

A STUDY OF CAPACITOR VOLTAGE
DIP COMPENSATION FOR THE
CONTINUOUS MINER,

by

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PREFACE

The numbering system employed in the following pages is as follows. Chapters are numbered in Roman Numerals as I, II, etc., sections within chapters are underlined.

Most parameters are defined when they are introduced. A bar over a character, as in \bar{I} , indicates a phasor quantity, the same character without the bar represents the magnitude of the phasor.

All motors mentioned are squirrel-cage induction motors and are started across-the-line.

I. INTRODUCTION

Electric power is essential to the modern mining operation to run continuous miners, shuttle cars, conveyor belts, fans, pumps, etc. With the increasing demand for coal there will be a growth in the number and size of electrical mine equipment required to match this demand. The electrical power system supplying modern coal mines must be engineered with the utmost precision and competency or major problems can develop.

Most coal mining companies buy bulk electric power from a power utility which is usually supplied from a distribution line located near the mine. Obviously, a limiting factor for any distribution line is its load-carrying capacity, however the occurrence of voltage dip will put an additional restriction on the size and type of electrical load that can be accommodated. Voltage dip occurs when the instantaneous power required is greater than the power that can be supplied without a significant drop in voltage. Voltage dip is most critical when the mine is supplied from a distribution line that also serves residential and commercial customers. Large induction motors, such as those on a continuous miner, have the undesirable characteristic of drawing several times rated current from their power supply under starting (locked-rotor) conditions. Intermittent loading of these motors, if great enough will also produce adverse voltage conditions on the power system. Under starting and intermittent load conditions voltage dip will occur producing light flicker or dimming, and also interferes with the proper operation of voltage sensitive devices.

The mountainous terrain of southern West Virginia and southwest Virginia makes construction of electric power lines difficult and expensive, and wherever possible it is desirable to supply electric service to a mine from existing distribution facilities. Since power utilities must provide protection for residential and commercial customers being served from the same distribution line, voltage dip incidental to mining is intolerable. Protection against this is covered in the power service contract between mining company and power utility. Under the terms of this contract a mining operation must supply the power utility with the sizes, types, and number of motors that will be used throughout the life of the mine.¹ From this data voltage dip calculations are made and the cost of electric service will be greatly increased if excessive voltage dip is predicted.

Voltage dip is a function of the total impedance, nominal voltage of the line, and the current that flows in the line. The conventional remedial measures deal with the first two line parameters. These measures are effective but also can be very expensive. Generally, the measures taken are: (1) reconductoring of the existing line; (2) construction of an express distribution line for the mine; (3) the use of a diesel engine - ac generator set; (4) conversion to a higher nominal distribution voltage.

The first measure, reconductoring, involves replacing existing conductors with conductors of a larger size. This will reduce line impedance which increases its capacity and reduces voltage dip. It

may be necessary to reductor the entire line or certain sections depending upon the existing conductor sizes.

The second measure, construction of an express feeder, requires a new distribution line serving only the proposed mining operation. This line will connect the mine to the nearest distribution substation by the most feasible route. The conductors will be sized according to the mines anticipated motor load thus producing minimum voltage dip. More significantly, the express feeder will isolate the mine from residential and commercial customers who would be adversely affected by voltage dip problems. The cost of 12kv line construction in mountainous terrain requiring extensive right-of-way clearing is roughly \$42,000 per mile.²

The third measure, a diesel-electric combination, is employed when the apparent voltage dip cannot be alleviated by the first two measures or when their costs are prohibitive. This measure involves the use of a diesel engine driving an ac generator so that the mine will be generating its own power. An average cost for the motor-generator set would be \$100,000.³

The fourth measure, conversion to a higher voltage, will be taken by the power utility when the over-all condition of the distribution line merits such a change. When the stability limits of a line are being approached by increased load growth, the utility company will increase the nominal voltage of the line. This will increase its capacity and the apparent voltage dip will be reduced to negligible levels.

The complete cost of each of the first three measures will be paid by the mining company and the cost of the fourth measure will be paid by the utility company. Since the cost of obtaining electric power service must be included when estimating the capital cost of mine development, there can be an unexpected increase if voltage dip is excessive. The mining engineer must consider this possibility.

There are alternative remedial measures other than those listed above to be considered, especially capacitor compensation applied to the specific case of the continuous miner. The objective of this study is: (1) to familiarize the mining engineer with the problem of voltage dip; (2) to show how objectionable levels of voltage dip are determined and how to calculate voltage dip on a radial distribution line; and (3) to study capacitor compensation for voltage dip. An extensive review of pertinent literature, especially dealing with capacitor compensation, was undertaken and laboratory experiments were conducted.

II. THE PROBLEM OF VOLTAGE DIP

Definition, Cause, and Effects

Voltage dip occurs when the voltage level of an electrical power system drops rapidly, relative to its normal operating value. The amount of voltage dip is a function of the impedance of the electrical power system, nominal voltage of distribution line, and the current that is required by the electrical load connected to it. During the normal operating cycle of many electrical devices the current demand fluctuates, and depending upon the value of system impedance, the voltage varies accordingly. If excessive, voltage fluctuations will have an undesirable effect upon the operation of lights and other appliances connected to the same electrical power system. The degree of these adverse effects depends upon the amplitude, character, and period of dip (time interval between consecutive voltage changes, a dip when load is applied, a rise when load is removed).⁴

The most common undesirable effect is light flicker, the change in illumination produced by an electric lamp per unit of time. The amount of lamp illumination depends upon the applied voltage which in turn is dependent upon the other electrical load connected to the power system.

Another problem that can result from voltage dip is the shrinkage of the picture on a television picture tube. The shrinkage is the result of low voltage being supplied to the television set. This problem is of minor significance relative to light flicker.

Determination of Objectionable Levels

The amount of flicker that is permissible cannot be stated concisely for several reasons. Persons trying to read by an electric lamp will perceive flicker to varying degrees, thus introducing the human element.⁵ The effect of flicker can be thought of as a combination of physiological and psychological factors. One individual may perceive a change in illumination and be annoyed by it; another individual will not notice it at all. This aspect is due primarily to physiological factors related to the ability of the eye and brain to sense the stimulus; and to a lesser extent the mental concentration of the individual.

The degree of annoyance flicker causes, is a function of an individual's psychological make-up or state of mind. There is a wide range of psychological reactions among people, but generally the greater the time interval between successive changes in illumination the less annoying it will be.

Many studies have been conducted to determine the threshold between objectionable and non-objectionable flicker for the average person. A graph has been developed for this purpose and is included later.

Also, the wattage of the electric lamps has an important effect upon the amount of perceivable flicker. The smaller the wattage rating of the lamps the more rapid will be the change in illumination that occurs with a change in voltage.

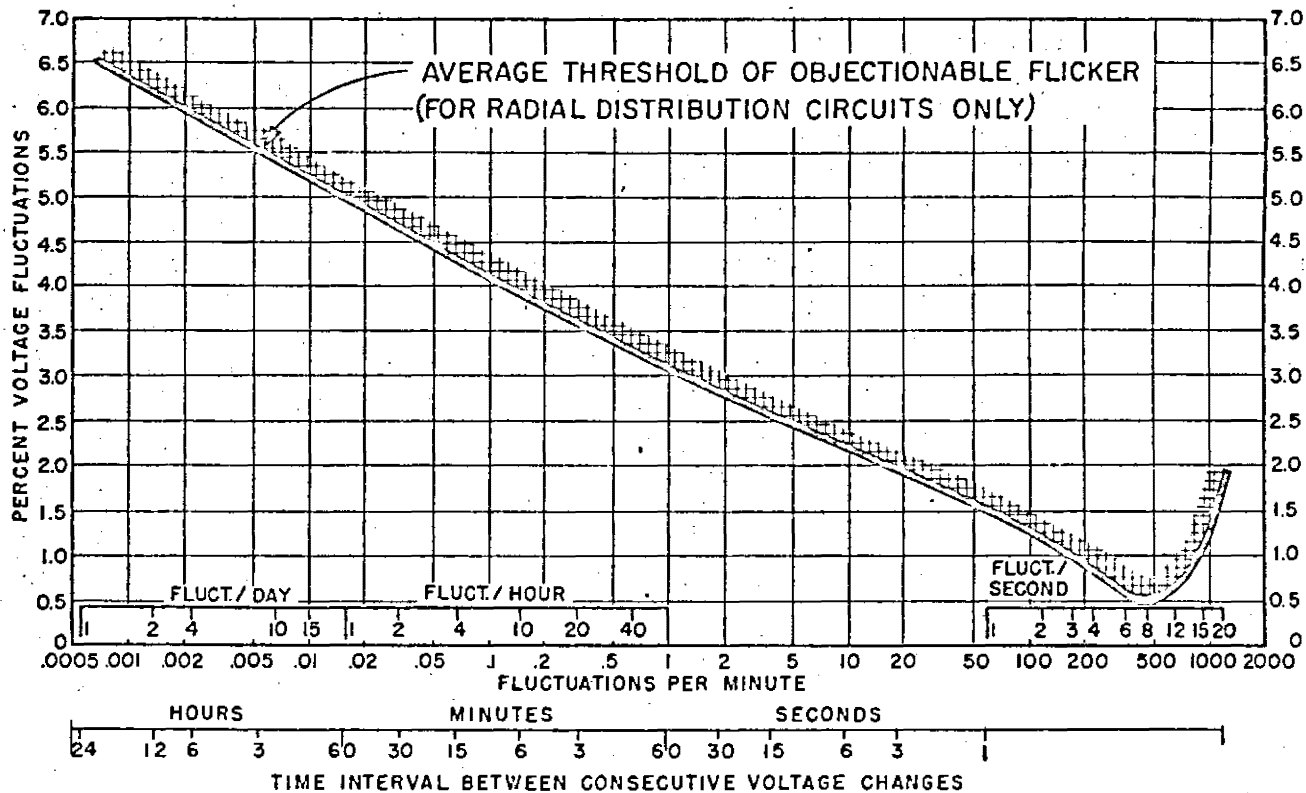
Another factor is the character of voltage fluctuation. This factor is used to categorize the types of voltage dip that can occur, they are: (1) gradual; (2) cyclic; and (3) abrupt dip.

Gradual dip is caused by loads which gradually increase or decrease but the duration of change is relatively short. This type of voltage fluctuation seldom causes trouble, therefore, it is not necessary to consider here.

Cyclic dip occurs from a periodic fluctuation in load applied to the power system where the period is very short but repeated over a long span of time. This type of change can occur with the operation of reciprocating pumps or compressors. Any cyclic light flicker that is perceivable is objectionable. The maximum amount of allowable voltage dip can be found given the frequency of dip, see Figure 1.

Abrupt dip is by far the most frequent and troublesome type and therefore, attracts considerable attention from the power system engineer. The worst condition for producing abrupt dip occurs at the instant an electric motor is started. This is due to the transient inrush of current which lasts until steady-state conditions are reached. The maximum dip occurs at the onset of starting where the inrush is at a maximum and the voltage rises gradually as the motor accelerates to its steady-state value. With across-the-line starting only the initial dip in voltage and the time interval between starts need be considered.⁴

Another example of abrupt dip occurs after the motor has started and is due to sudden or varying amounts of mechanical load being



applied. The load may come on suddenly and be removed gradually. An example of this type of loading would be the operation of a hoist or elevator. The load may also be applied gradually and then removed suddenly. This type of loading could occur from a conveyor belt where the volume of conveyed material increases uniformly and then decreases suddenly. Finally, abrupt changes occur due to the intermittent mechanical loading of electrical motors where the load is applied suddenly and removed suddenly. Some examples of electrical machinery subjected to this type of loading are rock crushers and, above all, the continuous miner.

To determine whether a particular type of abrupt loading will cause an objectionable amount of light flicker depends upon the resulting amplitude of voltage change and the period of the dip. If the period is less than one-half a second an individual does not distinguish between successive changes but interprets them as one event. The number of times a voltage dip of this type occurs is the parameter used to determine the maximum amount of dip. Some types of equipment producing abrupt dips with periods of one-half to six seconds are arc furnaces, arc welders, and rock crushers. Some equipment with loading intervals between six seconds to two minutes are hoists, cranes, and continuous miners. A loading interval between two minutes to twenty-four hours is produced by water pumps.⁴

For mining operations the continuous miner has large induction motors that are most likely to produce excessive voltage dip when starting and subjected to intermittent loading and not

the loading interval. If a voltage dip greater than 2.5 percent is calculated during starting, a review of the frequency of occurrence is necessary. The estimated total number of starts per unit of time for this miner and other miners producing dips greater than 2.5 percent is undertaken. This will depend upon the number of continuous miners already receiving power from the distribution circuit and their location. This estimated number of starts is located (see Figure 1, p. 8) on the fluctuation per unit of time scale and the amplitude of dip is located. If the calculated amplitude of dip is less than this value, electric power service will be supplied.

The occurrence of intermittent loading is difficult if not impossible to estimate. If a distribution circuit is having voltage dip problems related to intermittent loading, a power service request with calculated starting voltage dip greater than 2.5 percent is likely to be denied.⁷

Calculation of Voltage Dip

There are basically three stages to a typical electric power system; generation, transmission, and distribution. Electric power originates at the generating station and must be transferred to some distant point where it is consumed. The transfer of electric power is accomplished by the transmission and distribution stages.

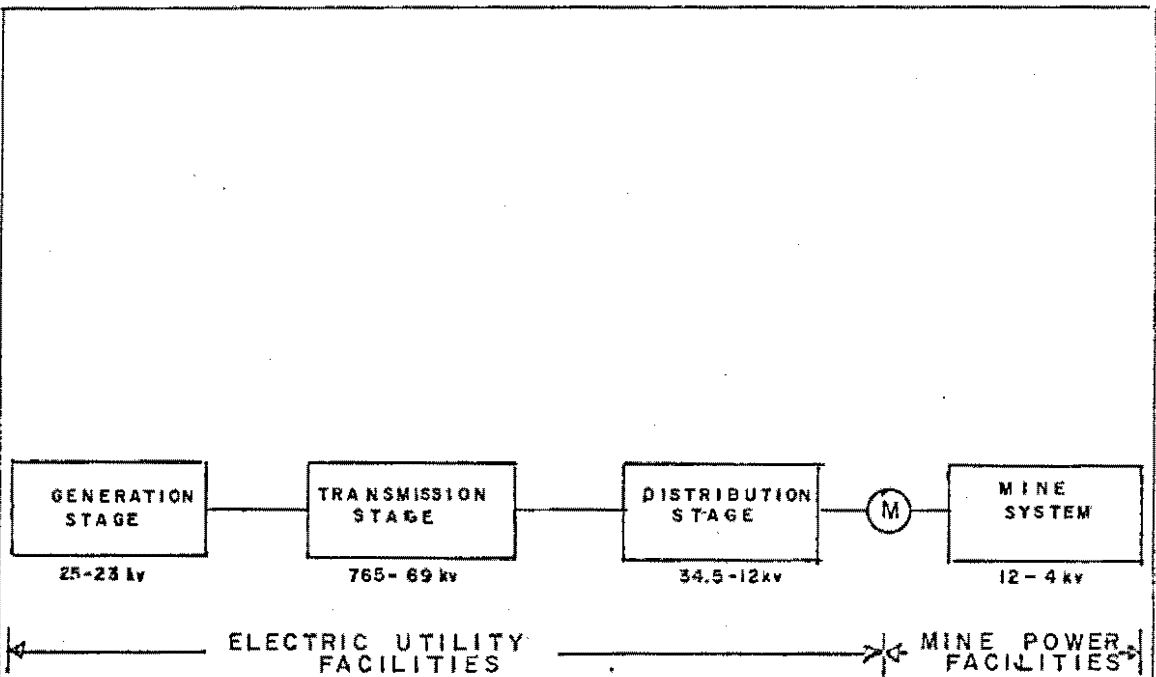
Usually during the generation stage a fuel is burned converting water to a high pressure steam that drives a turbine serving as the prime-mover for an electric generator. The electric generator produces three-phase ac power at a voltage in the range of 25..

kilovolts. There may be several generators per generation station and there are many generation stations throughout the nation.

Electric power is transferred over the longest distances during the transmission stage. The generator voltage is stepped up to a higher transmission voltage that will minimize line losses. Some nominal transmission voltages are: 69, 138, 345, 500 and 765 kilovolts. There are transmission systems serving large areas of the nation interconnecting to form a mesh circuit that increases the capacity and reliability of the power system.

The distribution stage is the last stage in electric power transfer. The transmission voltage is stepped down to the distribution voltage at a substation, and from the substation the distribution circuits fan out to deliver the power where it is finally consumed. Some common distribution voltages are 4.16, 12.46 and 34.5 kilovolts. The distribution line is a radial feeder that may supply residential, commercial, and mining customers from the same circuit. Electrical power is usually delivered to the mine from the distribution circuit nearest to the mine location. The power is metered in the vicinity of the mine and from the metering point the mine's power distribution system delivers the power to where it is consumed.

A block diagram for a general power system is shown in Figure 2. From the generation stage to the metering point are the power utility facilities; beyond the metering point are the mine power facilities. The mining company is responsible for any disturbance it causes that interferes with the normal operation of the rest of the power system.



NOTE: M = Metering Point

Figure 2. Block Diagram for a Typical Electrical Power System

Excessive voltage dip resulting from the normal operation of a continuous miner will produce light flicker at points connected to the same distribution circuit. Also, the resultant flicker may occur on other circuits connected to the same substation transformer bus. Due to the large electrical capacity of the generation and transmission systems, voltage dip is usually confined to the distribution system.

Electric power utilities must calculate voltage dip when the following conditions occur: (1) a new mine submits a request for electric service; (2) an existing mine desires to increase its power demand above the level prescribed in its original contract. The voltage dip calculation is done to determine the dip at the metering point.

To obtain a mathematical expression for voltage dip, electrical concepts must be examined. The electric power system is dynamic and complex requiring several simplifying concepts to analyze it. First, it must be assumed that all three-phase conductors are carrying an equal amount of electrical load. This is valid in most cases and is normally used in power system analysis. When balanced conditions occur it allows a three-phase system to be modeled as a single-phase system, with one phase wire and a corresponding ground. The second concept allows a Thevenin's equivalent circuit for the power system to be derived. Thevenin's theorem states that any linear two terminal active network can be replaced by a single voltage source in series with a single equivalent impedance.

The nominal voltage, impedance and load current of the distribution line are the main parameters effecting voltage dip, therefore, the distribution system is of major concern. The single-phase circuit representation for the power system is shown in Figure 3. The Thevenin's voltage source \bar{V}_S is the distribution voltage of the distribution line. The source impedance Z_S is the Thevenin's equivalent impedance for the generation and transmission mesh circuit, plus the substation transformer impedance, converted to the distribution voltage base. The distribution line impedance is Z_L and \bar{V}_{MP} is the receiving-end voltage at the metering point. \bar{I}_L is the line current flowing per phase in the distribution line. It should be emphasized that \bar{I}_L is the phasor summation of current supplying residential, commercial, and mining load located at various points on the line. The value of the current is greatest at the substation, decreasing toward the end of the line in relation to various load locations.

To solve for the receiving-end voltage \bar{V}_{MP} , a simple loop equation can be written as

$$\bar{V}_{MP} = \bar{V}_S - \bar{I}_L (Z_S + Z_L) \quad (1)$$

From this equation the metering point voltage will equal the source voltage minus the voltage dropped across the power system resulting from the line current \bar{I}_L and the impedance $(Z_S + Z_L)$.

The component of line current causing voltage dip results from the operation of large induction motors such as in the continuous miner.

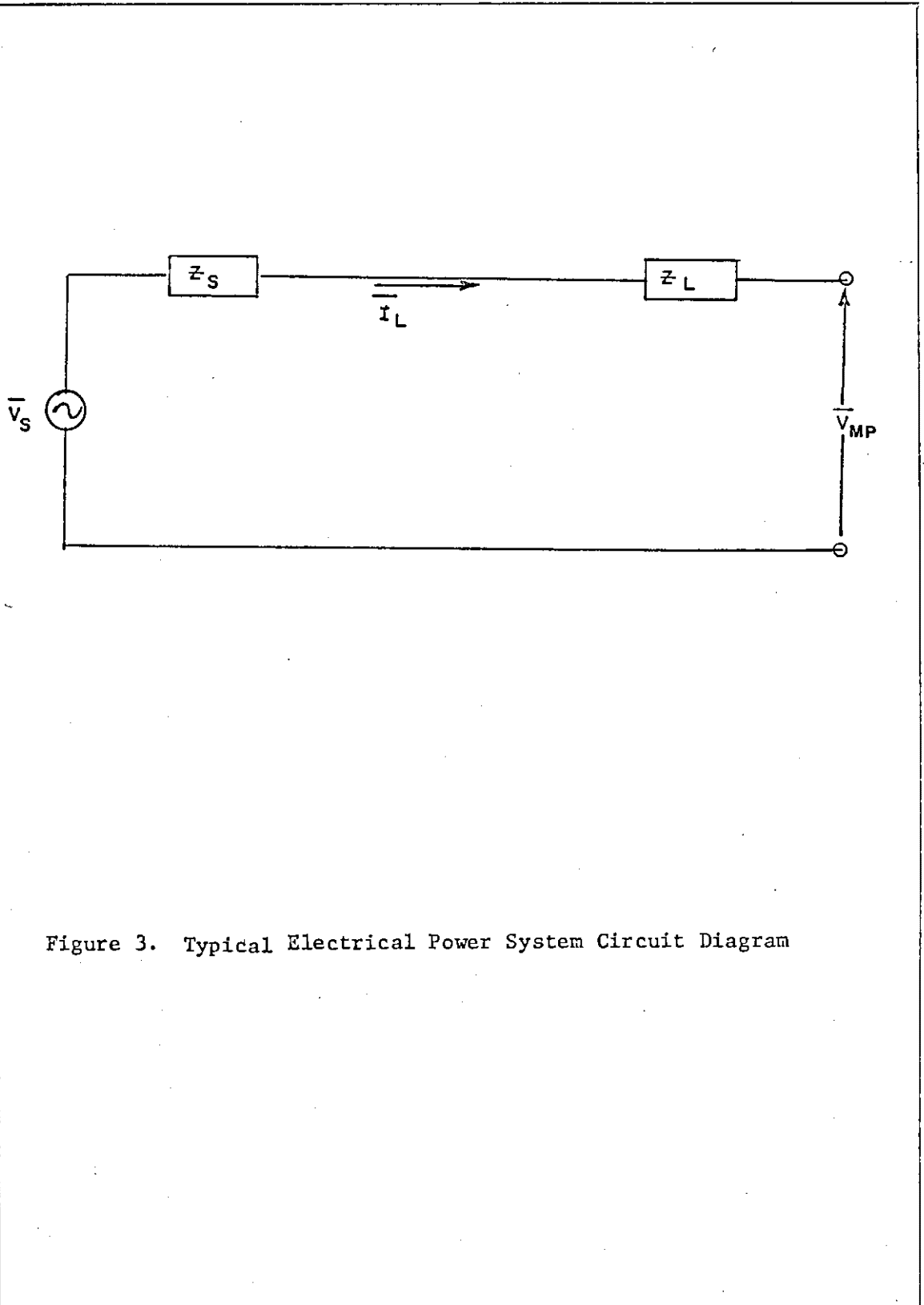


Figure 3. Typical Electrical Power System Circuit Diagram

The ac response of an electrical circuit can be divided into three states: subtransient, transient, and steady-state. The three states occur when there is a change taking place in the circuit, especially the starting of a continuous miner. The subtransient state lasts from 0 to 0.033 second; the transient state lasts from 0.033 to 0.166 second after the initiation of a change. Steady-state conditions occur from approximately 0.166 second until another change is initiated in the system.⁸ Voltage dip occurs when the line current is in transition between two distinct steady-state values.

The impedance of the power system consists of Z_S and Z_L , where Z_S is the Thevenin's equivalent impedance of the generation and transmission systems, plus the substation transformer impedance. The distribution line impedance Z_L , is a distributed impedance dependant upon the size, spacing, and length of the line. The impedance consists of a resistive and reactive component that can be written as

$$Z_L = (R_L + jX_L)\ell \quad (2)$$

where ℓ is the length of line per thousand feet. The values of R_L and X_L are given in Tables 1, 2, and 3, for various conductors and with a geometric mean spacing of 4.69 ft., in units of ohms per thousand feet. Therefore, the line impedance is a minimum at the source and increases with the length of the line reaching a maximum at the end.

Equation (1) may now be rewritten as

$$\bar{V}_M = \bar{V}_S - (\bar{I}_L + \bar{I}_L') (Z_S + Z_L) \quad (3)$$

TABLE 1
 Impedance of Copper Conductor in OHMS per Thousand Feet,
 Three-Phase Geometric Mean Spacing: 4.69 Feet, Conductor
 Temperature: 50°C

Phase Conductor Wire Size	Strands	Positive Sequence Impedance Components	
		R_L	X_L
500,000CM	19	.0246	.1195
450,000	19	.0273	.1206
400,000	19	.0307	.1220
350,000	19	.0348	.1235
300,000	19	.0407	.1254
250,000	19	.0487	.1275
4/0	19	.0574	.1294
3/0	12	.0723	.1309
2/0	7	.0911	.1360
1/0	7	.1150	.1386
1	7	.1449	.1413
2	7	.1809	.1434
3	3	.2280	.1460
4	1	.2847	.1506
6	1	.4527	.1559
8	1	.7197	.1612

NOTE:

For geometric mean spacing of 4.0 Ft. subtract .0034 from X_L

For geometric mean spacing of 3.5 Ft. subtract .0064 from X_L

For geometric mean spacing of 3.0 Ft. subtract .0100 from X_L

For geometric mean spacing of 5.0 Ft. add .0017 to X_L

Source: McGraw-Edison Company⁹

TABLE 2

Impedance of Aluminum Conductor Steel Reinforced Conductor in OHMS per Thousand Feet, Three-Phase Geometric Mean Spacing: 4.69 Feet, Conductor Temperature: 50°C

Phase Conductor Wire Size	Strands	Positive Sequence Impedance Components	
		R_L	X_L
795,000CM	26	.0244	.1108
715,000	26	.0273	.1119
666,600	54	.0303	.1133
636,000	26	.0307	.1133
605,000	26	.0326	.1138
556,500	26	.0352	.1148
500,000	30	.0390	.1150
477,000	26	.0409	.1167
397,500	26	.0491	.1188
336,400	26	.0580	.1206
300,000	26	.0648	.1220
266,800	26	.0729	.1233
4/0	6	.1121	.1453
3/0	6	.1369	.1528
2/0	6	.1695	.1566
1/0	6	.2121	.1595
1	6	.2614	.1612
2	6	.3201	.1612
3	6	.3920	.1604
4	6	.4867	.1600
6	6	.7538	.1627

NOTE:

For geometric mean spacing of 4.0 Ft. subtract .0034 from X_L

For geometric mean spacing of 3.5 Ft. subtract .0064 from X_L

For geometric mean spacing of 3.0 Ft. subtract .0100 from X_L

For geometric mean spacing of .50 Ft. add .0017 to X_L

Source: McGraw-Edison Company¹⁰

TABLE 3

Impedance of Bare All-Aluminum Conductor in OHMS per Thousand Feet
 Three-Phase Geometric Mean Spacing: 4.69 Feet, Conductor
 Temperature: 50°C

Phase Conductor Wire Size	Strands	Positive Sequence Impedance Components	
		R_L	X_L
795,000CM	37	.0248	.1138
750,000	37	.0263	.1146
715,500	37	.0277	.1150
700,000	61	.0282	.1152
636,000	37	.0309	.1163
600,000	61	.0328	.1169
556,500	37	.0352	.1180
500,000	37	.0392	.1189
477,000	37	.0411	.1195
450,000	37	.0436	.1203
400,000	37	.0498	.1214
397,500	19	.0492	.1220
350,000	37	.0557	.1231
336,400	37	.0580	.1237
300,000	37	.0650	.1252
266,800	37	.0731	.1265
250,000	37	.0778	.1271
4/0	19	.0920	.1284
3/0	19	.1159	.1311
2/0	19	.1466	.1347
1/0	19	.1845	.1377
1	7	.2330	.1413
2	7	.2934	.1428
3	7	.3701	.1466
4	7	.4661	.1492
6	7	.7424	.1547

NOTE:

For geometric mean spacing of 4.0 Ft. subtract .0034 from X_L

For geometric mean spacing of 3.5 Ft. subtract .0064 from X_L

For geometric mean spacing of 3.0 Ft. subtract .0100 from X_L

For geometric mean spacing of 5.0 Ft. add .0017 to X_L

Source: McGraw-Edison Company¹¹

where \bar{I}'_L is the change in current between successive steady-state values of \bar{I}_L . From the above relation the drop in \bar{V}_M is directly related to the value of \bar{I}'_L and Z_L . Thus the remedial measures must either decrease \bar{I}'_L or Z_L or both.

During the operation of a continuous miner the worst condition of voltage dip occurs at the instant the cutting head motors are started. Under starting conditions the current required by the motor is its maximum or locked-rotor value. This value of current is approached each time the motor is loaded excessively. Starting and intermittent loading occurs so fast (in the transient range) that regulators or load-tap changing transformers can not react quickly enough to correct the drop in voltage, thus, the voltage all along the line dips.

There are several methods for calculating voltage dip, a simple equation for this purpose is:

$$\% V_{DIP} = \frac{SKVA \times 100}{SKVA + FKVA} \quad (4)$$

where:

SKVA = starting or locked-rotor kva at point where motor will be located.

FKVA - maximum three-phase fault in kva at any point on the system where voltage dip is to be determined. ¹²

The starting kva can be calculated by several methods. If the locked-rotor current is known,

$$SKVA = \sqrt{3} V_{MP} I_{LR} \quad (5)$$

where:

V_{MP} = the magnitude of voltage line to line at the metering point.

I_{LR} = locked-rotor current in amperes.

The value of locked-rotor current may be obtained from a set of average data, see Table 4, or from the manufacturer. If the locked-rotor current cannot be found by these methods and the N.E.M.A. code letter for the motor is known then the SKVA may be obtained, see Table 5. A rule-of-thumb method, where one horsepower approximately equals one kva, may be used in the absence of all the above information. Therefore the starting kva would become:

$$SKVA = 6 \times HP \quad (6)$$

where:

HP = the horsepower rating of the motor.

The maximum three-phase fault kva may be calculated as follows:

$$FKVA = \frac{MVA_B \times 1000}{Z_T} \quad (7)$$

where:

MVA_B = the mega volt-ampere base which is an arbitrary normalizing factor yielding values in per-unit. A value for $MVA_B = \frac{V_B^2}{Z}$, where V_B is the nominal voltage of the line, will allow values of impedance in ohms to be used without the necessity of converting to per-unit.

Z_T = the summation of Z_S and Z_L in ohms.

The value of Z_S and Z_L may be obtained from the power utility, if Z_L is not known then tables may be used (See Tables 1, 2, and 3, pp. 17,

TABLE 4
Approximate, Average Data on Normal-Torque Normal
Starting KVA, Squirrel-Cage Induction Motors, 440 Volts,
60 Cycles, Three-Phase

Motor hp	Syn- chro- nous rpm	Efficiency		Power factor		Full- load kilowatts	Full- load amperes	Locked- rotor amperes
		Full load	½ load	Full load	½ load			
5	3,600	83.5	81.0	0.86	0.71	4.5	6.8	43
	1,800	83.5	81.0	0.86	0.73	4.5	6.8	43
	1,200	82.5	80.0	0.82	0.66	4.5	7.2	43
	900	82.0	79.0	0.76	0.58	4.5	7.9	42
10	3,600	85.0	82.5	0.88	0.75	8.8	13.0	93
	1,800	85.0	82.5	0.88	0.77	8.8	13.0	77
	1,200	84.5	82.0	0.84	0.72	8.8	13.8	77
	900	84.0	81.0	0.80	0.65	8.8	14.6	77
20	1,800	86.5	84.0	0.89	0.78	17.2	25.4	150
	1,200	86.5	84.0	0.86	0.75	17.2	26.2	150
	900	85.0	82.5	0.84	0.70	17.5	27.3	150
	600	84.5	82.0	0.74	0.60	17.6	31.2	140
30	1,800	87.5	85.0	0.90	0.80	25.5	37.2	215
	1,200	87.5	85.0	0.88	0.77	25.5	38.0	215
	900	86.5	84.0	0.86	0.72	25.9	39.6	215
	600	86.0	83.5	0.78	0.64	26.0	43.8	200
50	1,800	88.5	86.0	0.91	0.79	42.2	60.8	400
	1,200	88.5	86.0	0.88	0.76	42.2	62.8	400
	900	88.0	85.5	0.85	0.69	42.4	65.5	400
	600	87.5	85.0	0.80	0.67	42.6	70.0	360
75	1,800	90.0	87.5	0.91	0.79	62.1	89.9	600
	1,200	89.5	87.0	0.88	0.76	62.5	93.3	600
	900	89.0	86.5	0.87	0.71	62.8	94.7	600
	600	88.5	86.0	0.82	0.69	63.2	101	550
100	1,800	90.5	88.0	0.91	0.79	82.4	119	800
	1,200	90.0	87.5	0.89	0.77	82.8	122	800
	900	89.5	87.0	0.87	0.71	83.2	126	800
	600	89.0	86.5	0.83	0.69	83.8	132	700
150	1,800	91.0	88.5	0.91	0.79	123.0	177	1,200
	1,200	91.0	88.5	0.89	0.77	123.0	181	1,200
	900	90.5	88.0	0.88	0.72	123.5	185	1,200
	600	90.0	87.5	0.85	0.69	124.5	193	1,000
200	1,800	91.5	89.0	0.91	0.79	163.0	235	1,600
	1,200	91.5	89.0	0.89	0.77	163.0	240	1,600
	900	91.0	88.5	0.88	0.72	164.0	245	1,500
	600	91.0	88.0	0.86	0.69	164.0	250	1,500
	450	90.5	87.0	0.82	0.65	165.0	264	1,300

NOTE: For 220 volts the full-load amperes and starting amperes will be twice those given above; for 2,200 volts approximately one-fifth those given above.

Source: Electrical Engineering for Professional Engineer's
Examination 13

TABLE 5

Locked-Rotor Indicating Code Letters

Code Letter	Kilovolt-Amperes per Horsepower with Locked Rotor	
A.....	0	— 3.14
B.....	3.15	— 3.54
C.....	3.55	— 3.99
D.....	4.0	— 4.49
E.....	4.5	— 4.99
F.....	5.0	— 5.59
G.....	5.6	— 6.29
H.....	6.3	— 7.09
J.....	7.1	— 7.99
K.....	8.0	— 8.99
L.....	9.0	— 9.99
M.....	10.0	— 11.19
N.....	11.2	— 12.49
P.....	12.5	— 13.99
R.....	14.0	— 15.99
S.....	16.0	— 17.99
T.....	18.0	— 19.99
U.....	20.0	— 22.39
V.....	22.4	— and up

Source: National Fire Protection Association Handbook of the National Electrical Code 14

18, and 19). The calculation of voltage dip for an actual circuit will be performed in the next chapter. From equation (4) it can be seen that voltage dip depends upon the current required by the continuous miner and the sum of impedance for the power system.

III. ANALYSIS OF VOLTAGE DIP CAUSED BY CONTINUOUS MINER OPERATION

The continuous miner consists of the following component parts: (1) the job-end; (2) basic tractor components; (3) running gear; (4) miscellaneous.

The job-end components excavate and load the coal onto a shuttle car. The excavator has a rotating drum or cutting head that is driven into the coal face. The coal is broken and falls onto the pan where gathering arms usually pull the coal onto a chain conveyor. The chain conveyor transports the coal from the pan to the rear boom of the machine and then dumps it into the shuttle car.

The basic tractor components include the parts necessary for the mechanical operation of the machine. Some of these are the power plants, transmission, controls, brakes, chassis, etc.

The running gear components usually supply the tramping and sumping force of the machine, which consists of the crawler tracks, suspension, and its immediate drive train.

Miscellaneous components consist of safety features such as sprays, methane detector, canopy, blowers, etc.¹⁵

The mechanical power for the cutting head is supplied by two squirrel-cage induction motors. These motors usually operate at 440 volts, 900 rpm and are delta-connected. Horsepower ratings for different manufacturers and models are given in Table 6, an average figure is 350 total connected horsepower. There can be smaller induction motors, powering the hydraulic pumps and in some cases providing

TABLE 6

Mining Machines - Horsepower Rating

Manufacturer	Model Number	Motor Requirements (Horsepower)
Wilcox	--	2-100
Lee-Norse	260	2-50
		2-100
Jeffery	120L	2-50
Jeffery	101MC	3-95
Jeffery	100L	1-125
Jeffery	120M	2-275
Jeffery	120H	2-300
Joy	10CM	2-175
Joy	11CM	2-175
Joy	12CM	2-175
Joy	14CM	2-90
Joy	16RB	1-150
Joy	15RU	1-185
		or
		1-230

Source: Appalachian Power Company¹⁶

the mechanical power for trammimg. These small motors are of much less significance compared with the power required by the cutting head motors.

The cutting head motors are water cooled because of space restrictions underground, an air-cooled motor with the same output power would be much larger. Water cooling of the motor permits longer operation at torques that would otherwise quickly overload, overheat, and damage it.¹⁷

The starting of the cutting head motors and the variable torque involved in cutting causes the voltage dip. The voltage fluctuation during starting and the real power required during a complete operational cycle are quite dynamic, see Figures 4 and 5.

A better understanding of the electrical power requirements for the miner can be facilitated by electrically analyzing the induction motor. Induction motors are equipped with a stator winding and a rotor that may be wound or of the squirrel-cage type. In normal use only the stator winding is excited with an ac source. Currents are made to flow in the rotor by magnetic induction and these currents produce a magnetic field distribution that interacts with the stator field to produce a net unidirectional torque. The frequency of the induced current in the rotor is dependent upon the speed of the rotor. This relationship between the rotor speed and the line frequency is such that the stator field is stationary in relation to the rotor field. The result is that the induction motor is capable of producing torque at any speed less than its synchronous speed. The synchronous speed is given as:

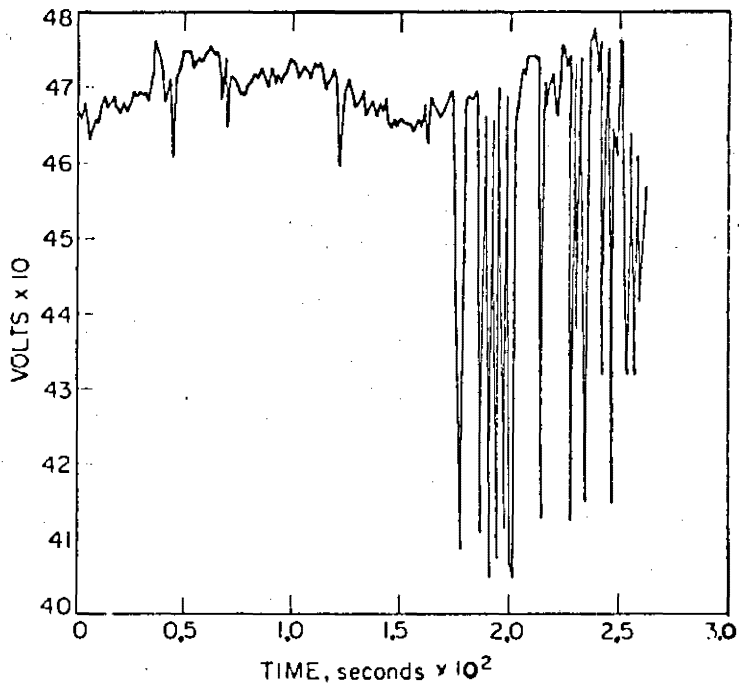


Figure 4. Voltage Fluctuations at Distribution Box During Miner Starting

Source: Bureau of Mines¹⁸

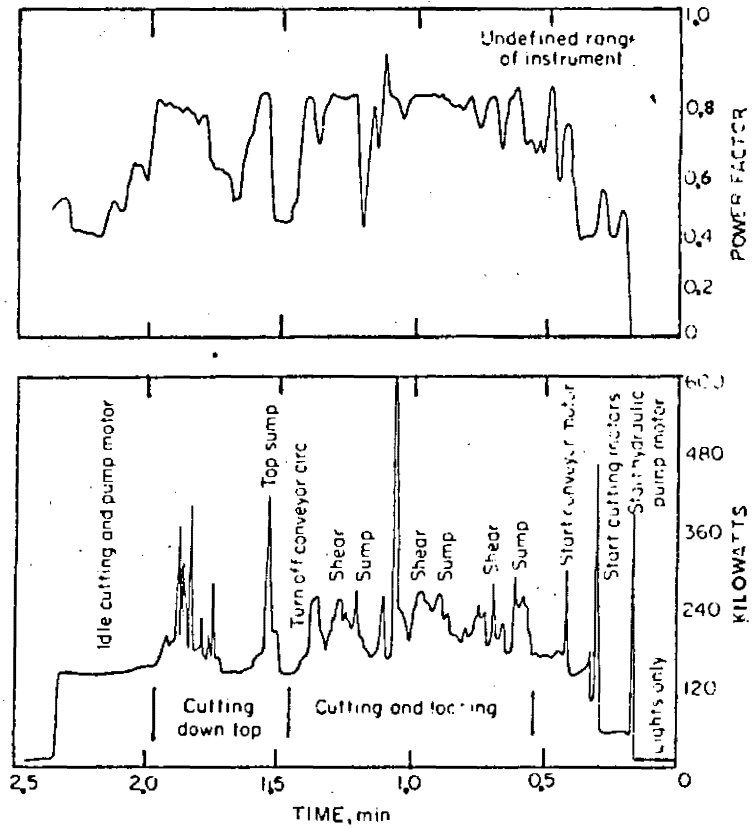


Figure 5. Typical Set of Cutting and Loading Electrical Parameters

Source: Bureau of Mines¹⁸

$$N_S = \frac{(120)F}{P}$$

where:

N_S = synchronous speed of rotor in rpm.

F = line frequency.

P = number of poles in motor.

The speed of the rotor must be less than N_S synchronous speed. This speed difference is called slip and is given as:

$$S = \frac{N_S - N}{N_S}$$

where:

N = actual speed of rotor in rpm.

An electrical circuit model representing the induction motor can be derived using the terminology of slip.¹⁹

Since the induction motor is similar to a transformer its steady-state circuit model is also similar to a transformer model. The circuit model, see Figure 6, consisting of a stator phase winding resistance R_1 , a stator phase winding leakage reactance X_1 , and a magnetizing impedance made up of the core loss resistor R_C and the magnetizing reactance X_ϕ , are the same as for a transformer. The circuit parameters for the rotor are the rotor winding resistance R_2' , rotor phase winding leakage resistance X_2' , and variable load resistor R_M . The load resistor is the electrical equivalent of a mechanical shaft.

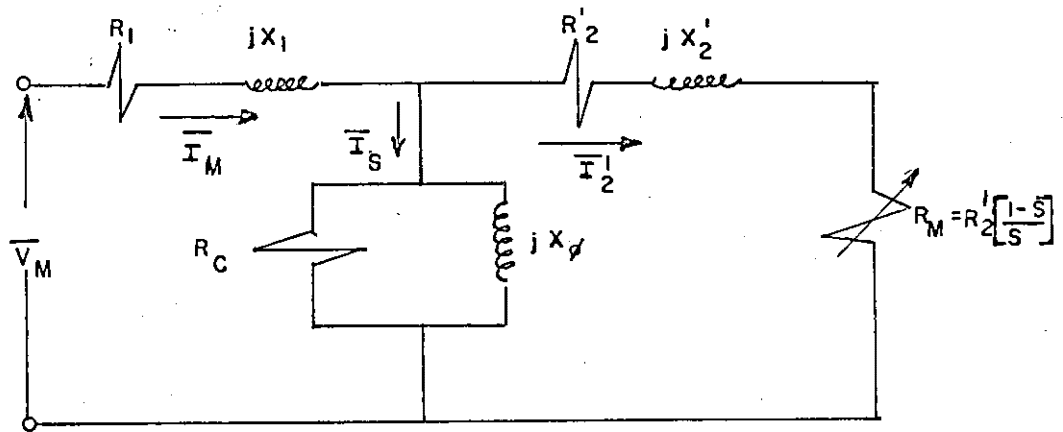


Figure 6. Equivalent Single-Phase Circuit Diagram of a Three-Phase Induction Motor

load. The prime notation is used to denote stator-referred rotor quantities. These circuit parameters are for wye-connected motors. Delta-connected motors may be represented in the same way but the parameters refer to the equivalent wye-connection. This circuit diagram is for one phase of a three-phase wye-connected motor only, the line current will be the same, but the power calculated from such a diagram must be multiplied by three.

With the aid of the circuit diagram, it is possible to visualize the power requirements of the induction motor during starting and intermittent load conditions. When starting the slip is equal to one ($N = 0$) thus R_M equals zero; the input impedance will therefore, be a minimum and the line current will be a maximum. From no load to full load $0 \lesssim S \lesssim 0.05$; from full load to maximum output torque (approximately 225 percent full load) $0.05 \lesssim S \lesssim 0.3$, for these two conditions $\infty \gtrsim R_M \gtrsim 2.33 R_2$ therefore, the line current can vary from its minimum (no load value) to 225 percent of the no load value. If the mechanical torque required is greater than the maximum output torque the motor will begin to stall and the line current will approach its starting (locked-rotor) value.²⁰

Total electric power S , measured in kva, is the vector sum of real power P , measured in kilowatts, and reactive power Q , measured in kilovars. The real power required by the motor does the work in the system, and is a constant value per mechanical load, and a function of R_M in the circuit model. The reactive power expresses the energy that is being stored in the magnetic fields and alternately flows

toward the motor and away from the motor at twice line frequency. Reactive power is a function of the input inductance of the motor. In like manner the total motor current \bar{I}_M can be resolved into a real component \bar{I}_R and inductive component \bar{I}_X , and when multiplied by the input voltage \bar{V}_M will yield P and Q respectively. The real power requirements of the miner during starting and various load conditions are given (see Figure 5, p. 29).

The real current is directly proportional to the mechanical torque required from the motor. The reactive current supplies the magnetic fields required to produce this output torque. The equivalent circuit model can be reduced to an equivalent input resistance R_0 and inductive reactance X_0 that will draw a real current and reactive current when a voltage is applied. Various values for R_M will yield various values for R_0 and X_0 thereby, drawing various values of \bar{I}_R and \bar{I}_X depending on the mechanical load that is applied to the motor. A measure of \bar{I}_R with respect to \bar{I}_X is known as the power factor PF and can be written as:

$$PF = \cos (\tan^{-1} I_X/I_R)$$

Various values of power factor during miner operation are given in Figure 5, p. 29. Although there are several approaches to analyzing an induction motor, this approach will facilitate capacitor analysis of the next chapter.

A Case Study

A coal mining operation situate, near Marvin in Buchanan County, Virginia requested electric power service from Appalachian Power Company on December 27, 1976. The service was to be primary metered at 12kv from pole number 326/94 on the Hales Branch-Dismal River 12KV distribution circuit. A Joy model 14CM continuous miner containing 2-90hP squirrel-cage induction motors (see Table 6, p. 26) was to be utilized.²¹

Voltage Dip Calculation for Case Circuit

From the one-line diagram for the circuit, see Figure 7, the length and size of the conductor can be derived; from Table 2 and 3, pp. 18 and 19, the impedance per kilofoot of conductor at a geometric mean spacing of 4.69 ft. was found. From this data the line impedance Z_L was calculated, see Table 7.

The voltage on the 12kv substation bus is held at 13.060 kv; if the mva base is chosen to be 13.060^2 then $MVA_B = 170.56$. The fault mva at the substation bus is 165 mva.²² The Thevenin's equivalent impedance Z_S in ohms is calculated as follows:

$$Z_S = \frac{MVA_B}{MVA_F}$$

$$Z_S = \frac{170.56}{165}$$

$$Z_S = 0.00 + j 1.034$$

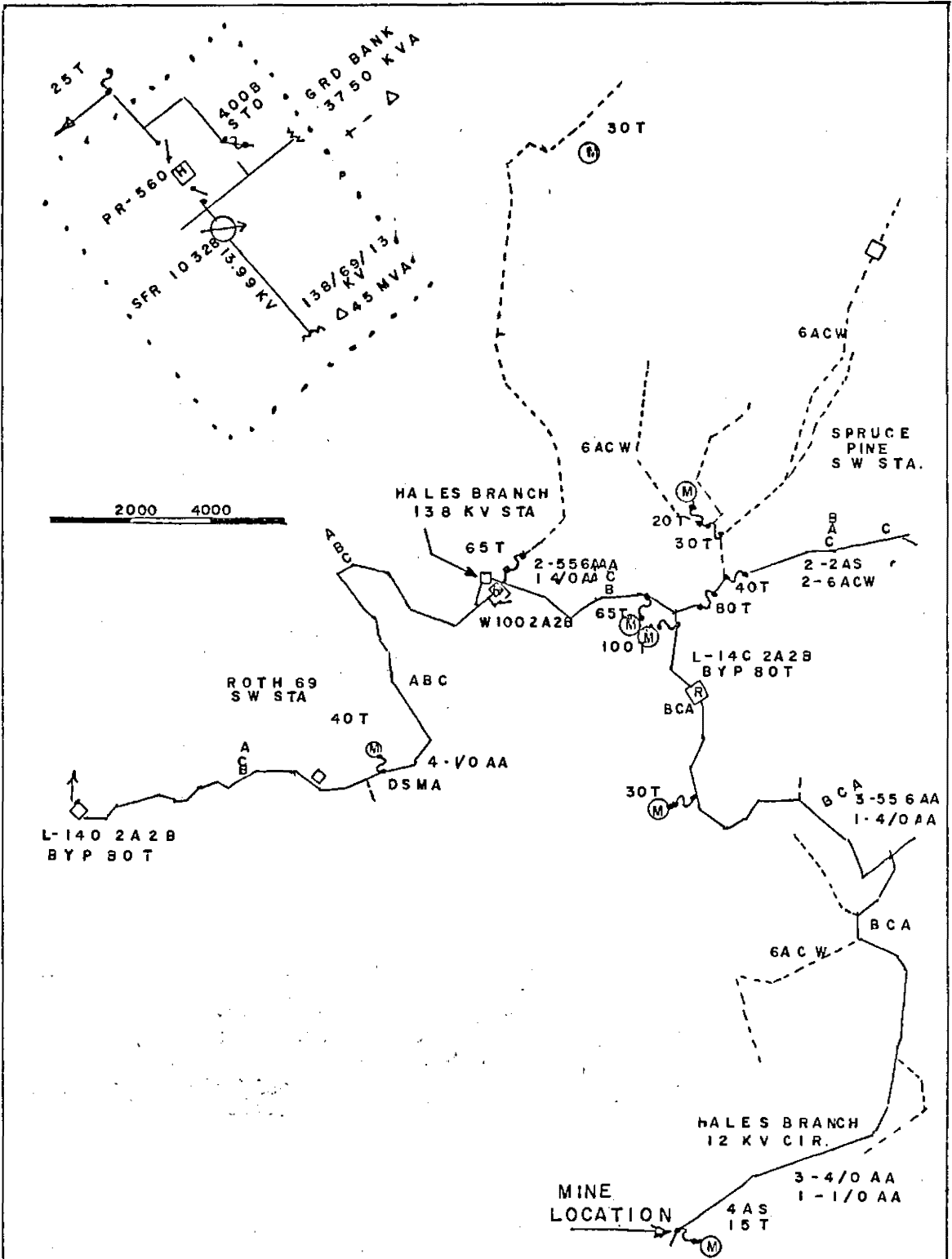


Figure 7. Case Study Circuit One-Line Diagram

Source: Appalachian Power Company⁷

TABLE 7

Distribution Line Data and Impedance Calculations for Case Circuit

Type of Conductor	Conductor Size (CM)	Length of Conductor, l (KILOFEET)	Impedance per kilofoot (OHMS)	Line Impedance, Z_L (OHMS)
All Aluminum	556	10.9	$0.0352 + j0.1180$	$0.384 + j1.286$
All Aluminum	4/0	12.9	$0.0920 + j0.1284$	$1.187 + j1.656$
Aluminum Steel Reinforced	1/0	8.0	$0.2121 + j0.1595$	$1.697 + j1.276$

Total Length = 31.8 Ft.

$$Z_L = 3.268 + j4.218 \text{ OHM}$$

Now, the total impedance Z_T can be found:

$$Z_T = Z_S + Z_L$$

$$Z_T = (0.0 + j 1.034) + (3.268 + j 4.218)$$

$$Z_T = 3.268 + j 5.252 = 6.186 \angle 58.11^\circ$$

The fault kva at the metering point is:

$$FKVA = \left(\frac{MVA_B}{Z_T} \right) \times 1000$$

$$FKVA = \frac{170.56}{6.186}$$

$$FKVA = \underline{27,572}$$

Next, the starting kva for the motors must be calculated. The average voltage V_{MP} at the metering point on a 126 volt base before the miner is started was approximately 118 volts and converting this voltage to a 440 volt base gives $V_{MP} = 412$ volts.

The nameplate data supplied by the mining company for the 90 hp motor was 440 volts, 900 rpm, code letter H. The starting kva in this case may be obtained by three methods.

Method One

The locked-rotor current for a 90 horsepower motor @ 440 volts, 900 rpm, and interpolating between 75 and 100 hp is approximately 720 amperes (see Table 4, p. 22). The total locked-rotor current for

both motors is 1440 amperes. The starting kva from equation (5), p. 20 is:

$$SKVA = \sqrt{3} V_M I_{LR}$$

$$SKVA = \sqrt{3} (0.412)1440$$

$$SKVA = \underline{1020}$$

Method Two

For a code letter H motor the starting kva is 6.3 - 7.09 kva per horsepower (see Table 5, p. 23). The starting kva is:

$$SKVA = 180(6.3) \quad \text{to} \quad SKVA = 180(7.09)$$

$$SKVA = \underline{1134} \quad \text{to} \quad SKVA = \underline{1276}$$

Method Three

If none of the above data is available for the motor the rule-of-thumb method must be used.

$$SKVA = 6(180)$$

$$SKVA = \underline{1080}$$

The above values for SKVA from Method Two must be used to yield the maximum percent voltage dip possible. It is recommended that the mining company obtain the exact locked-rotor current from the manufacturer because this may yield a lower value of percent voltage dip.

The percent voltage dip may now be calculated from equation (4), p. 20:

$$\% V_{DIP} = \frac{SKVA (100)}{SKVA + FKVA}$$

$$\% V_{DIP} = \frac{1276 (100)}{1276 + 27,572}$$

$$\% V_{DIP} = \underline{4.4}$$

If the lower value of starting kva from Method Two is used the dip is 3.9 percent yielding an average of 4.1 percent. The estimated number of starts for dips greater than 2.5 percent averaged over the entire circuit was 8 per hour. Locating 8 fluctuations per hour (see Figure 1, p. 8) allows a 3.9 percent dip. After considering the lower value of dip and the long-term plans of the mining company to purchase 69 kv service to supply all its mines, the power service was obtained.⁷

Figure 8 is a recording voltmeter strip-chart of voltage versus time taken at the metering point for the mine. The voltage on the chart multiplied by 103.92 will yield line-to-line voltage. The time scale is thirty minutes per division. An expanded time scale would show the voltage dip more clearly but such a chart was not available.

The real power consumption shown in Figure 5, p. 29, would be proportional to voltage fluctuation of Figure 4, p. 28. The largest dips occur during starting and cutting down top, also, it appears the cutting motors were stalled at about one minute during cutting and

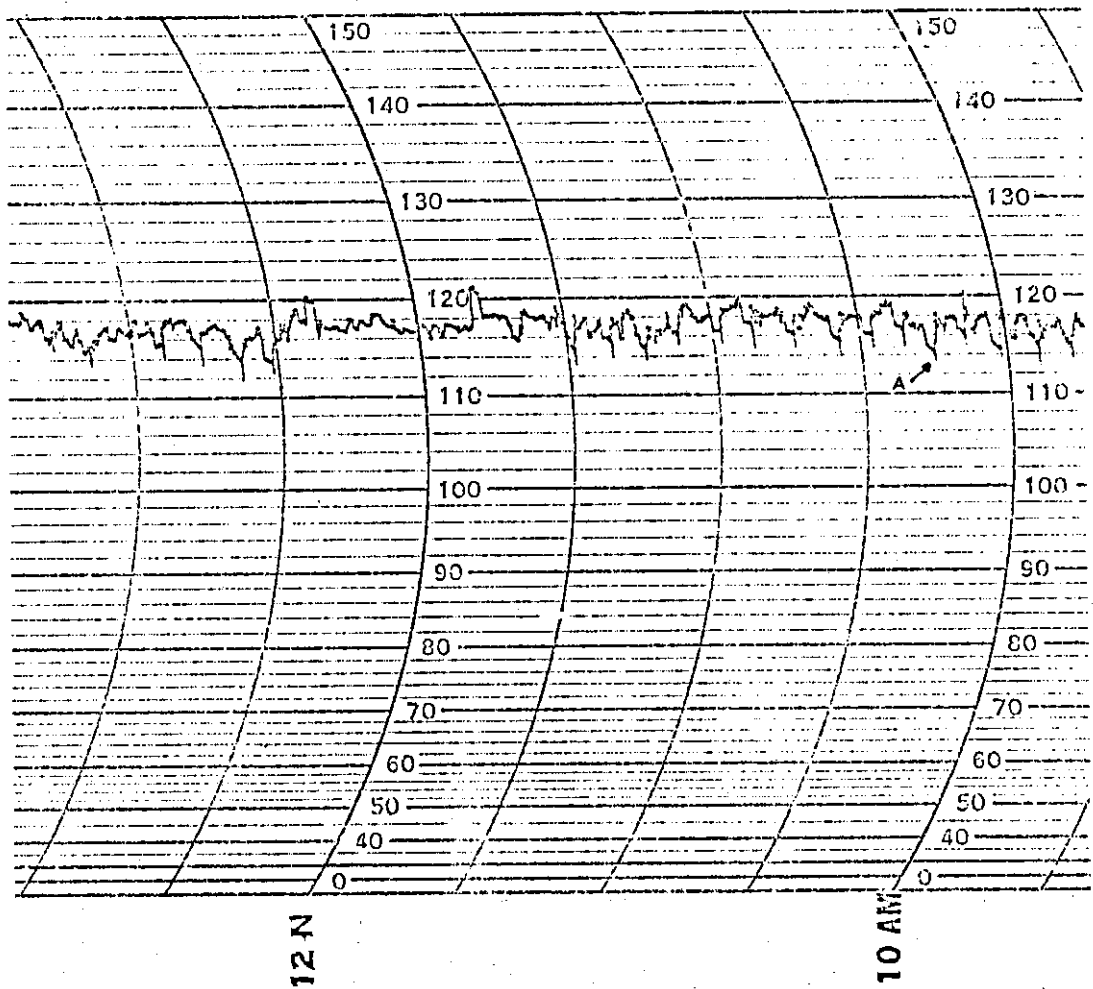


Figure 8. Recording Voltmeter Strip-Chart of 12KV Case Circuit at Metering Point

Source: Appalachian Power Company⁷

loading. It is difficult to determine exactly what part of the operational cycle caused the voltage dips of Figure 8. It would appear the miner was started or stalled thirteen times and ten lesser occurrences of voltage dip resulted from 10 a.m. to 12 noon. This would average about seven starts per hour and at point "A" the voltage dip is approximately four percent. At seven starts per hour would yield a 4.2 percent maximum voltage dip (see Figure 1, p. 8). Therefore, at its present mode this miner can operate but is at the threshold of objectionable flicker.

If this mining operation desired to open another section utilizing a similar continuous miner the number of starts would result in excessive flicker. Other miners operating from the same distribution line would further complicate matters. It is for these reasons that each mining power service request must be carefully considered on a case-by-case basis.

Remedial Measures

A number of corrective pieces of equipment and procedures can be used to minimize voltage dip. A listing of these appear in Table 8, classified according to technical and economical feasibility. This study was done by Westinghouse Electric Corporation and added to "Electrical Transmission and Distribution Reference Book" in the third edition of 1947. To improve this list or to study every measure would be beyond the scope of this study, therefore, the measures most likely to produce the desired results are examined.

TABLE 8

Light Flicker Remedial Measures Comparison Chart

Source of Flicker	Remedial Measures											
	1	2	3	4	5	6	7	8	9	10	11	12
	M-G Sets	Phase Converters	Synchronous Condensers	Series Capacitors	Shunt Capacitors	Voltage Regulators	Compensating Transformers	Motor Starters	Excitation Control	Load Control	Flywheels	Supply Circuit Changes
Generating Equipment												
Prime Movers.....	B	B	B	B	B	B	B	B	B	B	AX	B
Excitation Systems.....	B	B	B	B	B	B	B	B	B	B	B	B
Short Circuits and Switching Surges.	B	B	B	B	B	B	B	B	B	B	B	AX
Utilization Equipment												
Motor Starting.....	AZ	B	AZ	AX	B	B	AZ	AX	B	AZ	B	AY
Motor Driven Reciprocating Loads..	AZ	B	AZ	AY	B	B	AZ	B	B	B	AX	AY
Motor Driven Intermittent Loads...	AZ	B	AZ	AY	B	B	AZ	B	AZ	B	AX	AY
Electric Furnaces.....	AY	AZ	AX	AZ	B	B	AZ	B	B	AY	B	AX
Electric Welders.....	AX	AZ	AY	AX	B	B	AY	B	B	AY	B	AY

A—Technically Suited
 B—Technically Unsited
 X—Frequently Economical

Y—Possibly Economical
 Z—Rarely Economical

Source: Westinghouse Electric Company⁵

Motor-generator sets and supply circuit changes, as discussed in the introductory chapter, are the measures presently being used. In the past other measures have been considered by power utilities and found to be unsatisfactory for technical or economic reasons.⁷ A study of capacitor compensation as an alternate measure was undertaken for the following reasons: (1) the capacitor is a common and comparatively inexpensive electric power system device; (2) perhaps modern technology could make them technically feasible; (3) if still not feasible the capacitor could be eliminated from future study.

IV. CAPACITOR COMPENSATION FOR VOLTAGE DIP

The terms "series capacitor" and "shunt capacitor" are abbreviations for series connected capacitor and shunt connected capacitor. It is the type of connection and not the type of capacitor that is implied. Due to the connection, series capacitors and shunt capacitors perform different functions. Proper application of capacitors require an understanding of how the capacitor functions in the circuit, therefore, it is necessary to derive equations for the two connections.

Equation for Series Capacitor Compensation

A series capacitor is connected in series with the load, see Figure 9, and is represented by capacitive reactance X_C . The impedances Z_S and Z_L of Figure 3, p. 15 can be combined to yield a resistance R_T and inductive reactance X_T , \bar{V}_S is the source voltage and \bar{V}_{MP} is the voltage at the metering point. \bar{I}_L is the line current supplying the motor. The loop equation for the circuit is:

$$\bar{V}_{MP} = \bar{V}_S - \bar{I}_L \left[R_T + j (X_T - X_C) \right]$$

If the value of X_C equals X_T then the total reactance of the line will become zero and the voltage drop across the combination will equal zero. For voltage dip compensation X_C should be chosen such that the dip will be reduced to a desirable level. Therefore, the series capacitor is an inductive reactance compensator that reduces voltage drop caused by inductive reactance in the power system. This

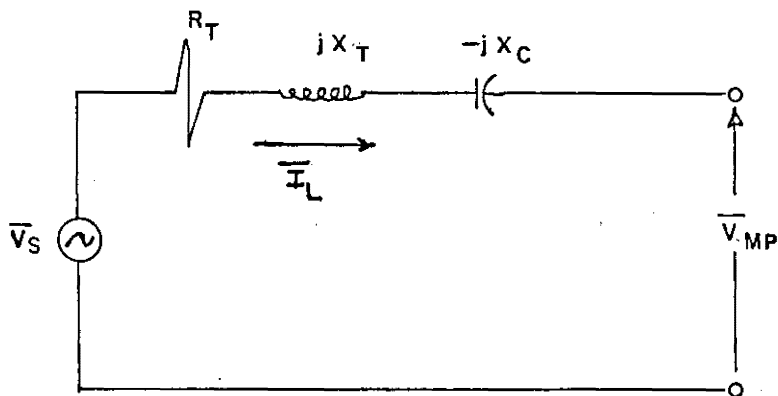


Figure 9. Electrical Power System with Series Capacitor, Equivalent Single-Phase Circuit Diagram

is done by causing a voltage rise that acts in opposition to the voltage drop across the system reactance.

Equation for Shunt Capacitor Compensation

A shunt capacitor is connected in parallel with the load, see Figure 10. The current \bar{I}_M drawn by the motor may be resolved into its resistive component \bar{I}_R and reactive component \bar{I}_X as explained in chapter three. The current \bar{I}_C drawn by the capacitor is 180 degrees out of phase with \bar{I}_X . The resultant current \bar{I}_L is the vector sum of \bar{I}_R , \bar{I}_X , and \bar{I}_C . The equation representing this connection is:

$$\bar{V}_{MP} = \bar{V}_S - \left[\bar{I}_R - j(\bar{I}_X - \bar{I}_C) \right] (R_T + jX_T)$$

If \bar{I}_C is chosen to equal \bar{I}_X in magnitude then the total current \bar{I}_L will be reduced to \bar{I}_R and the voltage drop will be minimized. Therefore, shunt capacitors supply inductive current compensation.

This circuit can also be analyzed by reversing the direction of \bar{I}_C , therefore, the capacitor would be supplying inductive vars to the motor. The capacitor could then be called an inductive var generator. \bar{I}_C would be flowing toward the source taking on a negative sign and \bar{I}_X would be flowing away from the source requiring a positive sign. The results of this analysis would be the same as above.

Literature Review

It is well known that series capacitors will almost instantaneously reduce transient voltage dip caused by the rapid and repetitive load fluctuations accompanying frequent starting of, and varying loads on

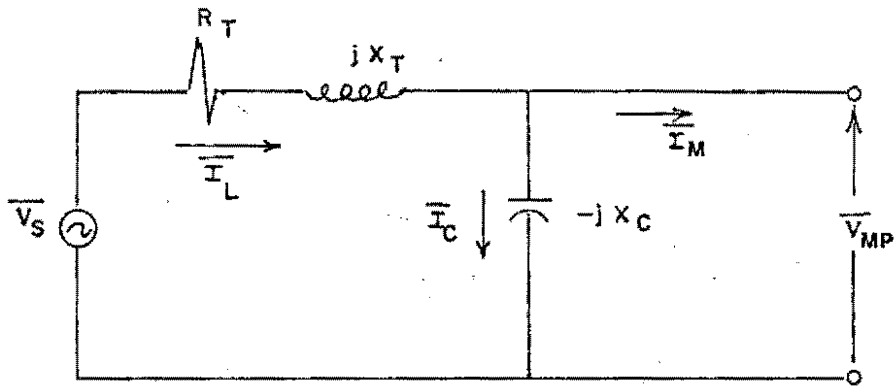


Figure 10. Electrical Power System with Shunt Capacitor;
Equivalent Single-Phase Circuit Diagram

induction motors.⁵ On distribution circuits this will reduce or eliminate flicker.²³

Although it appears that the series capacitor is the ideal solution for voltage dip, they have many disadvantages. The disadvantages are: (1) excessive voltage rise under fault conditions; (2) location of application restrictions; (3) ferro-resonance; (4) hunting of motors; (5) self-excitation of induction motors.

The first disadvantage is that a fault, located at a point beyond the capacitor location, will result in a voltage across the capacitor that is several times its maximum working value.²⁴ This overvoltage condition will be experienced down the distribution line beyond the capacitor location and is likely to damage electrical devices connected to it.

The second case, requires the location of the capacitor ahead of the point where flicker is to be reduced, since it effects only points beyond its installation.²⁴ This means a location between the metering point and power utility substation where Z_T results in allowable voltage dip. If an overvoltage condition occurs due to the capacitor, all electrical equipment down the line will be subjected to this overvoltage.

In the third instance, an unloaded or slightly loaded transformer draws a high transient exciting current when first energized. With a series capacitor a resonant condition can exist such that a continuous high current equal to, or even greater than, the full load current will persist into steady-state.²⁵ This condition is known as ferro-resonance.²⁴

In the fourth case, motor hunting can occur on synchronous and induction motors being supplied through a series capacitor. This condition results in the motor never settling down to its normal speed, but instead oscillating between different speeds causing among other things, objectionable cycle flicker.²⁴

The final disadvantage, self-excitation of induction motors fed through a series capacitor, will generate other voltages of lower than normal frequencies producing new objectionable voltage fluctuations.²⁵ The rotor will rotate at a speed below normal.²⁶ This condition is known as sub-synchronous resonance resulting from X_C , X_L and inductive reactance of the motor producing a circuit resonance at a frequency below line frequency. This condition exists only during motor starting and may cause damage to the motor by heating and excessive vibration.²⁴

There have been circuit protective devices such as shunt resistors, spark gaps,²⁴ shunting contactors, resonance suppressors, and combinations of these²³ that have been used successfully. None of these devices are 100 percent effective and the best results have been obtained only with small motors and small series capacitors.²⁴

Shunt capacitors have been used successfully for power factor correction since 1914.⁵ Although, shunt capacitors are excellent for this purpose they are not well suited to voltage dip compensation. In the past, shunt capacitors could not be switched in fast enough to prevent voltage dip since the dip itself is used to initiate the switching.²⁴ Permanently connected shunt capacitors do not improve

voltage dip, as they just increase the normal voltage level,²⁷ in fact, they may worsen the situation.²⁴

As noted before, motor starting and excessive intermittent loading of the continuous miner produces the voltage dip problem. Shunt capacitors that are switched at the instant the motor is started will reduce voltage dip. However, after the motor reaches its no-load speed, the capacitor current necessary to compensate for starting current will provide an excessive voltage rise at a leading power factor.⁵ This problem has been overcome by switching a bank of shunt capacitors at the instant the motor is started, which by a timing relay is switched off when the motor comes up to speed.²⁸

The disadvantages of shunt capacitors are: (1) harmonic currents; (2) resonance; (3) motor self-excitation; (4) restriking of breakers when switching off capacitors.

For instances 1, 2, and 4 the solutions are relatively simple.²⁴ Therefore, shunt capacitors have been used successfully for power factor correction without any major problems by power utilities and mining companies for many years.

In the third case, induction motor self-excitation can result when the shunt capacitors and motor are switched as a unit, with damaging overvoltages developed each time the unit is switched off the line. If the load inertia continues to turn the rotor after the unit is disconnected from the source, the capacitors will excite the motor and generate high voltages. These may be harmful to equipment

insulation and hazardous to personnel. However, this condition will not occur if the motor and capacitors are not switched off as a unit.²⁹

There is no doubt that series capacitors will provide voltage dip compensation but its disadvantages are great. The circuit protective unit is a well designed piece of equipment but it has its limitations. The location of the capacitors is such that one failure could damage utility, residential, and commercial electrical equipment resulting in huge costs to the power utility. For this reason power utilities in most cases will not use series capacitors.⁷ The cost of the protective equipment alone in 1968 was as much as \$12,000 and for this reason was considered too expensive for motor starting compensation.²⁸ The mine electrical power system is very dynamic and there are occasions that produce non-linear circuit conditions resulting from such things as current chopping by vacuum breakers and capacitance of underground cables.³⁰ The prediction of series capacitor operation under these conditions is impossible and would vary from mine to mine. In addition, the circuit parameters would vary as development progressed, and almost certainly would cause motor and resonance problems. For the foregoing reasons the series capacitor was dropped from further consideration.

There should be much less trouble with the use of shunt capacitors. They are being used for surge protection with only few problems in mine power systems although, they may cause severe prestrike transients from vacuum breaker operation, but such problems have not caused excessive damage.³⁰ Shunt capacitors when switched properly have been claimed

to minimize voltage dip due to starting a 400 horsepower, 2400 volt, code "J" induction pump motor.²⁸ The voltage charts, see Figure 11, for this operation shown a voltage dip of 9.8 percent at the pumping plant without compensation.

Upon starting at the pumping plant of a 12.5 kv distribution line, the period of the dip was about 9.0 seconds. A 2700 kva delta-connected bank of capacitors was switched on at the instant the motor was started and timed to switch off in 9 seconds. Since these results are very good, see Figure 12, it was decided to study shunt capacitor compensation for intermittent loading of a squirrel-cage induction motor. A laboratory analysis was devised for this purpose and the results are given in the next chapter.

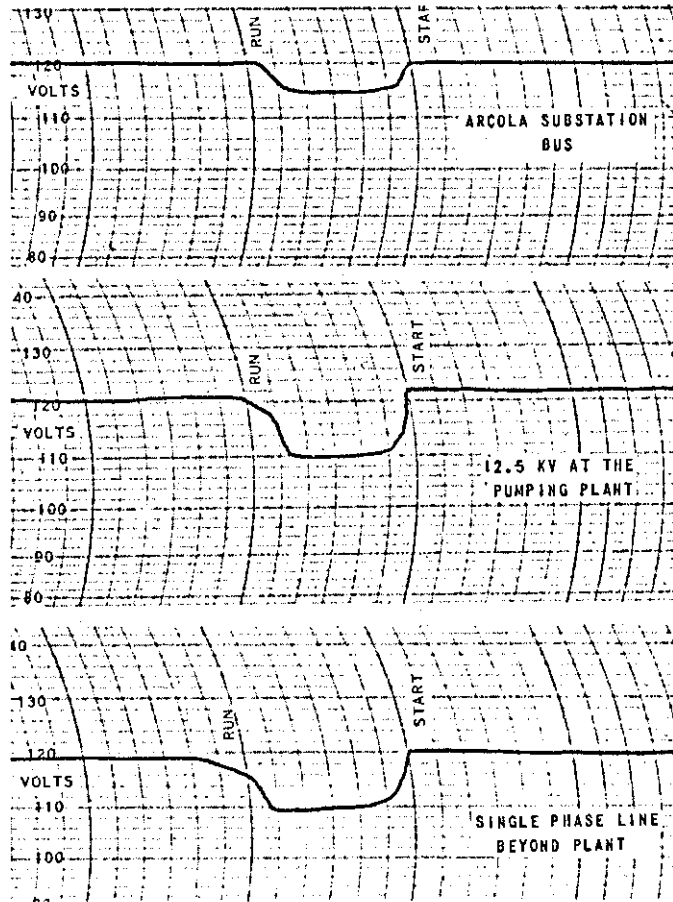


Figure 11. Voltage Charts for Across-the-Line Starting of a 400-HP, Code J Motor Showing Voltage Dip Caused by Motor Starting

Source: Electric Light and Power²⁸

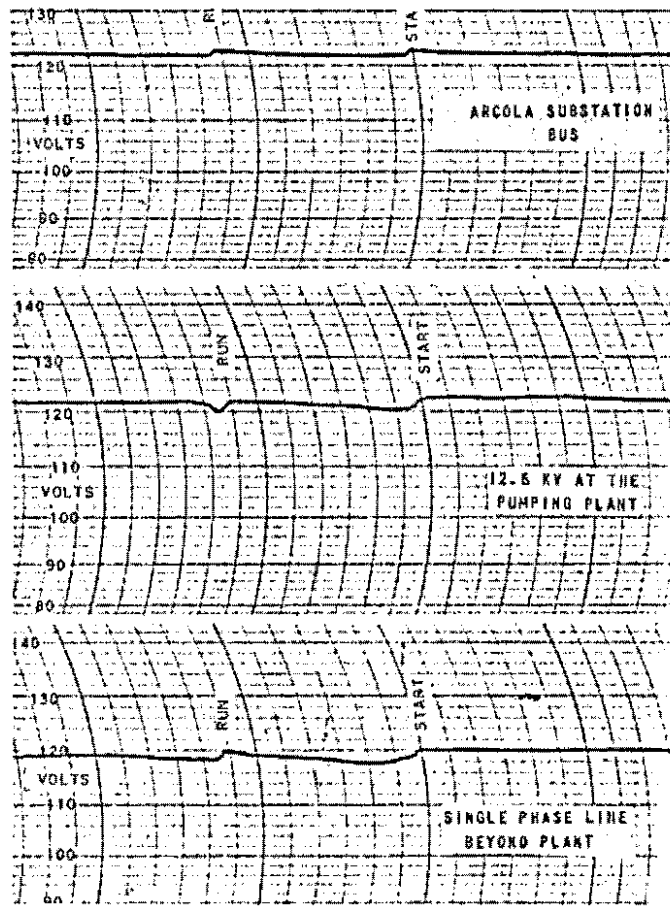


Figure 12. Voltage Charts for Across-the-Line Starting of a 400 HP, Code "J" Motor with Shunt Capacitor Compensation

Source: Electric Light and Power²⁸

V. LABORATORY INVESTIGATION

Laboratory Set-Up

The purpose of the laboratory experiment was to study voltage dip compensation for a squirrel-cage induction motor handling an intermittent load. To provide for the protection of the motor a loading value of 138 percent load was arbitrarily chosen for this case. The waveform of the voltage dip was observed when the load was varied instantaneously from zero to 138 percent load.

Two compensation schemes (1) shunt capacitors; and (2) shunt capacitor with second un-loaded induction motor were applied to determine their feasibility.

The circuit was fed from a grounded-delta 240 volt source through a three-phase variac. Three single-phase variacs were connected to supply the line impedance, see Figure 13. The induction motor was ungrounded-wye-connected and rated at 5 hp, 240 volt, 14 amp, and 1800 rpm. The motor served, through a belt drive, as the prime mover for a dc generator. The mechanical load on the motor was varied by switching in a resistive load rack on the output of the dc generator. The line-to-line voltage of two phases at the motor was reduced by a three-phase variac to excite the primaries of the 115/6 volt scope input transformers (see Figure 13) this reduced the voltage to the desired level for a dual trace storage oscilloscope. Pictures were taken of the resulting waveforms and the two-wattmeter method was used to obtain the necessary electrical data.

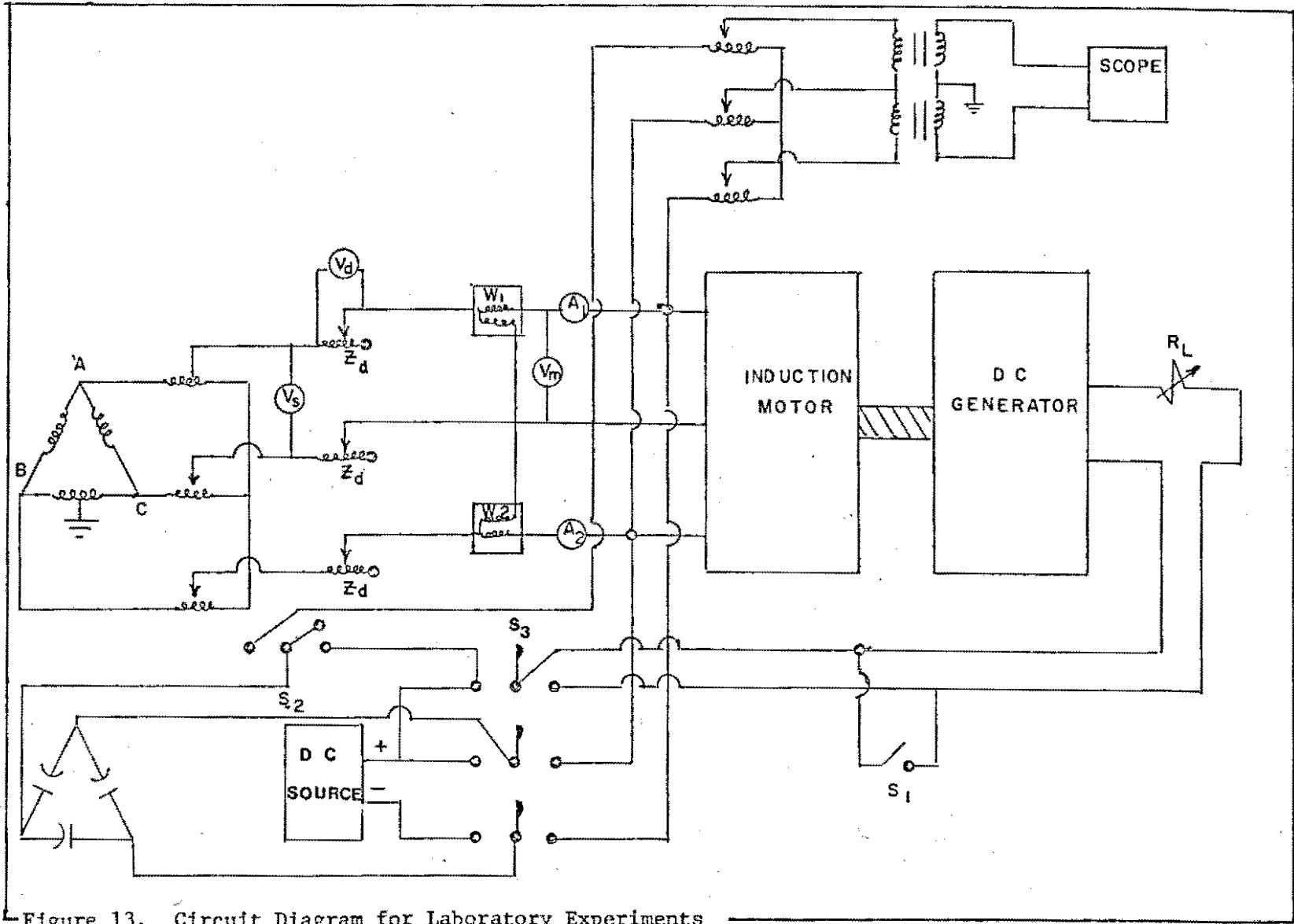


Figure 13. Circuit Diagram for Laboratory Experiments

There were some inherent problems with this arrangement. Since voltage characteristics of two phases are sufficient to represent the three-phase system it was only necessary to observe the waveform of two phases. The voltage source for the laboratory was a grounded-delta-connection and the phase voltages were referenced to this ground, resulting in waveforms of different magnitudes. Therefore, when calculating dip from the waveforms it is necessary to compare the same trace. The variacs, used to supply the line impedance, had iron cores producing an inductive reactance that was current dependent. Finally, to produce a voltage dip that showed well on the scope resulted in motor voltages near its stability limits.

Shunt Capacitors

Data was recorded and calculations were made, see Table 9, to provide parameters for the equivalent single-phase circuits of Figures 14 and 15 and the following capacitor calculations. The calculated voltage dip from the recorded data was 3.0 percent. When comparing point "A" of the no load voltage waveform, see Figure 16, and point "B" of the 138 percent load waveform, see Figure 17 shows a voltage dip of about 3.5 percent confirming these calculations. The value of capacitors required to maintain a motor voltage of 202 volts was difficult to calculate due to the non-linearity of X_L ; therefore, 4.34 kva was used. This value would almost compensate for the total inductive kvar of the motor at 138 percent load.

TABLE 9

Data and Calculations for 5 HP, 240 VOLT, 1800 RPM, Ungrounded-Wye-Connected Squirrel-Cage Induction Motor at No-Load and 138% Load

Load Conditions	W ₁ WATTS	W ₂ WATTS	I _L AMPS	V _S VOLTS	V _M VOLTS	Z _L OHMS	Z _M OHMS	θ DEGREES	Q KVAR	I _R AMPS	I _X AMPS
No Load	980	-248	7.1	244	202	0.50 + j3.44	5.35 + j15.53	-72.86	2.37	2.09	6.78
138% Load	3400	1380	19.2	242	196	0.58 + j1.47	4.76 + j3.48	-42.83	4.43	14.08	13.05

NOTE: Calculations Were Made From Following Equations:

$$Z_M = \frac{V_M}{\sqrt{3}I_L} \left/ \tan^{-1} \sqrt{3} \frac{W_1 - W_2}{W_1 + W_2} \right. \quad \text{In Polar Form}$$

$$I_R = I_L \cos \theta$$

$$\theta = -\cos^{-1} \frac{W_1 + W_2}{\sqrt{3} V_M I_L}$$

$$I_X = I_L \sin \theta$$

$$Q = \frac{\sqrt{3} V_M I_L \sin \theta}{1000}$$

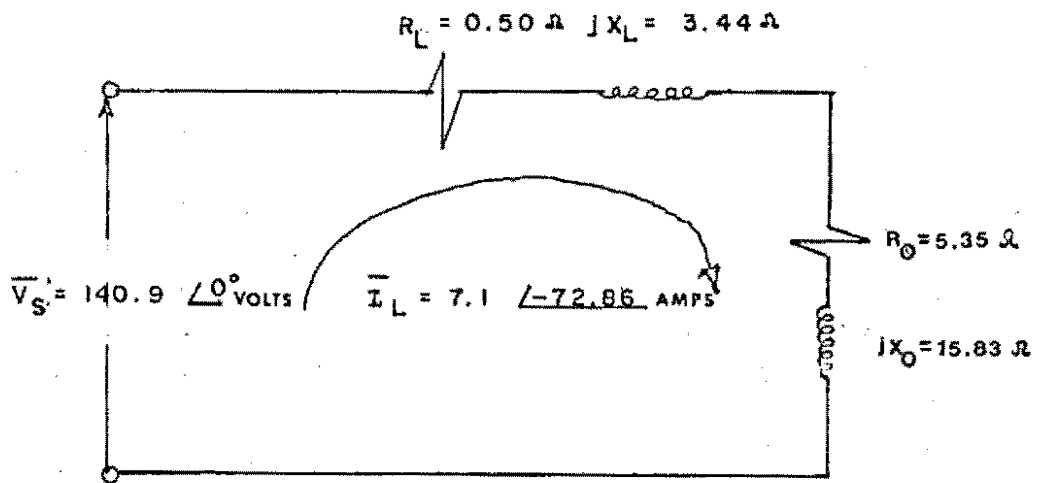


Figure 14. Equivalent Single-Phase Circuit Diagram for Experimental Circuit and Output Impedance of a 5 HP, 220 VOLT, 1800 RPM, Delta-Connected Squirrel-Cage Induction Motor at No-Load

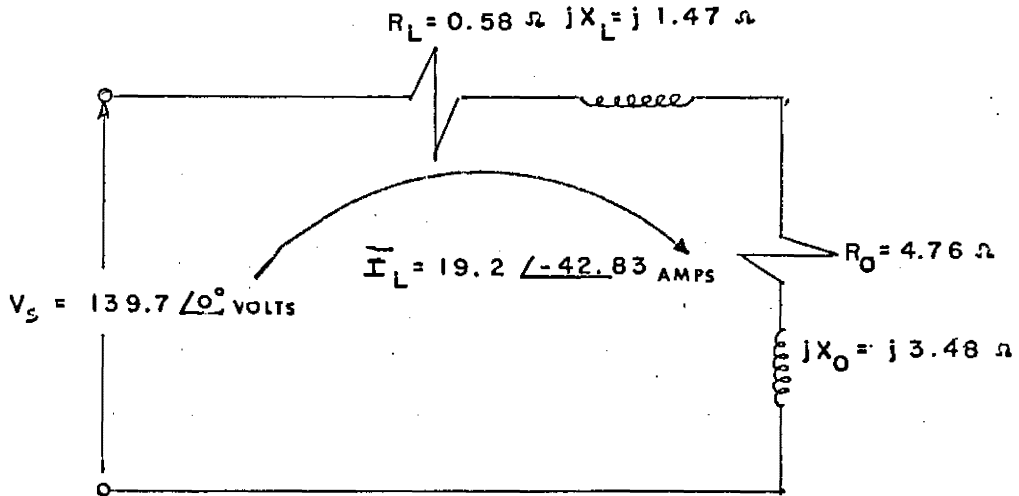


Figure 15. Equivalent Single-Phase Circuit Diagram for Experimental Circuit and Output Impedance of a 5 HP, 220 VOLT, 1800 RPM, Delta-Connected Squirrel-Cage Induction Motor at 138 Percent Load

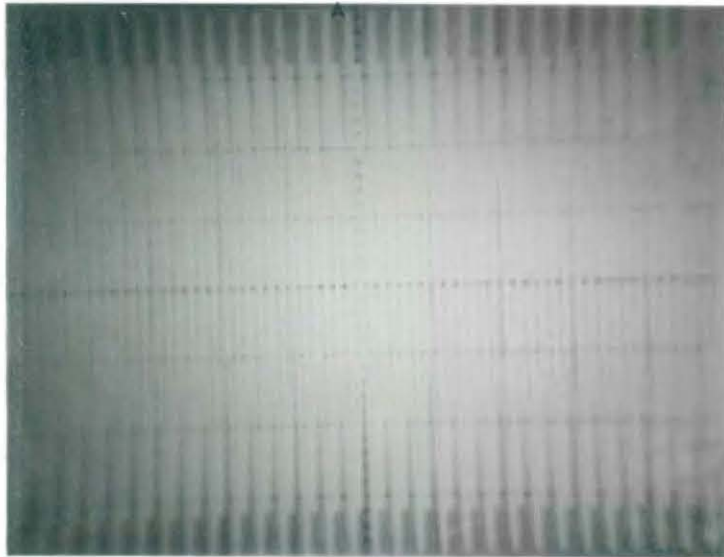


Figure 16. Oscilloscope Voltage Waveform For Motor at No-Lead,
Vertical Scale: 5 Volt/Division. Horizontal Scale:
50 Milliseconds/Division



Figure 17. Oscilloscope Voltage Waveform for Motor at 138 Percent Load, Vertical Scale: 5 Volt/Division, Horizontal Scale: 50 Milliseconds/Division

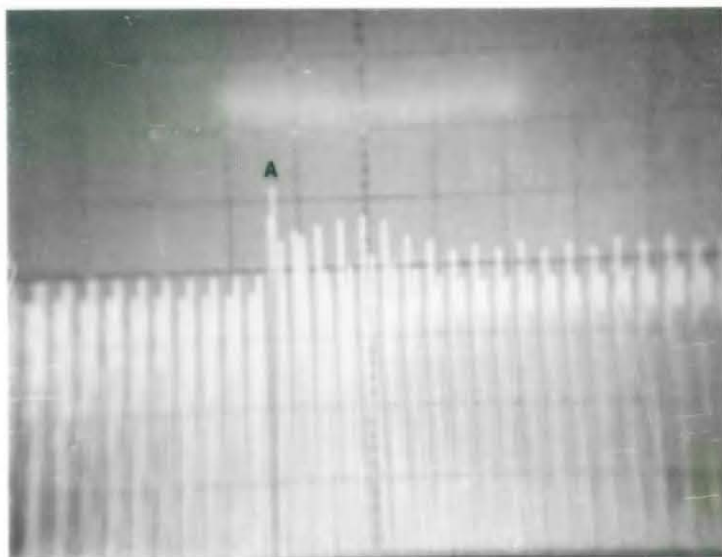


Figure 18. Oscilloscope Voltage Waveform for Motor with 4.34 KVAR Shunt Capacitors at 138 Percent Load, Vertical Scale: 1 Volt/Division, Horizontal Scale: 50 Milliseconds/Division

The scope trace was repositioned to show the positive half of the waveforms which allowed a vertical scale of 1 volt per division. A delta-connected bank of capacitors (see Figure 13, p. 56) equal to 4.34 kvar was switched by S_3 with load and the voltage waveform of Figure 18 resulted. The results show a high capacitor charging transient at point "A" during the first cycle after switching. The switching was repeated many times producing similar results but on some occasions a motor stall occurred, see Figure 19. Since the motor was operating at a loaded motor voltage near its stability limit the period of capacitor charging could be enough in some cases to produce the stall. If the capacitor unit was charged and switched in when the line voltage was equal to the capacitor voltage the large initial charging transient could be eliminated. The phases of the capacitor unit were charged to 0, -248, and 248 volts ($\pm 202 \times \sqrt{3} \times 0.866$) respectively, by switching S_2 to the right and S_3 to the left, from a dc source (see Figure 13, p. 56) the load and charged capacitor unit were then switched, by first switching S_2 to the left and S_3 to the right, trying to hit the instant the line voltage equaled the charged voltage of the capacitor unit. An electronic switching control could be designed for this purpose but since one was not available the above procedure was repeated until the capacitor charging transient was eliminated, see Figure 20.

The final voltage waveform of Figure 20 shows a voltage rise greater than 3.5 percent that will produce a worse condition for flicker than if the load was switched by itself. After ten cycles

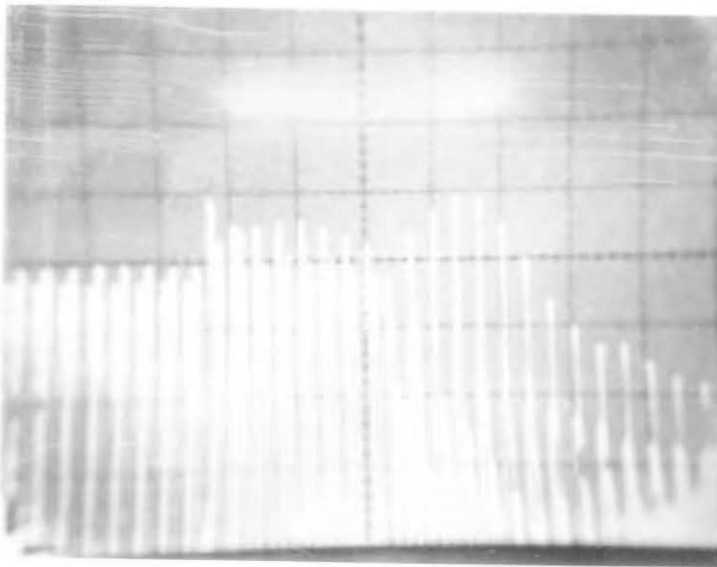


Figure 19. Oscilloscope Voltage Waveform for Motor Stall with 4.34 Shunt Capacitors at 138 Percent Load, Vertical Scale: 1 Volt/Division, Horizontal Scale: 50 Milliseconds/Division

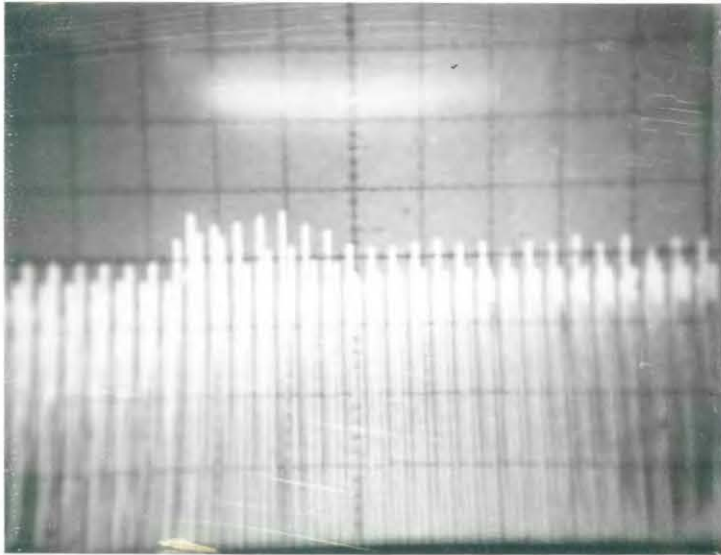


Figure 20. Oscilloscope Voltage Waveform for Motor with Charged 4.34 KVAR Shunt Capacitors at 138 Percent Load, Vertical Scale: 1 Volt/Division, Horizontal Scale: 50 Milliseconds/Division

there is a voltage rise possibly due to overcompensation of the capacitors or the steady-state conditions have not been reached. If overcompensation is the problem it could be eliminated on a distribution line where X_L is constant and the exact amount of compensation could be calculated. Other values of capacitors were tried but the results did not improve.

The major problem is the voltage rise during the first ten cycles after switching. The impact of the load and capacitor on the system produces a dynamic condition that is impossible to predict explicitly from the available information.

Shunt Capacitors and Second Unloaded Induction Motor

A second induction motor of equal specifications was connected to the circuit of Figure 13, p. 56, in parallel with first motor and capacitors were permanently connected. The load was switched as before and the resulting waveform, see Figure 21, was noted. It was thought the capacitors could provide the excitation of the second motor and perhaps it would generate enough power to compensate for the dip.

The resulting waveform shows an oscillating condition and voltage dip about equal to switching the load by itself. Different values of capacitance were tried with similar results and a larger sized motor was not available. Based on these observations this scheme was judged ineffective but, a larger motor may have worked.

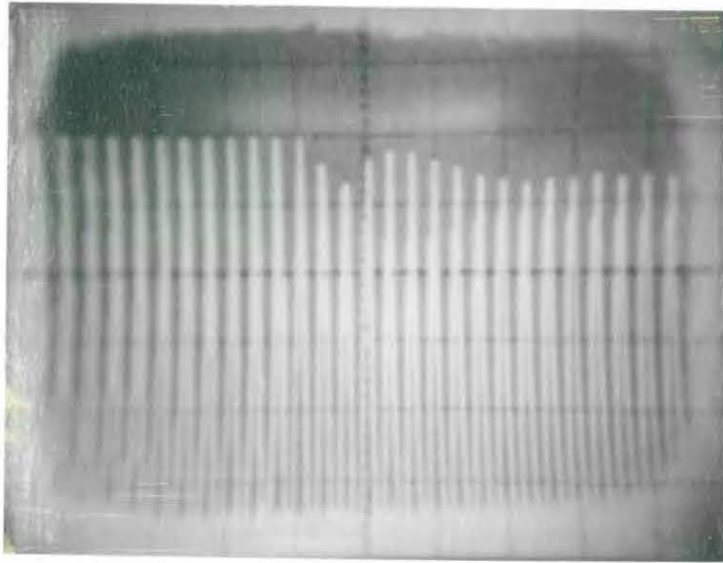


Figure 21. Oscilloscope Voltage Waveform for Motor with 4.34 KVAR Shunt Capacitors at 138 Percent Load and Second Unloaded Induction Motor, Vertical Scale: 1 Volt/Division, Horizontal Scale: 50 Milliseconds/Division

VI. RESULTS OF LABORATORY AND ANALYTICAL STUDIES

It appears from the literature that voltage dip due to motor starting can be reduced or eliminated by switching in a fixed bank of capacitors equal to the starting kva at the instant of starting. However, the laboratory results suggest that dip incidental to intermittent loading cannot be solved in a similar manner. The analysis of any power system to determine its transient response requires the use of mechanical principles as well as electrical concepts.

A possible explanation for the intermittent load characteristics (see Figure 20, p. 66) can be deduced by analyzing the power requirements of the motor and mechanical load being supplied by it. The power delivered to the motor when it is running at constant speed N is equal to the power output of the motor plus losses in the motor. If the mechanical load on the motor is increased, the motor cannot supply the entire load until its input power increases. This input power cannot be supplied instantaneously by the power system and the time required depends on the time constant of the supply circuit. Therefore, the rotor must slow down and slip increases. While the power input is increasing, the excess of power required by the load over the input power to the motor is supplied by the stored energy in the rotating masses. As the rotor speed decreases, the stored mechanical energy supplies part of the load. The rotor will oscillate around the new point of equilibrium and will settle down to a new

speed. If the increase in load is too large or is applied too suddenly, the motor may stall, in which case the stability limit will have been exceeded. The greater the reactance of the power system the greater is the likelihood of losing stability. If the power loss due to friction, windage, and core loss is neglected a power equation can be written as follows, ³¹

$$P_A = P_E - P_S$$

where:

P_A = power required to accelerate rotor and mechanical load in megajoules/second

P_E = total electromagnetic power developed by the motor in megajoules/second

P_S = output power supplied to the shaft of the rotor in megajoules/second.

Since power equals the product of the moment of inertia, the angular acceleration, and the angular velocity the power required to accelerate the rotor and load is,

$$P_A = I\alpha\omega$$

where:

I = moment of inertia of rotor and load in megajoules-second²/electrical degree²

α = angular acceleration of rotor in electrical degrees/second²

ω = angular velocity of rotor in electrical degrees/second.

The slip may be written in terms of angular velocity as,

$$S = \frac{\omega_S - \omega}{\omega_S}$$

where:

S = slip in per-unit

ω_S = synchronous angular velocity of stator
in electrical degrees/second.

The above equation may be written as,

$$S = 1 - \frac{\omega}{\omega_S}$$

and rearranging,

$$\omega = \omega_S (1 - S).$$

The acceleration power may now be written in terms of slip as,

$$P_A = I_a \omega_S (1 - S).$$

The maximum electromagnetic torque developed in megajoules/electrical degree by the motor is given as,

$$T_{MAX} = \frac{3 V_M^2}{2 \omega_S \left[R_1 + \sqrt{R_1^2 + (X_1 + X_2)^2} \right]}$$

where V_M , R_1 , R_2 , X_1 , and X_2 are circuit parameters of the motor as given in Chapter III, p. 30.¹⁹ The above equation may now be rewritten in terms of power as,

$$P_{MAX} = T_{MAX} \omega = \frac{A\omega V_M^2}{\omega_S} = A(1 - S) V_M^2,$$

where:

$A =$ a constant value in mhos =

$$\frac{3}{2 \left[R_1 + \sqrt{R_1^2 + (X_1 + X_2)^2} \right]}$$

and

$$\omega/\omega_S = 1 - S.$$

The power equation may be rewritten as,

$$P_A = I\alpha\omega_S(1 - S) = A(1 - S) V_M^2 - P_S$$

and rearranging,

$$P_{MAX} = A(1 - S) V_M^2 = I\alpha\omega_S(1 - S) + P_S.$$

The power delivered to the shaft may be written as,

$$P_S = T_S \omega_S(1 - S),$$

where:

$T_S =$ Shaft torque in megajoules/electrical degree

so that

$$P_{MAX} = A V_M^2 = \omega_S(I\alpha + T_S).$$

Every power system has an inherent time constant which is the time required for the transient component of current to equal zero. For a series R - L circuit the total current (transient component plus steady-state component) supplied from a sinusoidal voltage source, $V_S \sin \omega_s t$ is: ³²

$$i = e^{-(R/L)t} \left[\frac{-V_S}{\sqrt{R^2 + \omega_s^2 L^2}} \sin(-\tan^{-1} \omega_s L/R) \right] + \frac{V_S}{\sqrt{R^2 + \omega_s^2 L^2}} \sin(\omega_s t - \tan^{-1} \omega_s L/R).$$

The time required for the transient component of the total current to become negligible is usually five times the time constant (L in henrys divided by R in ohms) of the power system supplying the motor. During this time the motor voltage is decreasing with the increasing current required when a sudden increase in mechanical load is applied and no power is delivered to the motor. After the transient component of current decays the motor voltage will rise and reach a new steady-state.

From the power equation P_{MAX} equals $\omega_s T_S$ during steady-state when α is zero. When a sudden load is applied T_S increases and since P_{MAX} cannot increase instantaneously the rotor will slow down and α will become negative compensating for the increase in T_S . The magnitude of power that the rotating masses can supply will depend upon the value of I and how fast the rotor slows down. The motor voltage will dip to a minimum until the transient current decays and

P_{MAX} will decrease as the square of this dip. If the time constant of the system is short the motor voltage will soon reach its new steady-state and the motor will settle-in to a new speed. This dip in voltage can be seen in Figure 22, points "A", "B", and "C". The shunt capacitor could almost instantaneously supply the increased power requirements by increasing the voltage at the motor. The capacitor in effect decreases the time constant by compensating for inductive current flowing in the power system. This would not allow the rotor speed to change excessively by increasing P_{MAX} .

If too much capacitance is switched with the load, P_{MAX} could become greater than before switching because of overcompensation and the rotor would accelerate to balance this. This could have produced the oscillations shown in Figure 20, p. 66. A plot of the voltage dip transient, resulting motor voltage transient with capacitors, and possible theoretical voltage transient if inertia was not present is shown in Figure 23 for switching in fixed amounts of capacitors. To compensate for intermittent voltage dip it would appear that a varying amount of capacitance equal and synchronized with the voltage required by the motor may provide the desired results.

A circuit has been devised that claims to provide high speed varying capacitor kvar for power factor control as well as flicker reduction when applied to an arc furnace, see Figure 24.³³ This is accomplished by sensing the change in inductive kvar required and pulsing the thyristor switching arrangement that controls the inductive reactance in parallel with the capacitor, C. The inductor in series

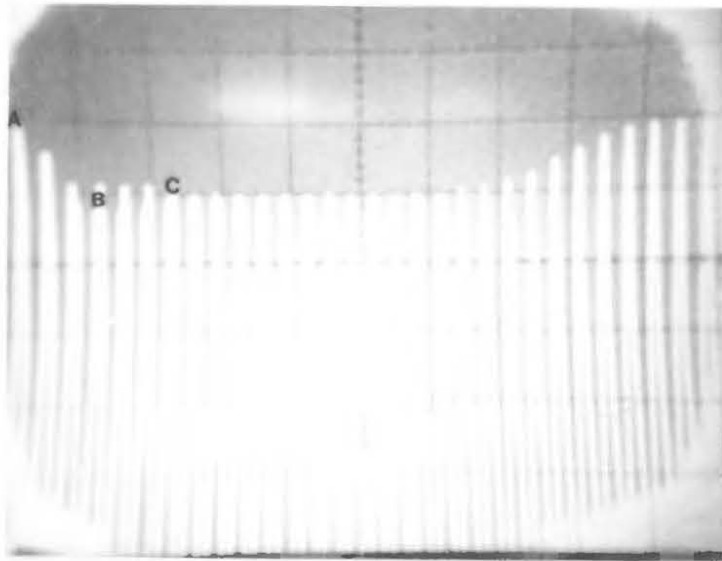


Figure 22. Oscilloscope Voltage Waveform Showing Loading Transition,
Vertical Scale: 1 Volt/Division, Horizontal Scale:
50 Milliseconds/Division

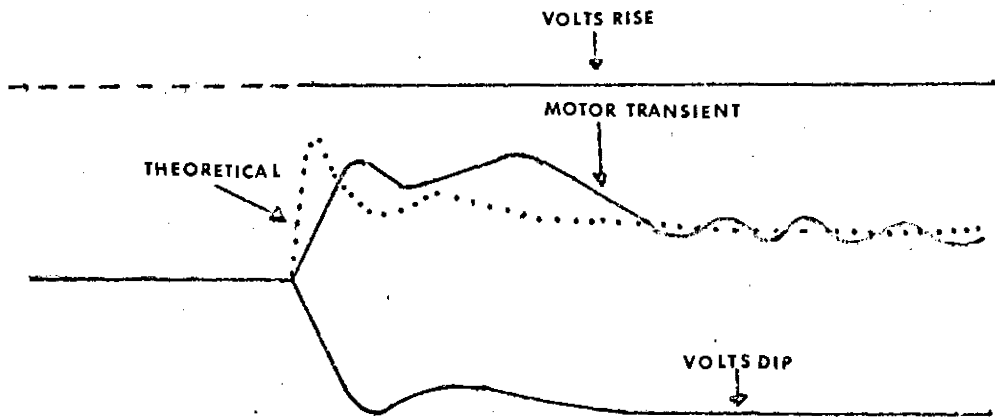


Figure 23: Plot of Voltage Dip Transient, Resulting Motor Voltage Transient With Shunt Capacitors, and Theoretical Voltage Transient Versus Time For Figure 20, p. 66.

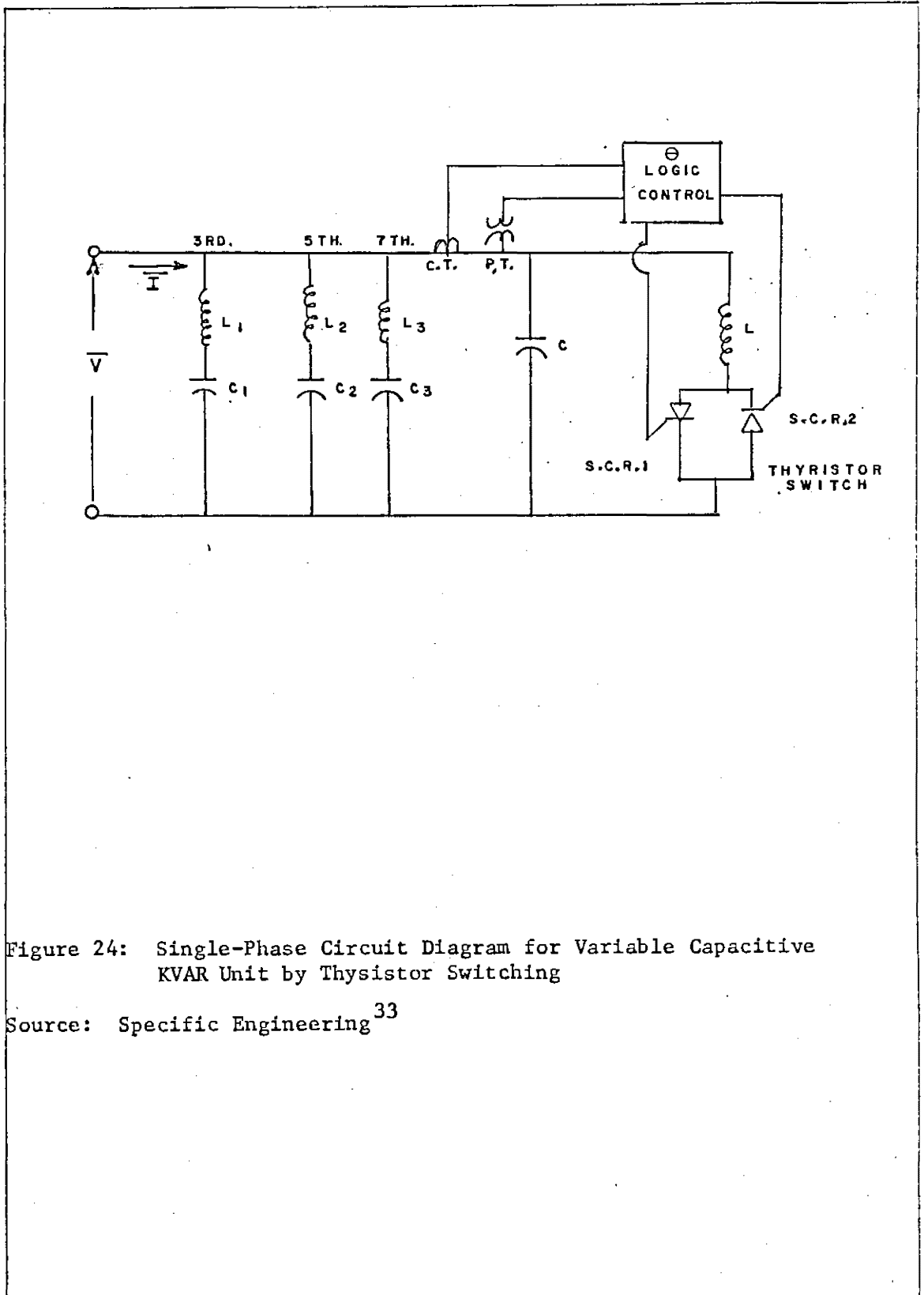


Figure 24: Single-Phase Circuit Diagram for Variable Capacitive KVAR Unit by Thyristor Switching

Source: Specific Engineering³³

with the phase-angle controlled static switch acts as a variable inductor with a claimed time response of one-half cycle. This will provide capacitive kvar from zero to maximum kvar of the capacitor. The shunting L-C branches control the third, fifth, and seventh harmonic that may be generated from this arrangement. The logic control and the inductor was not available in the laboratory to test this circuit with an induction motor.

When a motor is started with no mechanical load the rotor is initially stationary, T_s is zero, and the angular acceleration is a large positive value therefore, absorbing power. The input impedance of the motor is mostly resistive requiring real power from the system. If a large capacitor unit is switched at the onset of starting it will produce a voltage rise by compensating for other inductive load connected to the power system. This will partially compensate for the starting voltage dip by increasing P_{MAX} . As the rotor accelerates the inductive current required by the motor increases and the capacitor will further compensate for the dip. Perhaps no oscillations will occur until the capacitor unit is switched off.

The voltage dip at the pumping station of Figure 11, p. 53 shows a transient period of about two seconds before the voltage reaches its minimum. The motor of this circuit drives a pump requiring six seconds to accelerate to full speed which may be due to the shaft load. The results after capacitor compensation (see Figure 12, p. 54) appear to agree with above analysis, although the

time scale is too long to observe any short transients that may have occurred.

VII. CONCLUSIONS AND SUGGESTIONS FOR FUTURE STUDY

Based on experience and the foregoing study the best way to handle the voltage dip problem is by prevention. It must be realized by the mine planning engineer that large induction motors such as those used on continuous miners cannot be supplied from 12kv distribution lines without causing voltage dip. It is estimated that in 85 to 95 percent of the cases the mining company has ordered and received their continuous miner before applying for electric power service.⁷ If electric service is denied, the additional capital expenditure may be great. The ideal solution is long-range mine electric power system planning. That is, if coal reserves warrant and several mines are to be located within a general area, buy bulk electric power primary metered at a high voltage, such as 69kv. Then a 12kv mine distribution system could be built to serve existing and future mine facilities. Total electric power costs would probably be less when averaged over the life of the reserves. This type of system would remove residential and commercial customers who are likely to complain about light flicker, also, electric power could be obtained at a lower rate.

In cases where reserves do not merit such an expenditure an alternative measure combining measures one and eleven of Table 8, p. 42, could be applied. This would be the utilization of a 12kv synchronous motor serving as the prime-mover for a 440 volt ac generator. A fly wheel large enough to supply the transient torque

requirements of the miner could be added to the rotor shaft of the motor. The motor would be started once a day or shift; therefore, the incidental flicker would be tolerable. The synchronous motor could also be over-excited to supply power factor correction with a resulting savings in power cost. The m-g set would replace the power center and eliminate its cost.

If an existing mine has voltage dip problems a bank of shunt capacitors switched on at the instant of motor starting and off a few seconds later could reduce starting voltage dip. A way of doing this would be to position the capacitor unit on the load-side of the power center and trigger it by a signal from a pilot wire added to the trailing cable. A switch that operates in conjunction with the starting switch of the miner could initiate this signal. A timing relay may be used to remove the capacitor bank after starting. There would be the initial cost of capacitors and a moving cost upon advance of the section.

The intermittent loading problem would be more difficult if not impossible to remedy with shunt capacitors. If care was taken to prevent overloading of the cutting head motors compensation would not be necessary. If this isn't possible perhaps the variable capacitor system could be used (see Figure 24, p. 77) and it may also compensate for starting voltage dip.

A dynamic model of the induction motor receiving power from a distribution line and shunt capacitors switched in with load may be derived. The resulting matrix could then be solved on a digital

computer. Also, the model could be programmed on an analog computer. These results would be helpful in determining the feasibility of shunt capacitor compensation for voltage dip.

It would be difficult if not impossible to simulate explicitly the electrical characteristics of continuous miner operation. Therefore, field studies are required to determine the success of the remedial measures mentioned above. A study is required to calculate the fly wheel dimensions of the m-g set necessary to compensate for voltage dip and the arrangement would need field testing. A capacitor bank switched at the instant of starting the miner could be arranged and the resulting voltage waveform could be recorded on a system developed by the Bureau of Mines and Pennsylvania State University for monitoring mine power transients.¹⁸ These results would provide the feasibility of voltage dip compensation by switching shunt capacitors. If feasible, the optimum size of the capacitor bank would then be determined from such a study. The variable capacitor unit would be more complicated to construct but its feasibility could be analyzed in the same manner.

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A STUDY OF CAPACITOR VOLTAGE DIP
COMPENSATION FOR THE CONTINUOUS MINER

by

James E. Hylton

(ABSTRACT)

Voltage dip and its detrimental effects due to starting and intermittent loading of the continuous miner are discussed. The necessary steps required to calculate voltage dip and to determine objectionable levels are developed. These steps are applied to a case study. A listing of possible remedial measures is presented and from among these capacitor compensation was further studied. A laboratory investigation was conducted to study shunt capacitor compensation for the intermittent loading of a 5 hp squirrel-cage induction motor. Possible shunt capacitor compensation schemes to overcome voltage dip are enumerated and briefly evaluated.