolerated. This can represent significant savings.
 - d. The program solution takes into account varying power factor and current, and motor and load characteristics.

APPENDIX A

BANK FORMING EXAMPLES

For X_c - 90 ohms and I_m - 200 amps, the required three-phase KVAR capacity is:

$$\frac{(3) (200)^2 (90)}{1000} = 10,800 \text{ KVAR}$$

For a 50 KVAR, 7.2 KV unit which is available, the reactance and current rating are:

$$\frac{(1000) (7.2)^2}{50} = 1036.8 \text{ ohms}$$

$$\frac{(1000) (50)^{1/2}}{1036.8} = 6.95 \text{ amps .}$$

Thirty units in parallel have a rating of 208 amps and 34.5 ohms. Three of these groups in series would give 103.5 ohms per phase and 13,500 KVAR total. If another combination of 34 units in parallel in each group were used, and then three groups were connected in series, the resulting bank would have a current rating of 236 amps, 91.5 ohms, and 15,300 KVAR total. This last bank has a closer ohmic value to the required, but there is excess KVAR capacity and to reduce costs other units should be tried.

A 50 KVAR, 4.16 KV unit has a 12 amp rating and 347 ohms. A bank can be formed by connecting groups of seventeen units in parallel and then four groups in series to give 81.6 ohms, 204 amps, and 10,200 KVAR total. The capacitive reactance value is low, but the resulting profile using this value would determine if it could be used.

Another possibility is a 50 KVAR, 4.8 KV unit rated at 10.4 amps and 462 ohms. A group of twenty units in parallel and four of these groups in series per phase will give 92.4 ohms and 12,000 KVAR (Westinghouse Electric Corp. 1965, p. 337).

Deviation of the resulting voltage from the specified limits, cost, and availability are factors to be considered for each particular case in deciding which units are to be installed.

For the 10 HP motor example which appears in the sample computer run (Appendix B), the KVAR required is:

$$\frac{(3) (.67) (154) (.25)}{1000} = 7.98 \text{ KVAR}$$

With a 7.5 KVAR, 230 volt unit, 28 units in parallel are necessary to give .25 ohms, and the resulting KVAR capacity is 675 KVAR total, which is obviously much too high. Using lower KVAR rated units will require more units to give .25 ohms, and higher KVAR units will reduce the number but the total KVAR will only be slightly less than 675. Low voltage installations with small loads usually require low ohmic and reactive power values, frequently making small size installations uneconomical.

APPENDIX B

SAMPLE COMPUTER RUN

LISTNH

```

1  REM THIS PROGRAM COMPUTES THE SINGLE PHASE VALUE
   REM OF SERIES CAPACITIVE REACTANCE REQUIRED TO
   REM COMPENSATE FOR INDUCTIVE VOLTAGE DROP DUE TO
   REM MOTOR STARTING.
2  REM THE SUPPLY CIRCUIT IS A THREE PHASE RADIAL
   REM FEEDER SINGLE PHASE PARAMETERS ARE USED (VOLTS,
   REM AMPS, OHMS, AND MKS UNITS.)
7  DIM X4(50),T(25,25),V2(25,25),I3(25),
   I4(25),Z6(25),Z7(25)
9  DIM W4(25),T8(25)
10 INPUT "MOTOR SYNCHRONOUS SPEED (RPM)";S1
11 W1=S1*(PI/30.0)      !SYNC ANG VEL IN RAD/SEC
15 Q1=3.0
20 INPUT "RESISTANCE OF STATOR CIRCUIT";R1
25 INPUT "RESISTANCE OF ROTOR CIRCUIT";R2
30 INPUT "REACTANCE OF STATOR CIRCUIT";X1
35 INPUT "REACTANCE OF ROTOR CIRCUIT";X2
40 INPUT "MAGNETIZING REACTANCE OF MOTOR";X5
41 INPUT "OPERATING SLIP (DECIMAL FRACTION)";S3
42 S4=(1.0 - S3) / 24.0      !SLIP DECREMENT
45 INPUT "RESISTANCE OF EQUIVALENT IMPEDANCE";R3
50 INPUT "REACTANCE OF EQUIVALENT IMPEDANCE";X3
55 INPUT "STATION BUS (STABLE) VOLTAGE";V1
60 INPUT "NOMINAL VOLTAGE AT MOTOR TERMINALS";V6
65 INPUT "MAXIMUM ALLOWABLE VOL. AT MOTOR TERM.";V7
70 INPUT "MINIMUM ALLOWABLE VOLT. AT MOTOR TERM.";V5
71 INPUT "MOTOR FULL LOAD CURRENT";I2
72 K2=V6*I2*.003
76 K1=K2/((1.096E-5)*(S1**2))      !MOM INERTIA IN MKS
81 INPUT "MAX. CAP. REACTANCE AVAILABLE";X6
82 PRINT: PRINT: PRINT: GOSUB 600
83 PRINT "NOTE: VOLTAGE MAGNITUDE IN VOLTS."
84 PRINT "NOTE: CURRENT MAGNITUDE IN AMPS, ANGLE IN RADIANS
85 X7=X6 / 24.0      !XC INCREMENT
86 PRINT "NOTE: ANGULAR VELOCITY IN RAD/SEC"
90 X8=X6/X7      !NO. OF CAP. REACT INCREMENTS
95 J9=25
105 J=1 !X4(CAP. REACT.) INDEX
110 X4(J)=0.0

```

```

120 K=J !GENERATING CAP. REACT. VALUES
125 J=J+1
130 X4(J)=X4(K) + X7
135 IF J<J9 GOTO 120
140 J=1
145 R4=R3 + R1
150 I=1
155 S=1.0
156 T=0.0 !INITIAL VAL. OF TIME
160 X9=X3 + X1 - X4(J)
165 V9=0.0 : W2 1.0/W1
210 U1=SQR(((R2*X5)**2 + (X2*X5)**2)/((R2/S)**2 + (X2+X5)**2))
!DEFINING ZTOR
211 Z1=ATN(-R2(S*X2)) - ATN((X2-X5)/(R2/S))
212 R6=U1*ABS(COS(Z1)) !RES AIR FIELD GAP
213 U2=SQR(R4**2 + X9**2)
214 Z2=ATN(X9/R4)
215 U3=U1*ABS(COS(Z1)) + U2**ABS(COS(Z2))
216 U4=U1*ABS(SIN(Z1)) + U2**ABS(SIN(Z2))
217 U5=SQR(U3**2 + U4**2) : Z3 ATN(U4/U3)!
ABS VALUE LINE MOTOR IMPD AND ANGLE
219 I1=V1/U5 : I3(I)=I1
220 P1=COS(Z3) !P.F. OF LINE MOTOR CIRCUIT
221 U6=SQR((R3**2 + (X3 - X4(J)**2))/U5)
222 Z4=ATN((X3 - X4(J))/R3) - Z3
223 Z5=ATN((-U6*ABS(SIN(Z4)))/(1.0 - U6*ABS(COS(Z4))))
224 P2=COS(Z5) !P.F. AT MOTOR TERMINALS
225 V2(I,J)=V1*(SQR(1.0 + U6*(U6 - 2.0*ABS(COS(Z4))))))
226 Z6(I)=Z5
240 T1=.92*Q1*(I1**2)*R6*W2
242 If I < > 1 GOTO 250
243 IF J < > 1 GOTO 250
244 T6=T1
250 W=(1.0 - S)*W1
260 GOSUB 500
270 IF T1 - T2 > 0.0 GOTO 280
275 PRINT "LOAD GREATER THAN MOTOR TORQUE"1 GOTO 330
280 DEF FNT4(W)=1.0 / (T1 - T2)
290 GOSUB 700
305 IF J=1 GOTO 360
310 IF V2(I,J) < V7 GOTO 340
315 IF J > 2 GOTO 330
321 PRINT "MAX VOLT EXCEEDED W/SMALLEST CAP REACT"
325 STOP
330 GOSUB 900
335 STOP
340 IF V2(I,J) > V5 GOTO 360
345 IF J < J9 GOTO 445
351 PRINT "INSUFFICIENT CAP REACT AVAILABLE"
355 STOP

```

```

360 V3=ABS(V2(I,J) - V6)
365 V4=V3 + V9
366 V9=V4
370 IF I=25 GOTO 385
375 I=I + 1 :S=S - S4
380 GOTO 210
385 IF J < > 1 GOTO 425
390 J2=J
391 FOR I=1 TO 25
392 I4(I) = I3(I) :Z7(I) = Z6(I)
393 NEXT I
400 GOSUB 900
405 M5=V4
410 IF J=J9 GOTO 455
415 J=J + 1
420 GOTO 150
425 IF V4 > M5 GOTO 440
430 J2=J
435 M5=V4
436 FOR I=1 TO 25
437 I4(I) = I3(I) :Z7(I) = Z6(I)
438 NEXT I
440 IF J=J9 GOTO 455
445 J=J + 1
450 GOTO 150
455 GOSUB 900
456 GOSUB 999 ! PLOT 1
460 STOP
500 REM SUBRT. FOR PIECEWISE LINEAR REP. OF LOAD TORQUE FUNCTION
502 IF (W - W4(1)) < 0.0 GOTO 520
503 IF (W - W4(1)) = 0.0 GOTO 505
504 IF (W - W4(1)) > 0.0 GOTO 510
505 T2=T8(1) :GOTO 545
510 IF (W - W4(25)) < 0.0 GOTO 530
511 IF (W - W4(25)) = 0.0 GOTO 515
512 IF (W - W4(25)) > 0.0 GOTO 520
515 T2=T8(25) :GOTO 545
520 PRINT "LOAD TORQUE CURVE DATA NOT WITHIN MOTORS SPEED RANGE"
530 FOR M=2 TO 25
531 IF (W - W4(M)) < 0.0 GOTO 540
532 IF (W - W4(M)) = 0.0 GOTO 535
533 IF (W - W4(M)) > 0.0 GOTO 535
535 NEXT M
540 I4=M - 1
541 T2=T8(I4) + (T8(M) - T8(I4))*(W - W4(I4))/(W4(M) - W4(I4))
545 RETURN
600 REM SUBRT. TO REQUEST LOAD CURVE DATA
605 PRINT:PRINT
610 PRINT "INPUT TWENTY FIVE VALUES OF THE LOAD TORQUE CURVE"
611 PRINT "IN ASCENDING ORDER"

```

```

620 PRINT "TYPE THE LOAD TORQUE VALUE AND THE CORRESPONDING"
630 PRINT "ANGULAR VELOCITY VALUE SEPARATED BY A COMMA FOR"
640 PRINT "EACH DATA POINT."
641 PRINT:PRINT
650 FOR I=1 TO 25
660 PRINT "DATA POINT NUMBER"; I
670 INPUT T8(I),W4(I)
680 PRINT
690 NEXT I
691 PRINT: PRINT: PRINT: PRINT: PRINT
695 RETURN
700 REM NUM. INTEG. SUBRT. TO FIND TIME
710 IF I=1 GOTO 745
715  $G = ((B1 + FNT4(W)) / 2) * S4 * W1$ 
740 T=T+G
745 T(I,J)=T*K1
746 B1=FNT4(W)
750 RETURN
900 REM PLOT SUBRT. HERE; MEANWHILE LIST RESULTS
902 PRINT: PRINT: PRINT
903 S=1.0
905 PRINT "TIME (SEC)"; "MOTOR VOLT", "AND VEL", " "; "MOTOR
CURRENT"
910 FOR I=1 TO 25 STEP 1
911 W=(1-S)*W1
915 PRINT T(I,J2),V2(I,J2),W,I4(I),Z7(I)
916 S=S - S4
920 NEXT I
921 IF J > 1 GOTO 930
922 PRINT: PRINT "CAPACITIVE REACTANCE 0.0"
923 GOTO 931
930 PRINT: PRINT "CAP. REACT."; X4(J2); "OHMS" PRINT: PRINT
931 RETURN
1200 END

```

READY

RUNNH

MOTOR SYNCHRONOUS SPEED (RPM)? 1200.0
RESISTANCE OF STATOR CIRCUIT? .294
RESISTANCE OF ROTOR CIRCUIT? .144
REACTANCE OF STATOR CIRCUIT? .503
REACTANCE OF ROTOR CIRCUIT? .209
MAGNETIZED REACTANCE OF MOTOR? 13.25
OPERATING SLIP (DECIMAL FRACTION)? .02
RESISTANCE OF EQUIVALENT IMPEDANCE? .159
REACTANCE OF EQUIVALENT IMPEDANCE? .111
STATION BUS (STABLE) VOLTAGE? 127.0
NOMINAL VOLTAGE AT MOTOR TERMINALS? 127.0
MAXIMUM ALLOWABLE VOLT. AT MOTOR TERM.? 139.7
MINIMUM ALLOWABLE VOLT. AT MOTOR TERM.? 114.3
MOTOR FULL LOAD CURRENT? 28.00
MAX. CAP. REACTANCE AVAILABLE? 0.4

INPUT TWENTY FIVE VALUES OF THE LOAD TORQUE CURVE IN ASCENDING ORDER.
TYPE THE LOAD TORQUE VALUE AND THE CORRESPONDING ANGULAR VELOCITY VALUE
SEPARATED BY A COMMA FOR EACH DATA POINT.

DATA POINT NUMBER 1
? 28.9,0.0

DATA POINT NUMBER 2
? 29.3,5.1

DATA POINT NUMBER 3
? 29.7,10.2

DATA POINT NUMBER 4
? 30.1,15.4

DATA POINT NUMBER 5
? 30.5,20.5

DATA POINT NUMBER 6
? 30.9,25.5

DATA POINT NUMBER 7
? 31.3,30.7

DATA POINT NUMBER 8
? 31.7,35.9

DATA POINT NUMBER 9
? 32.2,41.0

DATA POINT NUMBER 10
? 32.6,46.1

DATA POINT NUMBER 11
? 33.0,51.3

DATA POINT NUMBER 12

DATA POINT NUMBER 13
? 33.8,61.5

DATA POINT NUMBER 14
? 34.2,66.7

DATA POINT NUMBER 15
? 34.6,71.8

DATA POINT NUMBER 16
? 35.0,76.8

DATA POINT NUMBER 17
? 35.5,82.1

DATA POINT NUMBER 18
? 35.8,87.2

DATA POINT NUMBER 19
? 36.3,92.3

DATA POINT NUMBER 20
? 36.7,97.4

DATA POINT NUMBER 21
? 37.1,102.6

DATA POINT NUMBER 22
? 37.5,107.6

DATA POINT NUMBER 23
? 37.9,112.8

DATA POINT NUMBER 24
? 38.3,118.0

DATA POINT NUMBER 25
? 38.7,123.2

NOTE: VOLTAGE MAGNITUDE IN VOLTS.

NOTE: CURRENT MAGNITUDE IN AMPS, ANGLE IN RADIANS.

NOTE: ANGULAR VELOCITY IN RAD/SEC.

TIME (SEC)	MOTOR VOLT	ANG VEL	MOTOR CURRENT	
.179694	104.353	0	125.407	-.769802E-1
.348093	104.387	5.13127	124.964	-.756569E-1
.505674	104.425	10.2625	124.482	-.742313E-1
.652868	104.469	15.3938	123.954	-.726916E-1
.790206	104.518	20.5251	123.375	-.071024
.918192	104.576	25.6563	122.737	-.692124E-1
1.03722	104.642	30.7876	122.031	-.672384E-1
1.14776	104.719	35.9189	121.244	-.650801E-1
1.25058	104.809	41.0501	120.365	-.627122E-1
1.34578	104.916	46.1814	119.374	-.601046E-1
1.43377	105.043	51.3127	118.251	-.057222
1.51499	105.195	56.4439	116.967	-.540226E-1
1.58987	105.379	61.5752	115.489	-.504575E-1
1.7222	105.885	71.8378	111.746	-.419909E-1
1.78052	106.237	76.969	109.338	-.369485E-1
1.83424	106.685	82.1003	106.431	-.312626E-1
1.8837	107.265	87.2316	102.866	-.248602E-1
1.92962	108.029	92.3628	98.4144	-.176992E-1
1.97263	109.054	97.4941	92.7397	-.982565E-1
2.0138	110.453	102.625	85.3391	-.149823E-2
2.05497	112.39	107.757	75.4502	-.654808E-1
2.10033	115.088	112.888	61.9303	-.125773E-1
2.16585	118.775	118.019	43.2053	-.129601E-1
5.61756	123.464	123.15	18.2529	-.12895E-2

CAPACITIVE REACTANCE 0.0

TIME (SEC)	MOTOR VOLT	ANG VEL	MOTOR CURRENT	
.078699	128.396	0	154.301	-.255654
.154144	128.212	5.13127	153.485	-.254535
.226382	128.015	10.2625	152.602	-.25331
.295453	127.804	15.3938	151.642	-.251962
.361427	127.579	20.5251	150.596	-.250474
.424373	127.337	25.6563	149.451	-.248825
.484341	127.078	30.7876	148.194	-.246988
.541404	126.798	35.9189	146.808	-.244932
.595731	126.497	41.0501	145.271	-.242617
.647311	126.172	46.1814	143.559	-.239997
.69623	125.821	51.3127	141.641	-.237011
.74259	125.441	56.4439	139.479	-.233584
.786499	125.03	61.5752	137.024	-.229621
.828072	124.586	66.7065	134.216	-.224999
.867449	124.107	71.8378	130.976	-.21956

TIME (SEC)	MOTOR VOLT	ANG VEL	MOTOR CURRENT
.904792	123.595	76.969	127.202 -.213095
.940322	123.052	82.1003	122.759 -.20533
.974219	122.489	87.2316	117.466 -.195899
1.00689	121.927	92.3628	111.075 -.184313
1.03879	121.407	97.4941	103.245 -.169927
1.07074	121.008	102.625	93.4945 -.151912
1.1043	120.878	107.757	81.1486 -.129284
1.14323	121.285	112.888	65.2655 -.101108
1.20196	122.693	118.019	44.6307 -.671771E-1
2.56924	125.824	123.15	18.6018 -.296528E-1

CAP. REACT. .25 OHMS

STOP AT LINE 460

READY

NOMENCLATURE¹

E_S	Supply end voltage.
E_R	Receiving end voltage.
H	Inertia constant of the motor.
I_C	Continuous current through the capacitor.
I_n	Normal current to other loads.
I_S	Motor inrush current.
I_{FL}	Full-load current.
I_M, I_m	Momentary total current through the capacitor.
I, I_1	Motor current.
J	Moment of inertia of the motor.
KVA	Kilovolt-amperes.
KVAR	Reactive kilovolt-amperes.
NS	Number of standard capacitor units required.
NS'	Nearest whole number to NS.
Q_1	Number of phases in the circuit.
r_1	Stator resistance.
r_2	Rotor resistance.
R	Resistance.
R_e	Circuit equivalent resistance.

1. Volts, amps, ohms, and MKS units used unless otherwise specified.

s	Rotor slip.
SUM	Sum of the voltage differences during motor acceleration.
T_L	Load torque.
T_M	Motor electrical torque.
V_{LL}	Line-to-line voltage.
VR	Voltage rating of the capacitor.
V_1	Stable (infinite) bus voltage.
V_2	Motor terminal voltage.
W	Angular velocity.
W_s	Synchronous angular velocity.
x_m	Magnetization reactance.
x_1	Stator reactance.
x_2	Rotor reactance.
X	Total feeder reactance.
X_c	Capacitive series reactance.
X_e	Circuit equivalent reactance.
X_L	Inductive feeder reactance.
Z_e	Circuit equivalent reactance.
Z_f	Parallel impedance combination of the magnetization reactance and rotor impedance.
θ	Power factor angle.

LIST OF REFERENCES

- Bates, W. H., "Series Capacitors Successfully Applied on Distribution Systems," Transmission and Distribution, pp. 90-95, October 1968.
- Beeman, Donald, Industrial Power Systems Handbook, McGraw-Hill, 1955.
- Bloomquist, W. C., and Wilson, R. C., Capacitors for Industry, John Wiley and Sons, New York, pp. 142-174, 1950.
- Brereton, D. S., Lewis, D. G., and Young, C. C., "Representation of Induction-Motor Loads during Power-System Stability Studies," AIEE Paper 57-159, August 1957.
- Buell, J. W., and Concordia, C., "Analysis of Series Application Problems," AIEE, June 28, 1937.
- Butler, J. W., and Concordia, C., "Analysis of Series Application Problems," AIEE Transactions, June 28, 1937.
- Fitzgerald, A. E., and Kingsley, Charles, Jr., Electric Machinery, McGraw-Hill, 1961.
- Gabbard, J. L., and Rowe, J. E., "Digital Computation of Induction Motor Transient Stability," AIEE Paper 57-683, December 1957.
- Johnson, A. A., "Application Problems of Series Capacitors," Westinghouse Engineer, p. 106, July 1948.
- NEMA, Shunt Capacitors, Standards Publication No. CP1, 1973.
- Wagner, C. F., "Self-Excitation of Induction Motors with Series Capacitors," AIEE Transactions, Vol. 60, pp. 1241-1247, 1941.
- Westinghouse Electric Corp., Electric Utility Engineering Reference Book, Vol. 3, pp. 335-363, 1965.

