FEEDER VOLTAGE REGULATOR CONTROL

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PREFACE PREFACE PREFACE

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INTRODUCTION

When the utilization voltage standards now in use were being determined, one of the major problems to be solved was reconciling the difference between the three-phase voltages on odd ratio (120/208 volt) and even ratio (120/240 volt) systems. Although utilization voltages to both power and lighting equipment were considered, it was realized that the life of lighting equipment was relatively short when compared to that of a motor. Therefore, it was the long-lived utilization equipment, such as electric motors, that became the determining factor in the establishment of reasonable voltage limits.

One solution to this problem, which was advanced at that time, was to establish a separate line of polyphase motors for operation at about 190 or 200 volts for use on the 208 volt system. The existing 220 volt motors would be satisfactory for the 240 volt system.

Simultaneously with this voltage utilization study, the motor manufacturers developed and placed on the market a three-phase motor that could be connected to produce high torques on either the 208 volt or 240 volt system. It was felt that this motor, together with the 208 volt line of motors, would fulfill the requirements for high torque on the 208 volt systems. This was particularly true since motors are designed for operation on voltages 10 percent above or 10 percent below their nameplate rating.

These conclusions and the resulting recommended voltage utilization standards were very satisfactory at the time they were adopted and would still be compatible today except for two points.

1. The three-phase motor which was referred to as being capable of producing high torques on both a 208 volt or a 240 volt system turned out to be wishful thinking on the part of those concerned. This motor never became economically feasible to build as a stock item and is not now available except by special order at an increase in price.
2. Because the motor manufacturer guaranteed his motors for operation at 10 percent undervoltage it was necessary that the motor be designed to carry the additional current required to produce rated output at the lower voltage limit. In so doing this, the manufacturer inherently built into the motor extra capacity that could be utilized if the voltage was maintained at rated (nameplate) voltage. This extra capacity, known as "service factor," has been used more and more in the application of motors. It has now become an acceptable practice by the fabricators of "packaged equipment," such as air conditioners, to utilize the service factor in the design of their equipment.

This practice of utilizing the service factor of motors in their application means that the design tolerances, which were the partial basis for determining present utilization voltage standards, are no longer available. These tolerances were also depended upon by the electrical supplier (electric utility) to allow for differences in voltage levels and voltage unbalances.

The most common voltage ratings for small motors manufactured in the United States are:

For Single-phase motors 115/230 volt

For Three-phase motors 220/440 or 120/208 volt

The above motor ratings are all available from the supplier as stock motors with the exception of the 120/208 volt motor. Whether this is a stock item depends upon the practice of the local warehouse and is usually classified as a special motor.

The most common source of power for these motors comes from two general types of distribution systems. These are the four-wire delta system, which is the 120/240 volt system, and the wye system, which is the 120/208 volt system.

The four-wire 120/240 volt system is used extensively to serve combined light and power loads in areas where the load density does not justify an underground network. This type of secondary may be supplied by either a two or three transformer bank. The two-transformer or open delta bank has the advantage of lower equipment cost while the three-transformer or closed delta bank has fewer losses and makes for better balance on the primary circuit.

In 1944 a study was made by Ebasco Services Incorporated as to the economical range of application for the open delta bank. The results of this investigation showed that in general the open delta bank was the more economical for the following cases.

12-kv or 13-kv Nominal Distribution Systems with Distributed Loads

1. Pure three-phase loads up to 75 kva approximately.
2. Combined single-phase and three-phase loads, having three-phase load up to 75 kva approximately with single-phase loads up to about 100 kva.

4-kv Nominal Distribution Systems with Distributed Loads

1. Pure three-phase loads up to 24 kva approximately.
2. Loads up to 25 kva three-phase combined with single-phase loads up to about 50 kva.

One of the undesirable features of the four-wire delta system is the unbalanced voltages which are characteristic of a combined light and power delta system. This unbalance is greatly accentuated when the supply is from an open delta bank. When these unbalanced voltages are applied to three-phase motors, they will produce backward torques, which will require greater forward torques to give the same shaft output. From information obtainable from one manufacturer the following table was prepared showing the maximum unbalances that would use all of a motor's service factor.[1]

	Percent of Nameplate (220 volts)				
Positive Sequence	90.00	95.00	100.00	105.00	110.00
Negative Sequence	1.50	3.25	4.75	5.62	6.50
Unbalance Factor	1.67	3.42	4.75	5.35	5.90

The unbalance factor used in this table is defined as the ratio of negative sequence voltage to positive sequence voltage expressed in percent. From the table of maximum unbalances and also from Tables 1A and 1B, which give the effect of voltage on other motor characteristics, it can be seen that the operation of a motor on an over voltage is definitely preferable to operation on an under voltage.

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[1] A S Anderson, Problems of Serving Lighting and Three-phase Motor Loads from a Delta Secondary. Ebasco Services Incorporated. Presented at Fifth Power Distribution Conference, Department of Electrical Engineering, University of Texas, Austin, Texas.

Table 1A

General Effect of Voltage Variation on Induction-motor Characteristics*

	Efficiency			Starting and Maximum Running Torque	Synchronous Speed	Percent Slip	Full Load Speed
	Full Load	3/4 Load	1/2 Load				
102% Voltage	Small Increase	Decrease ½ to 2 Points	Decrease 7 to 20 Points	Increase 44%	No Change	Decrease 30%	Increase 1.5%
110% Voltage	Increase ½ to 1 Point	Practically No Change	Decrease 1 to 2 Points	Increase 21%	No Change	Decrease 17%	Increase 1%
Function of Voltage				$(\text{Voltage})^2$	Constant	$\frac{1}{(\text{Voltage})^2}$	(Synchronous speed slip)
90% Voltage	Decrease 2 Points	Practically No Change	Increase 1 to 2 Points	Decrease 19%	No Change	Increase 23%	Decrease 1½%

* See Table 1B for other voltage characteristics.

Table 1B

General Effect of Voltage Variation on Induction-motor Characteristics*

	Power Factor			Full Load Current	Starting Current	Temperature Rise Full Load	Maximum Overload Capacity
	Full Load	3/4 Load	1/2 Load				
102% Voltage	Decrease 5 to 15 Points	Decrease 10 to 30 Points	Decrease 15 to 40 Points	Decrease 11%	Increase 25%	Decrease 5 to 6 C	Increase 44%
110% Voltage	Decrease 3 Points	Decrease 4 Points	Decrease 5 to 6 Points	Decrease 7%	Increase 10 to 12%	Decrease 3 to 4 C	Increase 21%
Function of Voltage					Voltage		$(\text{Voltage})^2$
90% Voltage	Increase 1 Point	Increase 2 to 3 Points	Increase 4 to 5 Points	Increase 11%	Decrease 10 to 12%	Increase 6 to 7 C	Decrease 19%

* See Table 1A for other voltage characteristics.

One method of improving the voltage balance at the point of utilization is to use single-phase feeder regulators with independent voltage controls. This will allow each phase to be regulated according to the magnitude and power factor of its load. With the three-phase regulator the regulation is controlled by the load on one phase, or as on some three-phase regulators, by the average load on two phases. If the feeder to be regulated has an express feeder of any length, then any unbalanced load will cause an additional voltage unbalance in the express feeder which could be eliminated if single-phase regulators were used.

With a wye type distribution system the single-phase 120 volt load may be supplied from any one of the three phases, thus making it possible to get some semblance of a balanced three-phase system. The transformer banks will also be symmetrical, each having transformers of equal sizes. Such a system as this is theoretically the best system from both the standpoint of voltage unbalance and economics of installation. However, in practice this type of distribution system is the cause of many a headache for the distribution engineer of the utility company.

As pointed out before the 208 volt three-phase motor is usually classified as a special motor. Because of this and the fact that the cost is usually about 5 percent above that of a 220 volt motor, it has been very difficult to get either the equipment supplier or customer to use 208 volt motors. A 220 volt motor will operate on a 208 volt system, but it does not leave sufficient allowances for tolerances due to voltage drops and voltage unbalances. This is particularly true where the service factor of the motor has been utilized in the design of the equipment as mentioned before.

Another factor which makes the 120/208 volt wye distribution system rather distasteful to some people is the lack of a standard 208 volt single-phase motor. This makes it necessary to use a 220 or 230 volt single-phase motor for those sizes where a 120 volt single-phase motor is not suitable.

Due to this seemingly lack of compatibility between voltages available on a utility system and standard utilization voltages for motors, it is fast becoming quite a problem for the utility to provide a voltage for its customers that will allow their electrical equipment to operate properly.

To improve the service to its customers, the electric utilities are constantly striving to improve the voltage regulation by the use of static capacitors, larger transformers, larger conductors, and better feeder voltage regulators. The feeder voltage regulator is today a greatly improved piece of apparatus when compared to those of a decade ago. However, with these improvements the feeder voltage regulator is still not capable of the type performance required by the operating utility companies.

This thesis will deal principally with the operation of the feeder voltage regulator. Included will be a review and recommendations for the setting of the line drop compensator. The shortcomings in the design of the presently available line drop compensators and a possible solution to this deficiency will be discussed.

Standard utilization voltages will also be reviewed in view of establishing primary voltage levels on a feeder system that will provide a better regulated voltage for the consumer.

Chapter II

FEEDER VOLTAGE REGULATORS

Control Equipment

Considerable distress has been experienced by those responsible for the proper operation of automatic feeder voltage regulators. These troubles have not been due so much to the improper operation of the regulating equipment but to the limitations of design of the control equipment. Although the control equipment now available on feeder voltage regulators has been greatly improved over the past decade it still is not capable of the type performance required by the operating utilities. Prior to about 1940 it was not uncommon to find the control equipment for feeder voltage regulators to be designed for operation at only one power factor, usually 80 to 85 percent. This type of control apparatus worked satisfactorily only as long as the power factor of the load being supplied remained constant and near the value for which the control equipment was designed. Some of the other types of control equipment manufactured during this period were not only designed for a particular power factor load but had a fixed ratio of resistance to reactance in the compensating circuit.

The control equipment on all modern distribution feeder regulators and supplemental regulators is fundamentally the same type regardless of the manufacturer. This control equipment consists mainly of a voltage-regulating relay,[1] sometimes referred to as a contact making voltmeter, a line-drop compensator,[2] current and potential transformers, and the operating motor with its control relays for changing the position of the feeder voltage regulator.

Feeder voltage regulators may be divided into two main types. The induction voltage regulator and the step voltage regulator.

An induction voltage regulator is a device having one or more windings in shunt and one or more windings in series with a circuit feeder for continuously adjusting the voltages or the phase relations of the circuit or both by changing the relative position of the shunt and series windings of the regulator.

A step voltage regulator is a device having one or more windings excited from the system circuit feeder or a separate source and one or more in series with the system circuit for adjusting the voltage or the phase relation or both in steps, without interrupting the load; and having a rating not exceeding 750 kva for three-phase and not exceeding 250 kva for single-phase.

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[1]A voltage-regulating relay is a voltage-sensitive device which is used on an automatically operated feeder voltage regulator to control the voltage of the regulated circuit.

[2]A line-drop compensator in a feeder voltage regulator is a device which causes the voltage-regulating relay to increase the output voltage of a feeder voltage regulator by an amount which compensates for the impedance drop in the circuit between the regulator and a predetermined location on the circuit (sometimes referred to as the feeder center or load center).

Accuracy Classification

Standard accuracy classes of control devices for induction and step-voltage regulators are as follows:

Accuracy Class	Over-all Percent Error
1	1%
2	2%
5	5%

The errors to be included in the determination of accuracy class are the maximum plus error and the maximum minus error for each of the following.

A. Changes in the ratio of the potential supply with regulator operation throughout its rated range from maximum raise to maximum lower with rated source voltage applied to the regulator.

B. Error of the voltage regulating relay, with its ballast, due to variations in ambient temperature.

C. Error of the voltage regulating relay, with its ballast, due to frequency variations of plus or minus 0.25% from the rated frequency of the regulator.

D. Error in resistance compensation due to changes in ratio of the current supply caused by changes in the phase angle of the current supply and line drop compensator for load variations from 100 to 25% of rated current at 0.8 power factor lagging, when the resistant element is set on the position marked as 50% of its full voltage range and the reactance element is set at 0.

E. Error in reactance compensation under same conditions as outlined in paragraph D with the reactance element set on the position marked as 50% of its full voltage range and the resistance element set at 0.

The over-all plus error is the sum of the maximum plus value of each of the five errors listed, and the over-all percent minus error is the sum of the maximum minus value of each of the five errors. The accuracy class is determined by the greatest of the over-all errors.

In determining the accuracy classifications for step-voltage and induction-voltage regulators according to American Standards Association and National Electrical Manufacturers' Association standards, it is necessary to make tests at only one power factor, 0.80 lagging. With the number of corrective capacitors now being used on distribution feeders for both power factor and voltage correction, it has become a practice to have the power factor corrected to approximately unity during peak conditions. Although some switched capacitors are used, it is not uncommon to have the feeders go as far as 60 to 70 percent leading during light loads because of the unswitched capacitors. With this type of operation the accuracy of feeder voltage regulators at 0.8 power factor is no longer an indication of the performance that may be expected from a particular regulator accuracy class.

A more appropriate test for accuracy classification would be a test at unity power factor and at zero power factor both lagging and leading, for various points on the resistance and reactance elements.

In general there are two types of modern line-drop compensators now being manufactured. The principal difference between these is in the primary relay used. One type uses a relatively high impedance primary relay, while the other uses a low impedance relay.

To reduce control errors due to ambient temperature changes and frequency variations, a high impedance ballast resistor of low temperature coefficient is placed in series with the low impedance primary relay. Because of this low impedance a heavy current is required to operate the relay. This current must also flow through the ballast resistor as well as the compensator resistance and reactance elements, thus causing a high power loss. The compensator elements must be large to handle these currents. It is because of these higher currents that the resistance of the reactance element becomes an appreciable part of the total compensation.

In the older reactance elements about 8 units of resistance drop were produced for 20 units of reactance compensation. Data obtained experimentally for a more modern line-drop compensator using a low impedance primary relay is shown in Table 2. The error in this particular reactance element is 4.68 volts for 20 volts of reactance compensation. Several other units were checked and found to contain an error of approximately 5 volts for 20 volts of reactance setting. A simplified schematic diagram of this type compensation circuit is shown in Figure 1.

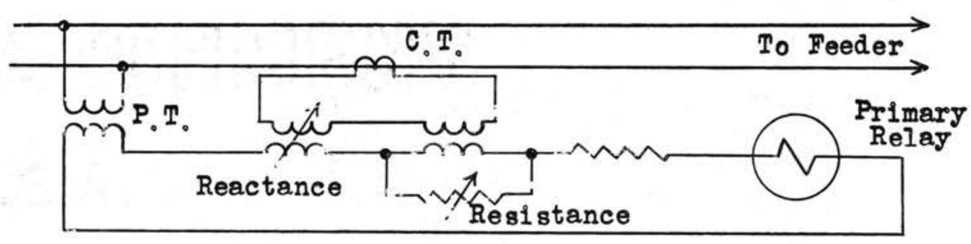

Figure 1

Simplified schematic diagram of a line-drop compensator, which utilizes a low impedance primary relay.

Table 2A

Low Impedance Type Line-Drop Compensator

Unity Power Factor

$X_{setting}$	$R_{setting}$	Actual Regulator Voltage	Calculated Regulator Voltage	Voltage Error In Volts
0	0	120.00	120.00	0
5	0	120.00	119.90	0.70
10	0	121.40	119.58	1.82
15	0	123.00	119.06	3.94
20	0	123.00	118.32	4.68

Zero Power Factor Leading

$X_{setting}$	$R_{setting}$	Actual Regulator Voltage	Calculated Regulator Voltage	Voltage Error In Volts
0	0	120.10	120.00	0.1
0	5	120.00	119.90	0.1
0	10	119.70	119.58	0.1
0	15	119.10	119.06	0.04
0	20	119.40	118.32	0.08

Zero Power Factor Lagging

$X_{setting}$	$R_{setting}$	Actual Regulator Voltage	Calculated Regulator Voltage	Voltage Error In Volts
0	0	120.10	120.00	0.10
0	5	120.10	119.90	0.20
0	10	119.90	119.58	0.32
0	15	119.30	119.06	0.24
0	20	118.40	118.32	0.08

Table 2B

Low Impedance Type Line-Drop Compensator

Approximately 0.8 Power Factor Lagging

Value of Resistance	Voltage at Regulator	Power Factor (Cos θ)	R Cos θ Volts	X Sin θ Volts	Total Voltage Drop	Error Volts
<u>X = 0</u>						
0	120.1	.795	0	0	0	+.10
10	127.8	.798	7.98	0	7.98	-.18[1]
20	135.6	.800	16.00	0	16.00	-.40
<u>X = 10</u>						
0	126.7	.785	0	6.18	6.18	+.52[1]
10	134.9	.793	7.93	6.09	14.02	+.88
20	142.8	.798	15.96	6.03	21.99	+.81
<u>X = 20</u>						
0	132.2	.801	0	11.98	11.98	+.22
10	140.9	.801	8.01	11.98	19.99	+.91
20	149.2	.798	15.96	12.06	28.02	+1.18

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[1]Points used for determining accuracy classification.

Even though there is quite an error in the reactance element, the overall accuracy of the line-drop compensator is fairly good for 0.80 power factor and can easily fulfill the requirements of ASA and NEMA for a Class 1 accuracy classification.

In some compensators of this type the ballast resistor is also the compensator resistor. This double use of the resistor reduces the total energy consumed. One manufacturer that makes both types of compensators claims a burden of approximately 44 volt-amperes for that with the double use resistor and 65 volt-amperes for the compensator with the separate resistors. This is a decrease of approximately one-third in the burden.

The other type of line-drop compensator incorporates a primary relay with a high impedance coil and a new type series ballast consisting of an inductance and capacitance. Since this ballast has a very low resistive component, its power consumption is about one-tenth that required by other types.

The compensator circuit used in conjunction with the high impedance primary relay employs a monocyclic network. A simplified schematic diagram of such a circuit is shown in Figure 2.

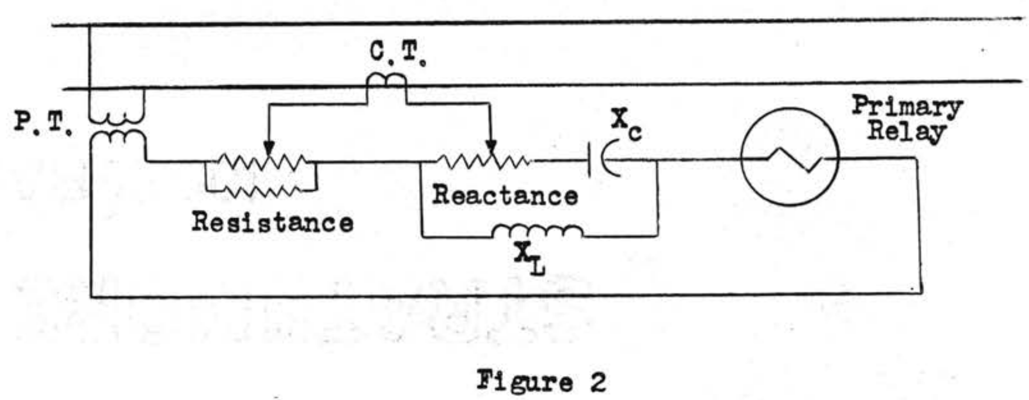

Figure 2

Simplified schematic diagram of a line-drop compensator, which uses a high impedance primary relay.

The reactance element of the compensator circuit is composed of a current dividing rheostat, a capacitor, and a highly inductive reactance. The capacitor and the reactor form a tuned circuit, which presents zero impedance to the flow of C.T. current, i.e., X_C equals X_L. The amount of C.T. current which will flow through the capacitor and reactor will depend upon the position of the continuously adjustable rheostat. The primary relay sees only the voltage drop across the reactor element of this circuit and the resistance element.

Experimental data obtained on a line-drop compensator, which uses a high impedance primary relay and a monocyclic network, is given in Table 3. Note the accuracy of this type unit. The reactance element has a maximum voltage error of 0.5 volts as compared to 4.68 volts error in the element of the unit using the low impedance primary relay.

In actual practice the voltmeter used to adjust and set the primary relay of a line-drop compensator is usually a 0.5 or 0.75 percent rated accuracy voltmeter with a 150 volt scale. The maximum error in the 0.5 percent accuracy meter would be ±0.75 volts. Therefore, to obtain accuracies greater than those found in the line-drop compensators, which use the high impedance relay, is rather futile.

Table 3

High Impedance Type Line-Drop Compensator

Unity Power Factor

$X_{setting}$	$R_{setting}$	Actual Regulator Voltage	Calculated Regulator Voltage	Voltage Error In Volts
0	0	120.00	120.00	0
8	0	120.00	119.69	0.31
16	0	119.50	118.93	0.57
24	0	117.60	117.58	0.02

Zero Power Factor Leading

$X_{setting}$	$R_{setting}$	Actual Regulator Voltage	Calculated Regulator Voltage	Voltage Error In Volts
0	0	120.00	120.00	0
0	8	120.00	119.69	0.31
0	16	119.00	118.93	0.17
0	24	117.40	117.58	-0.18

Zero Power Factor Lagging

$X_{setting}$	$R_{setting}$	Actual Regulator Voltage	Calculated Regulator Voltage	Voltage Error In Volts
0	0	120.00	120.00	0
0	8	119.80	119.69	0.11
0	16	118.90	118.93	-0.03
0	24	116.90	117.58	-0.68

Chapter III

THE VOLTAGE REGULATOR LINE-DROP COMPENSATOR

Basic Settings

Feeder voltage regulators as used on distribution feeder circuits have two basic functions.

1. Correct for voltage variations that occur to the source voltage so the output will remain uneffected by these changes.
2. Compensate for voltage variations which occur in the load area served.

To perform these functions automatically, a device known as a line-drop compensator is used in conjunction with a primary relay, sometimes referred to as a contact making voltmeter or voltage regulating relay. Although there have been several variations of the line-drop compensators in use in the past, only two are in common use today. The differences between these two types are described in Chapter II. Both are basically the same, consisting of a resistance element and reactance element in series to simulate the actual line impedance of the feeder circuit to be controlled. A simplified schematic diagram of a step type regulator and its associated line-drop compensator circuit is shown in Figure 3.

The resistance and reactance elements of the compensating circuit are in series with the primary relay and the potential source which is to be regulated. Thus, any voltage which appears across the resistance

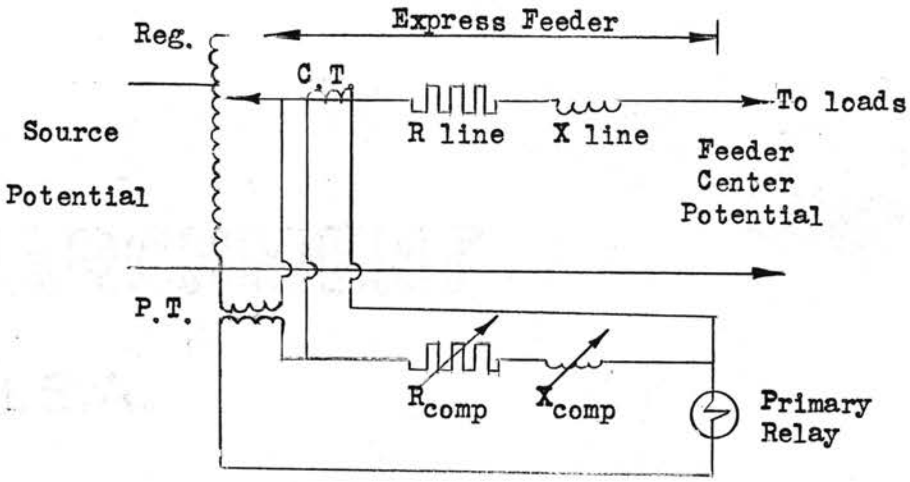

Figure 3

Simplified schematic diagram of a step type regulator and its associated line-drop compensator.

and reactance elements will be added to or subtracted from that of the source potential. Since the current transformer in the line or feeder causes a current to flow through the compensator resistance and reactance elements that is proportional to the load current, the voltage which appears across these elements will be proportional to the load current. By the proper selection of the settings for the resistance and reactance elements of the compensator, the contact making voltmeter will see a voltage proportional to that existing at some point on the system being supplied.

To illustrate the procedure for setting a line-drop compensator, let us assume a 2.4/4.16 kv express feeder one mile long with 336,000 circular mil acsr conductors on a standard 8'-0" crossarm. The resistance and reactance of this feeder would be 0.3073 + j 0.6241 ohms. If the rated primary current for the regulator is 300 amperes and the primary relay is adjusted to operate on a voltage band centered about 120 volts, then the current and potential transformer ratios will be

300:5 or 60:1 and 2400:120 or 20:1, respectively. At full load, 300 amperes, a one volt drop will appear on the secondary of the potential transformer for every 20 volts drop in the primary circuit. The total voltage drop in the express feeder as seen on the secondary of the potential transformer is given by the equation:

$$\text{Voltage Drop} = \frac{I_{CT}}{\text{PT Ratio}} (R + j\,X)$$

where: I_{CT} = Rated primary current of the current transformer in amperes.

PT Ratio = Potential transformer ratio.

R = Line resistance in ohms.

X = Line reactance in ohms.

For the above case this becomes

$$\text{Voltage Drop} = \frac{300}{20} (0.3073 + j\,0.6231) = 4.61 + j\,9.36 \text{ volts.}$$

In order to hold the voltage at the end of the express feeder, commonly called the feeder center, to a constant value, it is necessary to adjust the compensator circuit to allow for the voltage drop in the express feeder. To do this set in 4.61 volts of resistance and 9.36 volts of reactance.

Fixed Shunt Capacitors

As can be seen, the setting of a line drop compensator is easy, as long as the voltage to be maintained at the feeder center is constant and there are no loads, capacitors, or tapped circuits between the regulator output terminals and the feeder center.

The increased use of shunt capacitors on distribution circuits for power factor correction and voltage improvement has made it necessary to obtain the proper coordination between these capacitors and the feeder voltage regulator. If the capacitors are on the source side of the regulator, then the operation of the regulator will not be affected. Similarly, if the capacitors are located beyond the feeder center, the operation of the voltage regulator will not be affected.

Often, however, it is necessary to install capacitors between the regulator and the feeder center, even though such an arrangement is considered very undesirable. This condition usually arises because of the physical arrangement of equipment in a substation, or to the rearranging of an existing circuit. Under these circumstances the capacitive current drawn by the capacitors will not flow through the entire length of the express feeder. The capacitive component of the current will, however, pass through the regulator control circuit line-drop compensator. The regulator will then respond as if the capacitors were at the end of the express feeder unless some adjustment or change is made in the control circuit. There are several methods for making this adjustment or compensation.

A very common method of correcting for this error is to increase the setting of the voltage regulator primary relay for the voltage rise caused by the capacitors and not corrected for by the normal operation of the compensator. This voltage error is given by the equation

$$\frac{CKVAR}{Reg\ KVA} \times \frac{L_1}{L} (R + j\ X)$$

where CKVAR = Capacitor KVAR

Reg KVA = Regulator rated through KVA (complex number)

L_1 = Distance from capacitor to feeder center

L = Length of feeder

R = Compensator resistance setting

X = Compensator reactance setting

Since the above correction would be a value dependent upon the power factor of the load, it becomes necessary to simplify the formula to get a fixed, but approximate, correction.

$$\frac{\text{CKVAR}}{\text{Reg KVA}} \times \frac{L_1}{L} (X)$$

Even though this is an approximate adjustment, the error due to making this approximation, under practical operating conditions, is small compared to the possible errors in instrumentation.

As an illustration let us assume a 900 kvar capacitor bank on the output terminals of a 300 ampere feeder voltage regulator. The express feeder is one mile long and the conductor is 336,000 circular mil acsr. The setting of the line-drop compensator as previously illustrated would be 4.61 volts of resistance and 9.36 volts of reactance. To maintain 120 volts at the feeder center, the primary relay would be adjusted for 120 volts plus the increase necessary to adjust for the error caused by the capacitors. The primary relay setting would be

$$120 + \frac{900}{2160}(9.36) = 120 + 3.9 = 123.9 \text{ volts.}$$

With this primary relay setting, Figure 4 shows the resulting feeder center voltage for various load power factors. The power factor is measured at the feeder center. The maximum error is approximately 0.15 volts, which for all practical purposes is negligible. See appendix for sample calculations.

It should be noted again, however, that this error is due to neglecting the resistance in making the adjusted primary relay setting. Thus the greater the setting of the resistance element, the greater the error will become. This resistance setting could be increased either by decreasing the conductor size or increasing the length of the feeder.

Although overcompensation is not discussed until Chapter V, it should be mentioned that the error caused by capacitors, as described above, may be much greater with certain types of overcompensation.

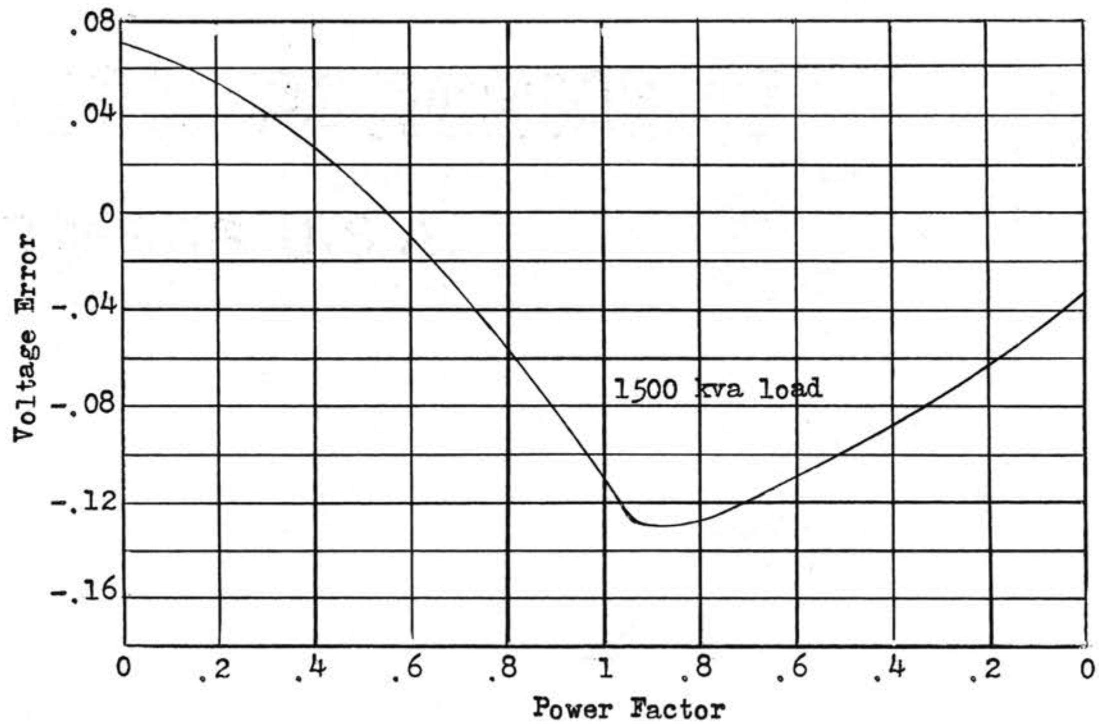

Figure 4

Voltage error due to 900 kvar of capacitors on output terminals of regulator supplying a 300 ampere feeder consisting of one mile of 336,000 circular mil acsr.

Switched Shunt Capacitors

The readjusting of the primary relay setting to compensate for shunt capacitors located between the feeder center and the output terminals of the feeder voltage regulator is limited to unswitched capacitors only. In order to obtain the proper compensation with switched capacitors, it becomes necessary to interconnect the control circuits of the regulator and the capacitor. This requirement usually limits the practical distance between the regulator and the switched capacitor bank.

In general, there are two methods for compensating for switched capacitors.

1. Interconnect current transformers between the capacitors and the compensator circuit so the component of capacitive current due to the capacitors is cancelled out of the compensator circuit.
2. Switch a fixed voltage bias in the compensator circuit. This method is equivalent to readjusting the primary relay as done in the case of fixed capacitors, the same error being prevalent in each.

The first method of correcting the compensator circuit for switched capacitors is the better of the two for it gives the correct compensation for all operating conditions and compensator settings. Figure 5 shows a simplified schematic diagram of this system. The current transformers are interconnected so the capacitive current is balanced out of the line-drop compensator circuit.

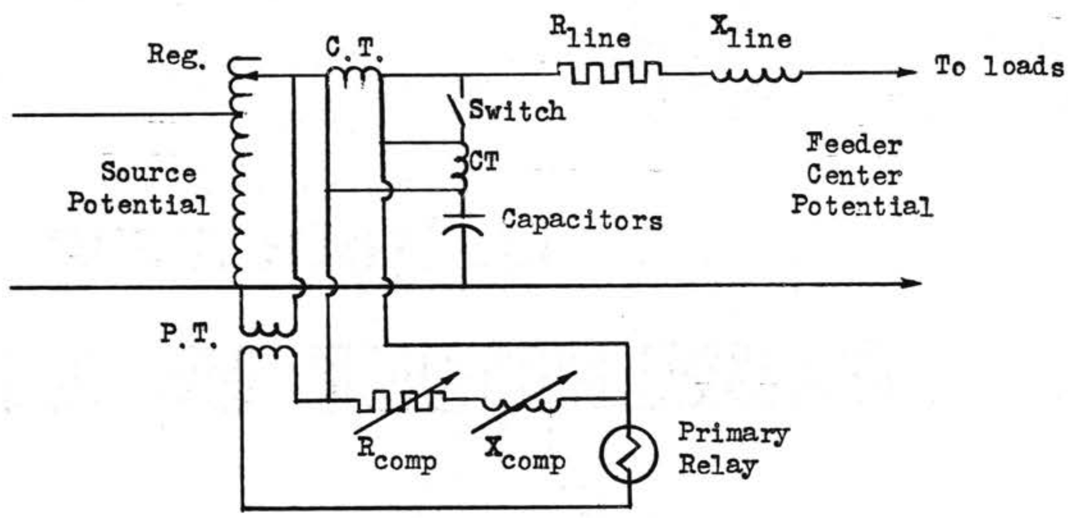

Figure 5

Simplified schematic diagram of compensating circuit with switched capacitors on the output terminals of the regulator using interconnected current transformers.

The second method of correcting the compensator circuit requires that a fixed voltage bias, usually a resistor, be switched in and out of the compensator circuit as the capacitor bank is switched. Although this method may be of sufficient accuracy for most applications, care should be exercised in applying it. Any modification of the compensator circuit, such as this, should be checked with the manufacturer. Figure 6 shows a simplified schematic diagram of a line-drop compensator using switched voltage bias.

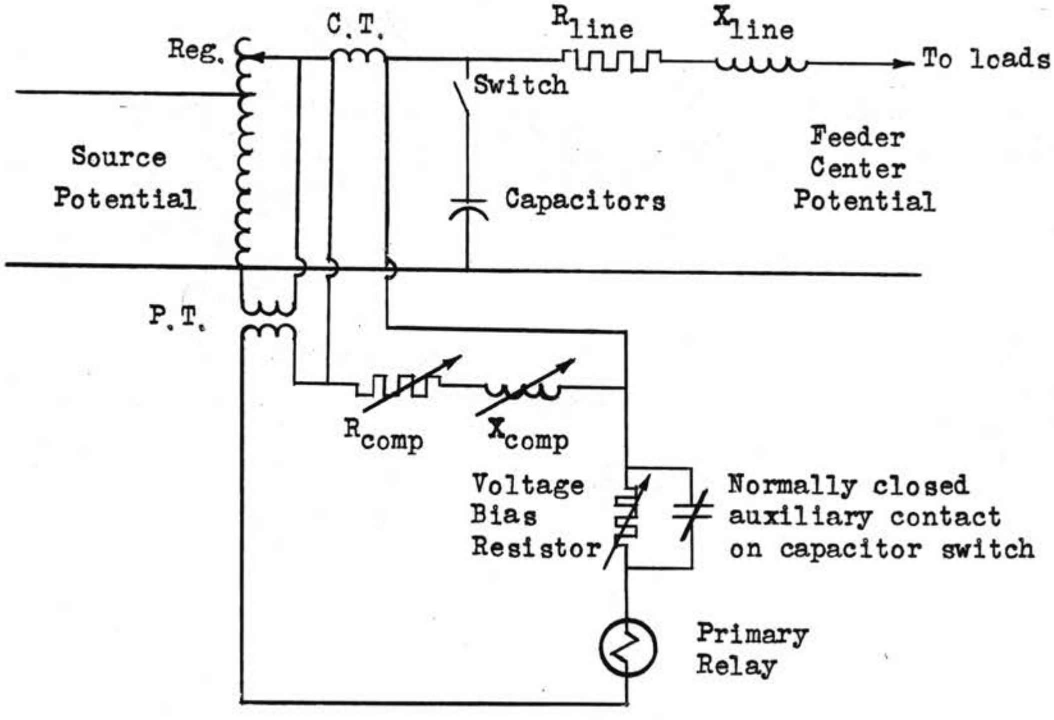

Figure 6

Simplified schematic diagram of compensating circuit using switched voltage bias.

The preceding discussion of line-drop compensators has been based on the premise that the voltage at the feeder center should be held constant. In actual practice it is usually found that this is not the case. Instead of holding a constant voltage at the feeder center, the voltage is allowed to vary with the load, from 100 percent voltage at no load to approximately 105 or 110 percent voltage at full load. This type of compensation, referred to as overcompensation, will be discussed in more detail in Chapter V.

Chapter IV

UTILIZATION VOLTAGES

Standard Utilization Voltages

An attempt to standardize utilization voltages dates back as far as 1899. From time to time since then the voltage standards and recommendations for the electric industry have been reviewed and reissued. In 1930 a document entitled "Preferred Voltage Ratings for A-C Systems and Equipment" was published as a result of a joint committee of the NELA and the NEMA. This was the first voltage standard to be sufficiently complete and satisfactory to the industry as a whole to warrant adoption.

After a number of years it became apparent that this publication was becoming obsolete and a revision was necessary. The reasons for this revision were:

1. The upward trend of utilization voltages.
2. The increased use of high and low voltage networks.
3. The changes in voltage regulating techniques.

After several years of study, a revision of the utilization voltages was published in May, 1949, as a joint EEI and NEMA publication.

In considering the rating and design of lamps, appliances and other electrical apparatus, it is recognized that the design voltage and/or range of voltages may be somewhat different from the nominal system voltage at the point of utilization. This is caused by the regulation in the circuit and the inability of the utility to maintain a constant voltage at the point of service. To allow for this regulation or variation in the utilization voltage, the electrical equipment manufacturers must design their products to operate satisfactorily over a range of voltages. The design voltages as set out in the EEI-NEMA publication, "Preferred Voltage Ratings for A-C Systems and Equipment," will vary with different types of appliances, lamps, etc., having the same voltage rating. These recommendations are based upon the power requirements of the apparatus and its normal load factor. An example of the differences in design mode voltages would be the comparison of the decorative incandescent lamp and the flood incandescent lamp.

In the case of a decorative incandescent lamp, a design voltage or mode of 122 volts has been chosen when designing for satisfactory illumination and long life. In the case of the spot and flood type incandescent lamp, a lower design (mode) voltage of 118 volts has been deemed satisfactory, as the spot and flood type lamps require more current and therefore will produce more voltage drop in the supplying circuit. In both the above cases the rating of the lamp is 120 volts.

Some of the voltages to be used as a basis for design of the more common devices and appliances are tabulated in Table 4.

It should be noted from this tabulation that the design (mode) voltage for the various equipments depends upon the normal application and load characteristics of that particular piece of apparatus.

For single phase, fractional and integral horsepower motors 115 and 230 volts were standardized several years ago, on the basis that most of such motors will operate on 120/240 volt systems. The 115 volt single phase motors are suitable for operation on 120/208Y networks. However, the operation of a 230 volt motor on a 120/208Y volt system is not con-

Table 4

Design Voltages for Some of the More Common Electrical Apparatus

Apparatus	Nominal System Voltage	Equipment Voltage Rating	Voltages to be Used as a Basis of Design		
			Minimum	Mode	Maximum
Irons - hand	120	118	107	118	122
Irons - ironers	120	115	107	115	122
Ranges - household type	120/240	118/236	110/220	118/236	124/248
Air conditioners - room type	120/240	115/230	107/214	115/230	122/244
Radios	120	120	110	122	127
Fluorescent lamps - residence	120	118	107	122	127
Incandescent lamps	120	120	110	122	127
Incandescent lamps - spot and flood	120	120	110	118	122
Signal and control transformers	120	120	110	122	127

sidered satisfactory. The voltage band of operation for motors as guaranteed by the manufacturer is plus or minus 10 percent of their nameplate value. A 230 volt motor should, therefore, operate on 207 volts; however, it should be remembered that the available torque varies as the square of the voltage. This means that a 230 volt, 5 horsepower motor, when operated on 208 volts, would be approximately equivalent to a 4 horsepower motor at rated voltage. See Tables 1A and 1B.

For three-phase, fractional and integral horsepower motors, 110 and 220 volts have been accepted as standard. When operating a 220 volt motor on a 208 volt supply, the motor must be derated approximately 10 percent. A 220 volt, 5 horsepower, three-phase motor operated on a 208 volt supply would be equivalent to a 4.5 horsepower motor at rated voltage.

In general the utilization voltages as recommended in the joint EEI-NEMA publication for the design of electrical equipment may be summarized by the following statements.

1. For light loads with high load factors, such as electric clocks, the minimum and maximum voltages to be used as a basis for design should be 110 volts and 127 volts, respectively.
2. For medium loads, such as refrigerators, the maximum and minimum design voltages should be 110 volts and 125 volts.
3. For heavy loads, such as electric ranges, the maximum and minimum design voltages should be 110 volts and 124 volts.
4. For heavy loads, with cords for plugging into a convenience outlet, such as an electric ironer, the maximum and minimum design voltages should be 107 volts and 122 volts.

Varying the design voltage limits and design mode of the different pieces of electrical equipment, in accordance with their power requirements, is equivalent to the designing of voltage compensation into the equipment. It is believed that the operating utility should capitalize on this variation in design voltage.

Most Economical Utilization Voltages

The preferred nominal utilization voltage as recommended by the EEI-NEMA publication, "Preferred Voltage Ratings for A-C Systems and Equipment," may not be the most economical voltage from the standpoint of the consumer. It is unfortunate that all types of electrical equipment do not have economical voltages near the same value. Since there is such a variation, a compromise is necessary.

When incandescent lamps are considered, it is relatively simple to determine the point of most economical operation, it being a function of energy costs and lamp replacement costs.[1]

The light output, efficiency and life of an incandescent filament lamp are all interrelated and will vary as the applied voltage is varied. Average values of lamp characteristics and their resultant exponential curves may be found in various lamp manufacturers' bulletins or lighting handbooks. From the information and the prevailing costs the most economical applied voltage may be determined. With an energy cost of two cents per kilowatthour the following table may be calculated. The costs are based on current prices of 120 volt inside frosted bulbs. Prices include federal tax. The lamp characteristics are taken from

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[1]Charles F Cameron, Lamps, Wire Size and Voltage Drop. Oklahoma Agricultural and Mechanical College, Stillwater, Oklahoma. Oklahoma Engineering Experiment Station Publication.

the IES Lighting Handbook and are based on an average output of 16 lumens per watt.

Table 5

Most Economical Utilization Voltage
for Incandescent Lamps

Lamp Wattage	Lamp Cost	Percent Voltage	Utilization Voltage
60	$0.18	102.1	122.5
100	0.20	105.7	127.9
150	0.24	107.8	129.2
200	0.35	106.9	128.2
300	0.44	108.6	130.5

It is interesting to note that the replacement cost of lamps would have to be approximately 0.372 cents per watt to make the most economical operating voltage and rated voltage synonymous. Since the present day cost of lamps is much less than this, with the possible exception of special purpose lamps, it can be concluded that the most economical operating voltage for incandescent lamps will in general be much greater than 120 volts, usually around 128 to 130 volts.

The efficiency and life of the fluorescent lamp, unlike the incandescent lamp, is not affected by variations in the applied voltage if maintained within the limits of its designed operating range. Excessive low or high voltage will, however, reduce the lamp life. With low voltage one is apt to find instability in the arc and starting may be very difficult if not unobtainable. High voltage, on the other hand, may cause excessive heating and premature end blackening. This is particularly true in poorly designed fixtures with inadequate ventilation.

The ballast as commonly used in conjunction with the fluorescent lamp is a current limiting device. On voltages over the specified range, the operating current becomes excessive and will cause the ballast to overheat. If this condition of overvoltage persists, it may cause the ballast to fail.

Fluorescent lamps and their auxiliaries are designed to operate well together over a range of voltages from 110 volts to 125 volts, inclusive, and in some cases may operate satisfactorily on circuits as low as 105 volts or as high as 130 volts. Some manufacturers of fluorescent lamp ballasts now make a ballast that is designed to operate on a range of voltages from 105 to 130 volts.

Heating appliances such as the electric range are very sensitive to changes in voltage. If we assume the heating element has a constant resistance then the surface temperature of the element will be a function of the square of the impressed voltage. The higher the voltage, the greater the temperature. Increasing the temperature will, however, reduce the life of the element.[1]

It is evident that there must be a voltage at which it would be most economical to operate a resistance heating element. To determine what this voltage is would be a study in itself, nevertheless we do know that to obtain acceptable operation, the voltage must be maintained reasonably high. The household type of range for operation on 120/240 volt system usually has a design voltage of 118/236 volts with a minimum of 110/220 volts and a maximum of 124/248 volts. The relays, thermostats, and other accessories are designed to withstand voltages up to and including 130/260 volts.

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[1]Riese, Russell L. "Electric Heating Element Economics". <u>Master's Thesis</u>, Oklahoma Agricultural and Mechanical College, 1950.

Chapter V

PRIMARY VOLTAGES ON DISTRIBUTION FEEDERS

General

Preliminary to the joint EEI and NEMA publication concerning voltage ratings for a-c systems and equipment, the EEI made a very exhaustive study of the utilization voltage problem with two objectives to be accomplished.

1. Determine reasonable utilization voltage spreads and the limiting values for which the manufacturers should design utilization equipment to operate.
2. Indicate desirable limits of service voltage spreads, corresponding to the utilization voltage spreads in (1), which can be used as a guide for the design and operation of distribution systems.

As a result of this investigation the Edison Electric Institute (EEI) published a report in October, 1942, publication No. J8, "Utilization Voltage Standardization Recommendations." This report recommended the following service voltage limitations.

	120/240 volt System	120/208 volt System
Maximum	127/254	127/220
Preferred Maximum	125/250	125/216
Preferred Minimum	113/226	117/202
Minimum	110/220	114/198

These maximum and minimum voltages were used as a basis for establishing the design voltage limits and design voltage modes of the various types of electrical apparatus, as set out in the joint EEI-NEMA publication.

From the study of utilization voltages, it was found that the minimum voltages for design purposes ranged between 107 and 110 volts. We can therefore conclude that the minimum voltage acceptable to the consumer would be 110 volts. Starting with this permise, the minimum allowable primary voltage may be determined.

To determine what may be expected in the way of voltage drop between the primary and customer's entrance switch, several different cases were studied. The details of these calculations are shown in Appendix B.

In all cases it was assumed that the secondary was a three-wire 120/240 volt system using No. 0 bare aluminum conductor with one foot spacing. The span lengths were assumed to be 120 feet, based on 60 foot urban lots, and the service drops were all three-wire No. 2 solid, neoprene insulated aluminum.

All demands are based on statistical load checks made of residential areas in the Oklahoma Gas and Electric Company system. The transformer loading monogram which is the result of these accumulated statistical load checks is included in Appendix B.

The voltage drops from the primary to the last customer's service entrance switch were calculated and the results plotted in Figure 7. From an inspection of this curve it may be seen that the probable maximum voltage drop, when using 15 kva transformers loaded to 140 percent of their nameplate rating, will be approximately 6.52 volts. When using a 25 kva transformer, the approximate voltage drop with 140 percent load will be 8.0 volts. If the voltage drop is limited to 6.6 volts, as one electric utility now does, then the load density which may be served will be limited to approximately 58 kva per 1000 feet, and still allow each transformer to feed two spans in each direction. The approximate load density for 58 kva per 1000 feet is 3200 kva per square mile. By raising this voltage limit to 8 volts, load densities up to 97 kva per 1000 feet may be served before it will be necessary to have transformer stations on every third pole. The approximate load density for 97 kva per 1000 feet is 6500 kva per square mile.

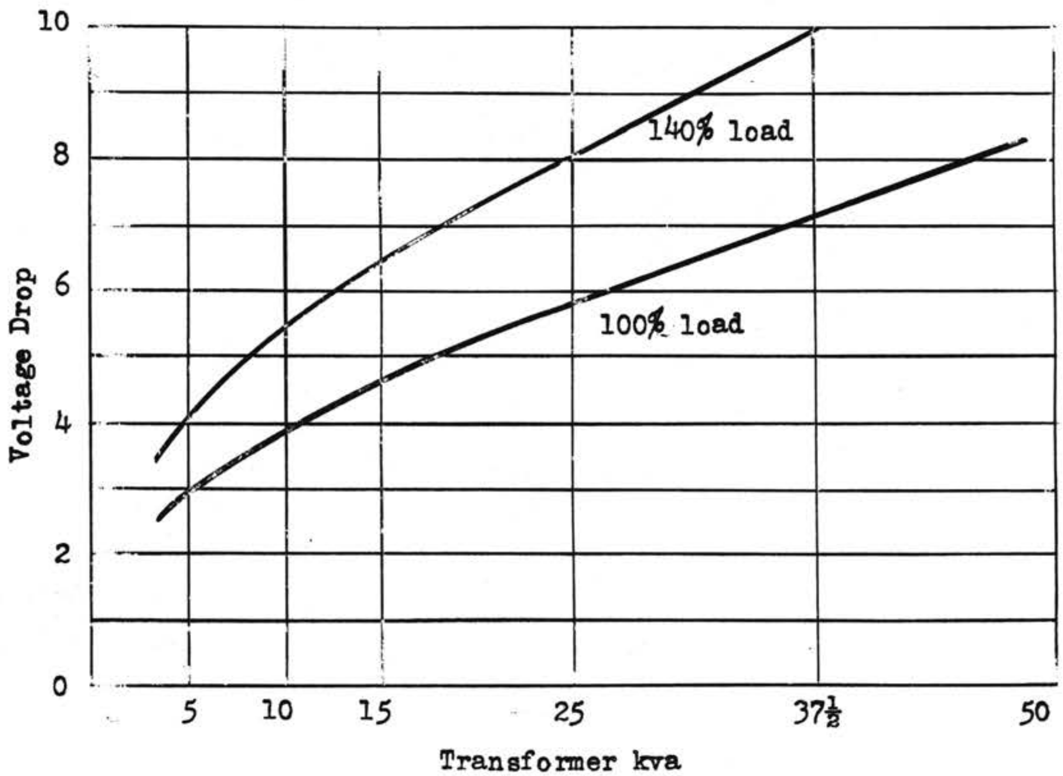


Figure 7

Voltage drop from primary side of transformer to last customer's service entrance for 100% and 140% transformer loads.

The value of secondary voltage drop which will be allowed not only should be thought of as a limiting condition, but also the most desirable. By extending the secondaries as far as possible, the number of customers served from the same transformer station will be increased and the cost per kva for serving them will be less. Voltage flicker which is usually a limiting factor in low density areas may be improved by secondary banking.

If we allow three volts of voltage drop in the customer's wiring and eight volts from the service entrance switch to the primary of the distribution transformer serving this load, then the voltage required on the primary to hold 110 volts at the customer's socket will be 110 + 3 + 8 = 121 volts.

As pointed out before, the maximum design voltage for the small energy consuming apparatus is 127 volts. Thus if we allowed only two volts drop from the primary of the transformer to the customer's socket with the feeder fully loaded then the feeder center voltage could conceivably be as high as 129 volts without exceeding the utilization design voltage of the electrical apparatus served. With 129 volts at the feeder center, a drop of 8 volts is allowed in the primary circuit under full load conditions.

As it would not be feasible to hold 129 volts at the feeder center continuously because of the losses due to over-excitation of the transformers and of the greater probability of exposing the customer's electrical equipment to overvoltages, a variable feeder center voltage should be used. From the standpoint of both the customer and the utility company, a voltage at the feeder center that varies from 120 volts at no load to 129 volts during the peak would be most favorable. This variation in the feeder center voltage may be obtained by setting in overcompensation in the line drop compensator, i.e., in addition to setting in the compensation required for the feeder, an additional amount would be set in, depending upon the amount of overcompensation required.

Overcompensation

With the presently available types of line-drop compensators, overcompensation may be set in the resistance element, the reactance element, or a combination of both. Setting in overcompensation in this manner has the effect of moving the point of regulation past the feeder center into the load area. There are a variety of methods now in use for obtaining the overcompensation required.

One method used by the Oklahoma Gas and Electric Company to get 6 volts of overcompensation is to set in an extra 5.1 volts of resistance and 3.2 volts of reactance. This method, which has been in use since 1938, was based on the voltage drop between the feeder center and what was then an average customer. These voltage drops were broken down as follows:

	Resistance Volts	Reactance Volts
Full load drop in 10 kva transformer	2.2	2.2
One-half of the permissible secondary drop (#6 copper on 8 inch racks)	1.8	0.6
Primary line (#6 copper on 8'-0" crossarm)	1.1	0.4
	5.1	3.2

It should be noted that these settings give 6 volts of compensation at only one power factor, 80 percent. To show the resulting feeder center voltages for various power factor loads, a curve, Figure 8, was calculated for a typical feeder under full load conditions. These calculations were based on a 300 ampere, 336,000 circular mil aluminum feeder one mile long. The overcompensation was assumed to be 5.1 volts of resistance and 3.2 volts of reactance. For loads with power factors near 0.80 lagging the overcompensation could be considered satisfactory. However, with the increased use of static shunt capacitors, the power factor is normally around unity power factor and can easily go into the leading range during light loads. Beginning at unity power factor and extending into the leading range, the voltage at the feeder center drops rapidly. To overcome this low voltage with leading power factors, it is sometimes recommended to reduce the reactance instead of increasing it. This will increase the voltage at the feeder center for the leading power factors, but will cause it to drop for lagging power factors. This can be seen from the calculated curve in Figure 9. This figure was based on the same feeder as Figure 8, except the reactance overcompensation was assumed to be minus 3.2 volts.

A compromise between the above two methods is to place the six volts of overcompensation in the resistance element only. This type of arrangement gives fair voltage response near unity power factor, but drops off rather quickly on both sides of unity. Figure 10 shows this characteristic.

An Improved Line-Drop Compensator (Tuttle Design)

From the preceding analysis it can be seen that the setting of overcompensation into the line-drop compensator of a modern feeder voltage regulator is at best a compromise. To obtain overcompensation that is independent of the power factor of the load is impossible with available equipment.

A line-drop compensator that would be capable of the performance desired would require that it be able to perform two independent functions. One function would be the ability to compensate for the voltage drop between the output terminals of the feeder voltage regulator and the feeder center for any load at any power factor. The second function desired would be a voltage compensation that was sensitive only to the magnitude of the load and independent of the power factor.

Any modern line-drop compensator is capable of performing the first function as this would require only a resistance and reactance element to simulate the feeder characteristics. To obtain the second function, it is suggested that an additional element be added to the compensator to perform this duty. A simplified schematic diagram of a line-drop compensator which contains this additional element is shown in Figure 11. This additional element consists of a rectifier in the current circuit, the output of which will be proportional to the current. Since this current is rectified, it will produce a flux in the coil on the primary relay that will always add arithmetically to the flux produced by the current from the other elements. In other words, any compensation in this new element would be independent of the power factor of the current flowing through it.

A feeder voltage regulator with a line-drop compensator of this type would be capable of compensating for the voltage drop to the feeder center and of providing overcompensation that would depend only on the magnitude of the load. The characteristic curve of the voltage at the feeder center for various power factors would be a straight line or constant voltage instead of a curve as shown in Figures 8, 9 and 10.

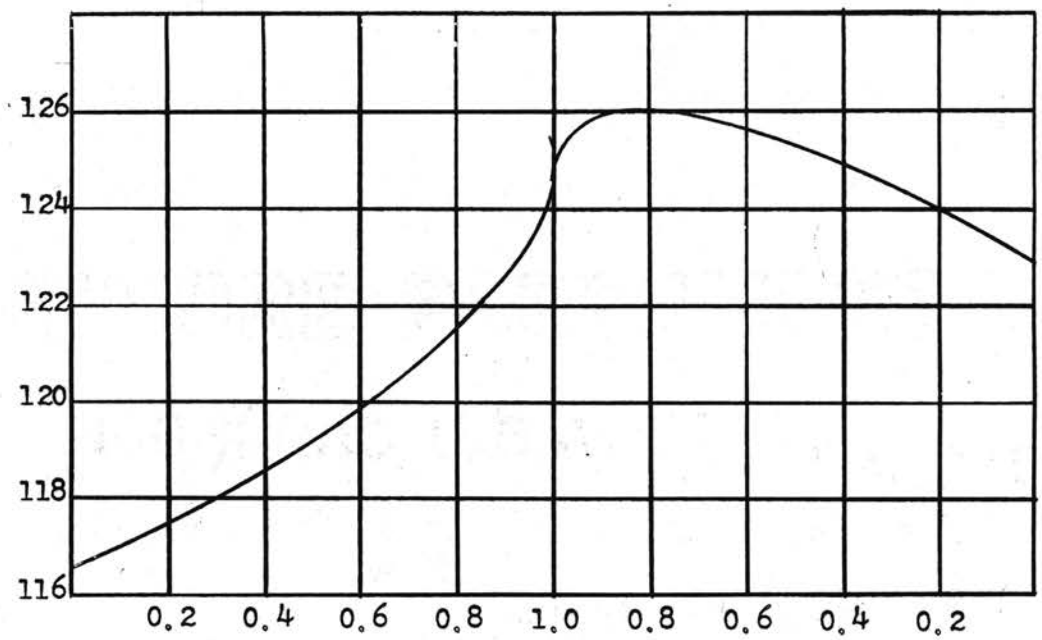


Figure 8

Feeder center voltage for various power factors at full load with 5.1 volts of resistance and 3.2 volts of reactance overcompensation

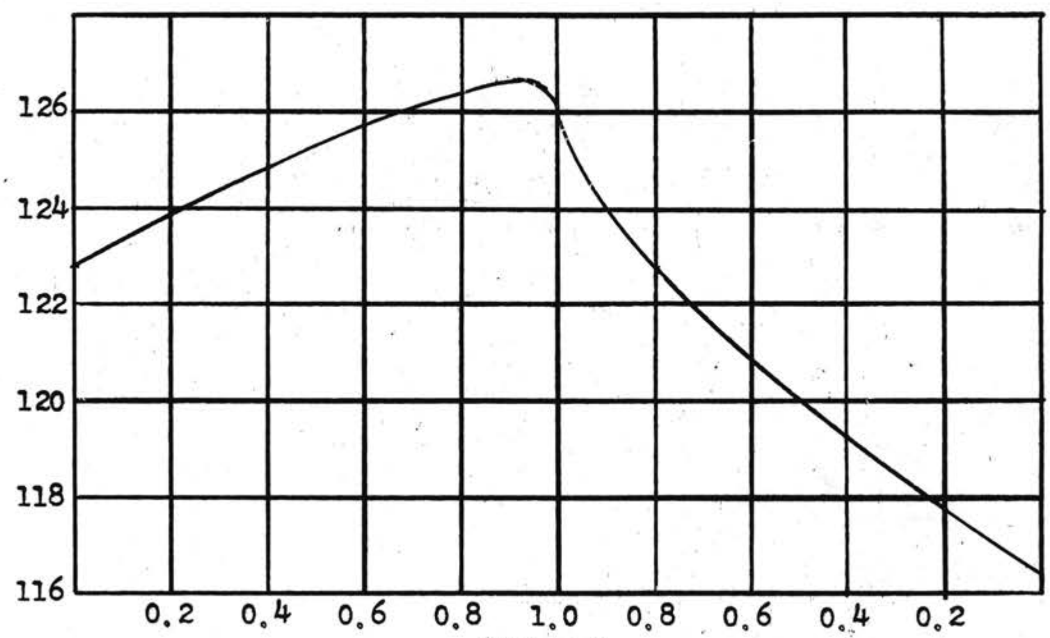


Figure 9

Feeder center voltage for various power factors at full load with 5.8 volts of resistance and -3.2 volts of reactance overcompensation

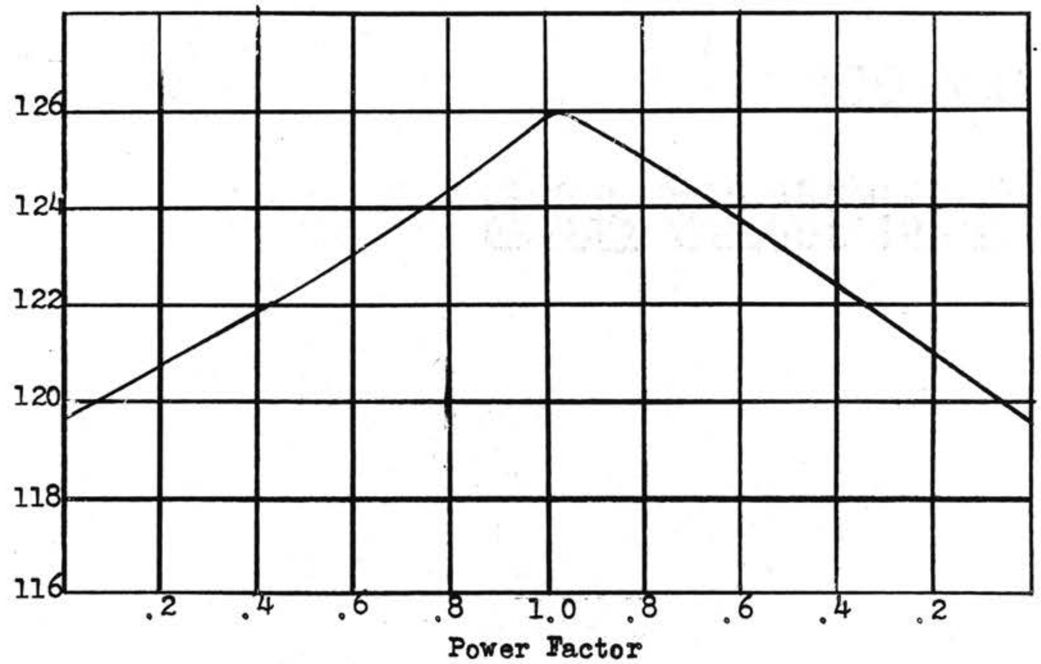
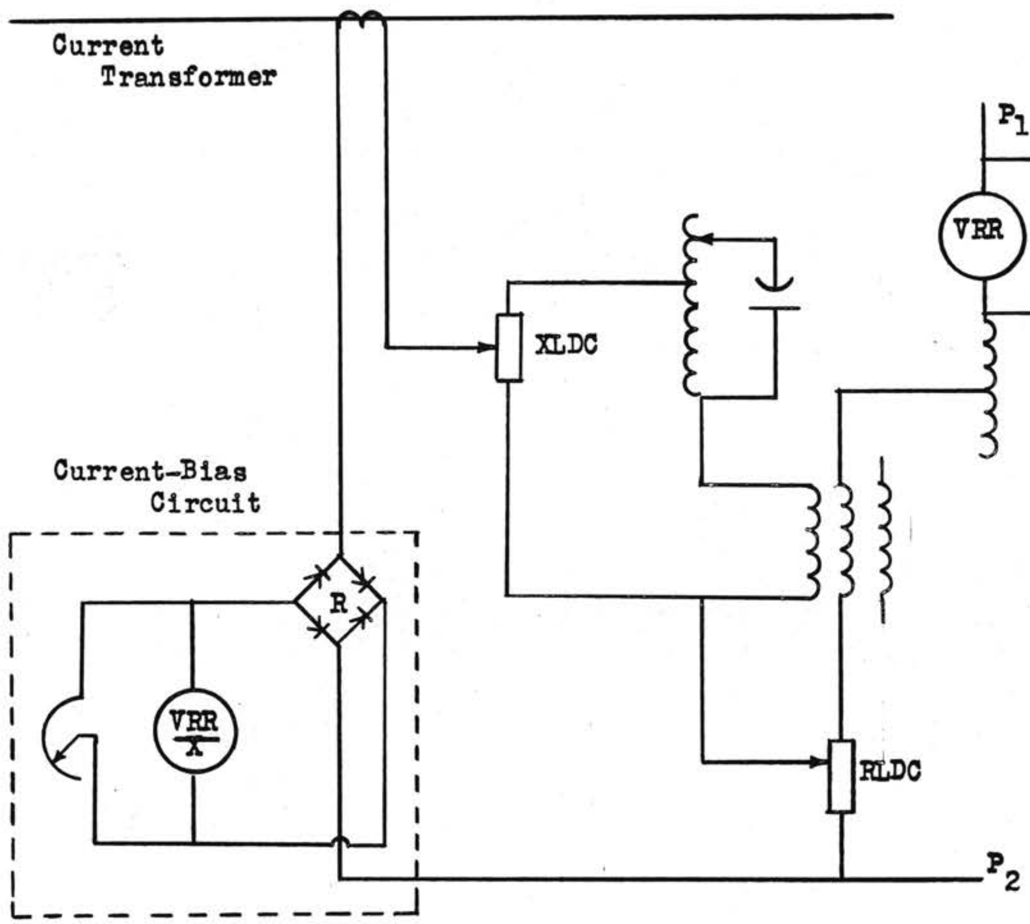


Figure 10

Feeder center voltage for various power factors at full load with 6.0 volts of resistance overcompensation



RLDC - Resistance Compensation Rheostat

XLDC - Reactance Compensation Rheostat

R - Rectifier

VRR - Voltage Regulating Relay Primary Coil

$\frac{VRR}{X}$ - Voltage regulating Relay Auxiliary Coil

(This coil applies a bias to voltage regulating relay setting that depends upon the magnitude of load current but is independent of load current phase angle.)

Figure 11

A Simplified Schematic Diagram of an Improved Line-Drop Compensator

Chapter VI

CONCLUSION

The problems involved in the setting of line drop compensators on feeder voltage regulators are not new. Although the methods presently being used have been satisfactory, they are fast becoming inadequate with present day operating practices. It is believed that this will be increasingly truer as more and more fixed capacitors are used on primary distribution circuits.

With the presently available line-drop compensators it is not possible to set in overcompensation that is independent of the power factor. One can get a compromise setting, however, that will give fair results over a limited range of power factors. The line drop compensator described in this paper, referred to as the Tuttle design, would very definitely be an improvement. It is capable of overcompensation voltage control that is independent of the power factor of the load. By closer control of feeder voltages the utility may take greater advantage of the range of utilization voltage over which electrical equipment is designed to operate.

In the selection of operating voltage ranges, it has been shown that operation at the higher end of the utilization voltage band will give the most acceptable performance from the standpoint of both the customer and the electric utility. For those pieces of electrical apparatus which do not show a marked economical difference in whether they operate in the low or high portion of their voltage range, such as the fluorescent light, it has been found that they are not harmed by the higher voltages. Usually the operation is much more satisfactory with the higher voltages than when operating on the lower part of the voltage range. This is particularly true of the electric motor and the resistance heating element.

It is not necessarily proposed that the nominal utilization voltages or the range of utilization voltages be changed, but that the utility design its system to take advantage of the voltage characteristics of the equipment it serves. By obtaining closer control of the feeder voltage and by favoring the higher voltages it should be possible to design a more economical distribution system.

The use of more and more fixed capacitors on distribution feeders in the future is a very real possibility. The principal objections to the use of more fixed capacitors are:

1. Apprehension of operating personnel when operating at leading power factors because of possible instability.
2. Difficulties encountered in setting overcompensation in the presently available line drop compensators.

With the advent of the continuous type generator voltage regulator, the problem of instability is no longer realistic. It may be some time, however, before the operating people are completely convinced of this. The second problem may be solved by using a line drop compensator of the design described in this paper, or one similar to it.

The specification requirements for a given accuracy classification of feeder voltage regulators, as adopted by the American Standards Association, are not sufficiently complete to give an indication of the type performance that may be expected from a particular accuracy class. A regulator with the highest accuracy classification may still give an unacceptable voltage error with present day distribution practices. These specifications should be revised and made complete enough to be applicable under any operating condition.

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TABLE OF SYMBOLS

E_o = Voltage at point compensator is set to reach.

With no overcompensation $E_o = E_2$.

E_1 = Voltage at regulator terminals.

E_2 = Voltage at feeder center.

E_3 = Voltage setting of voltage regulating relay that gives correct value of E_2 with capacitors on the output terminals of voltage regulator.

E_r = Voltage drop in compensator circuit caused by load current.

E_d = Voltage drop in feeder as seen by the compensator circuit.

E_c = Voltage rise in compensator circuit caused by capacitor current.

I_p = Rated primary current of regulator.

P.T. = Potential transformer.

C.T. = Current transformer.

R = Compensator resistance setting in volts.

X = Compensator reactance setting in volts.

r = Resistance of feeder conductor.

x = Reactance of feeder conductor.

CKVAR = Kilovars of capacitors.

RKVA = Rated regulator kva.

VRR = Voltage regulating relay (primary relay).

A = Arctan $\frac{X}{R}$.

B = 90-A.

θ = Angle of load current with respect to voltage at regulator output terminals.

α = Angle between E_2 and E_3.

τ = Angle between E_2 and E_c.

η = Angle between E_c and E_3.

β = Angle between E_1 and E_2.

$\phi = A + \theta$.

$\gamma = 180 - \phi -$

ψ = Angle of feeder plus angle of load.

APPENDIX A

The following is a sample calculation to obtain the voltage at the feeder center when six volts of resistance overcompensation have been set into the line drop compensator. The procedure is the same regardless of the type of overcompensation being used. The information known is as follows:

1. Resistance and reactance of feeder.

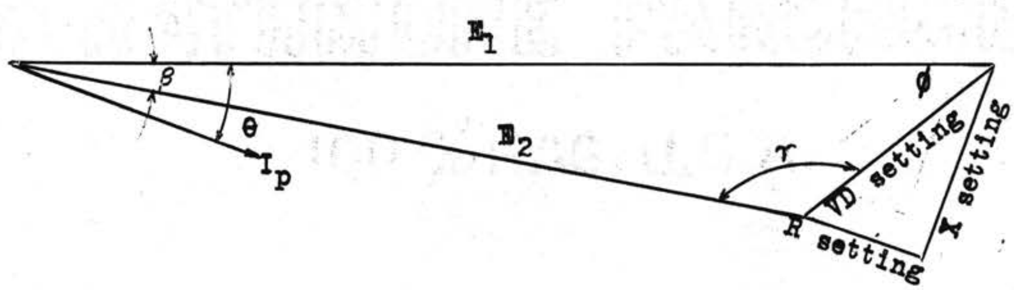
   $r + jx = 0.3073 + j0.6241$ ohms

2. Resistance and reactance setting of the line drop compensator elements in volts.

   $R + jX = 10.61 + j9.361$ volts

3. Voltage setting of voltage regulating relay. In this example it was assumed to be 120 volts.

The angle of the load at the regulator output terminals, θ, was taken to be -20 degrees for this sample calculation. This is a lagging power factor of 94%.



Using the law of sines,

$$\frac{\text{Sin } \beta}{E_c} = \frac{\text{Sin } \phi}{E_2}$$

$$\phi = A + \theta = 41.42 - 20.0 = 21.42 \text{ degrees}$$

$$\text{Sin } \phi = 0.3678$$

$$E_c = 10.61 + j9.361 = 14.15 \underline{/41.42^o}$$

$$\text{Sin } \beta = \frac{E_c}{E_2} \text{ Sin } \phi = \frac{14.15}{120}(0.3678) = 0.04337$$

$$\beta = \text{Arcsin } 0.04337 = 2.486 \text{ degrees}$$

$$\Upsilon = 180^o - \phi -$$

$$\Upsilon = 180^o - 21.42 - 2.486 = 156.094 \text{ degrees}$$

$$\text{Sin } \Upsilon = 0.4078$$

$$E_1 = E_o \frac{\text{Sin } \Upsilon}{\text{Sin } \phi} = 120 \frac{0.4078}{0.3678} = 133.05 \text{ volts}$$

Actual voltage drop in express feeder from regulator output terminals to feeder center as seen by regulator is given by the following equation:

$$E_d = \frac{I_p\ (r + jx)}{\text{P.T. ratio}} = \frac{300 \underline{/-20}}{20} (0.3073 + j0.6241)$$

$$E_d = 7.5333 + j7.2193$$

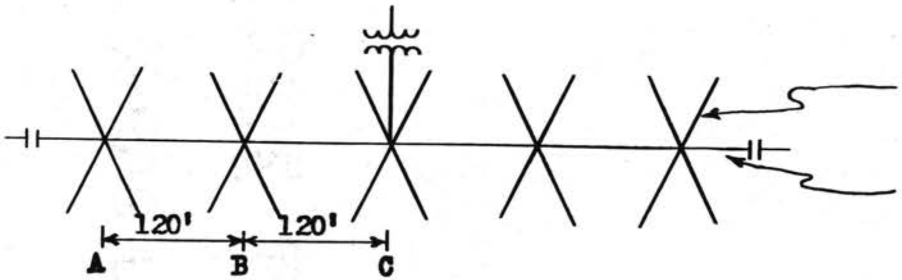
Voltage at feeder center

$$E_2 = 133.05 - 7.53 - j7.22$$

$$E_2 = 125.52 - j7.22 = 125.73 \text{ volts}$$

APPENDIX B

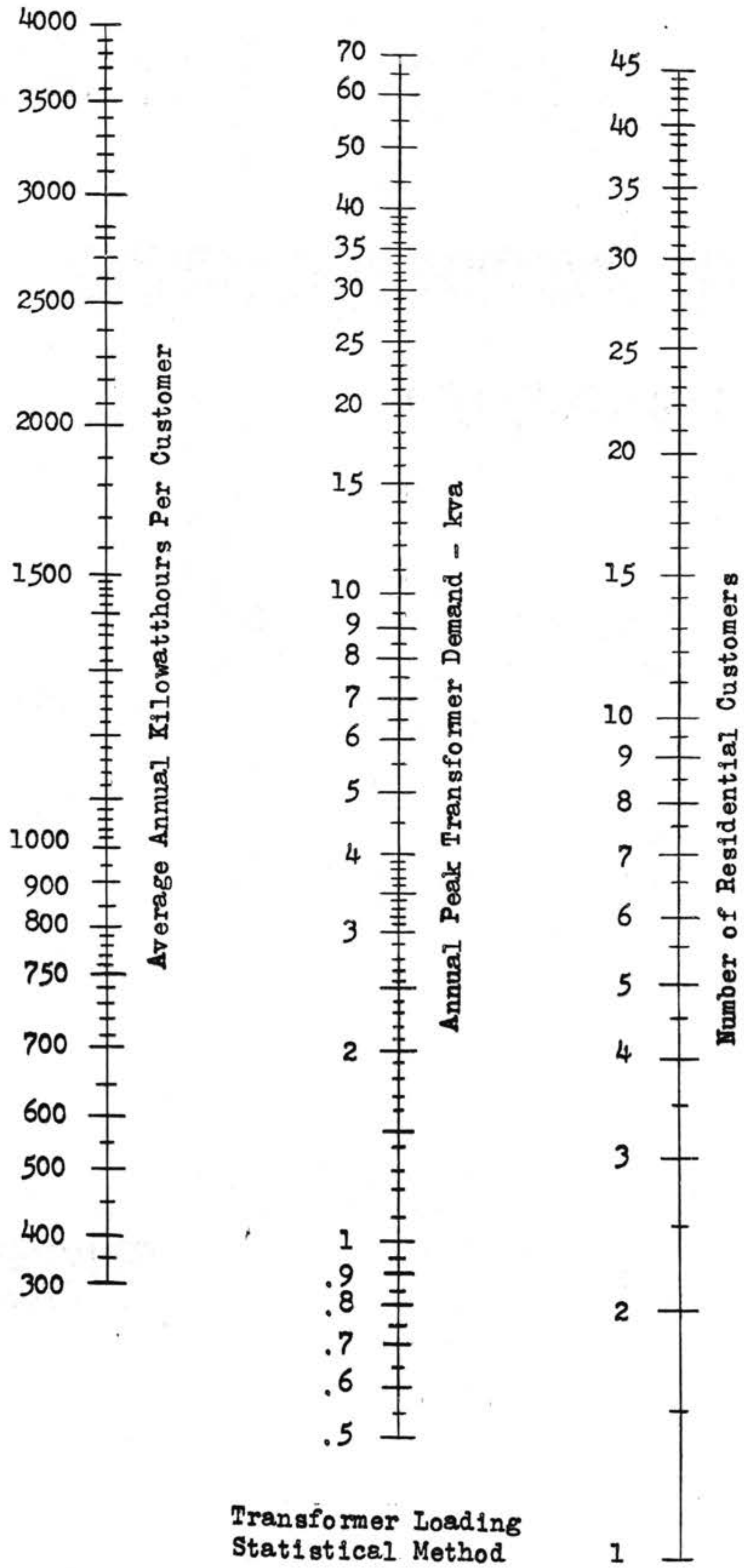
Data for Load Curves in Figure 6



Service - 3 wire #2 aluminum 75 ft long
$r + jx = .024 + j.0094$ ohms

Secondary - 3 wire #0 aluminum
$r + jx = .02545 + j.01491$ ohms/span

Kva of transformer	5	10	15	25	37½
Annual kwh per customer	535	1190	1700	2900	4220
Load density kva/1000 ft	8.33/11.67	16.65/23.30	25.00/35.00	41.70/58.40	62.50/87.50
Current in service	2.75	5.54	8.33	13.95	20.22
Current in span A-B	6.75	13.82	20.22	34.60	50.80
Current in span B-C	11.04	22.26	32.50	54.60	79.90
Voltage drop in service	0.07 + j0.03	0.13 + j0.52	0.20 + j0.08	0.34 + j0.13	0.49 + j0.19
Voltage drop in span A-B	0.17 + j0.10	0.35 + j0.21	0.51 + j0.30	0.88 + j0.51	1.28 + j0.76
Voltage drop in span B-C	0.29 + j0.17	0.57 + j0.33	0.82 + j0.48	1.39 + j0.81	2.04 + j1.19
Voltage drop in transformer	1.85 + j1.37	1.98 + j1.92	1.86 + j2.20	1.79 + j2.25	1.35 + j2.57
Total	2.38 + j1.67	3.03 + j2.98	3.39 + j3.06	4.40 + j3.70	5.25 + j4.71
Voltage drop - 100% load	2.9	4.27	4.56	5.74	7.07
Voltage drop - 140% load	4.06	5.99	6.38	8.04	9.91



Transformer Loading
Statistical Method

APPENDIX C

The following is a sample calculation of the voltage error caused by capacitors on the load terminals of a feeder voltage regulator. The voltage regulating relay is set to compensate for a voltage rise given by the equation

$$\text{Voltage Rise} = \frac{CKVAR}{RKVA} (X)$$

To obtain 120 volts at the feeder center, i.e., $E_2 = 120$ volts, then the voltage at the regulator terminals, E_1, must be 120 volts plus the voltage drop in the express feeder.

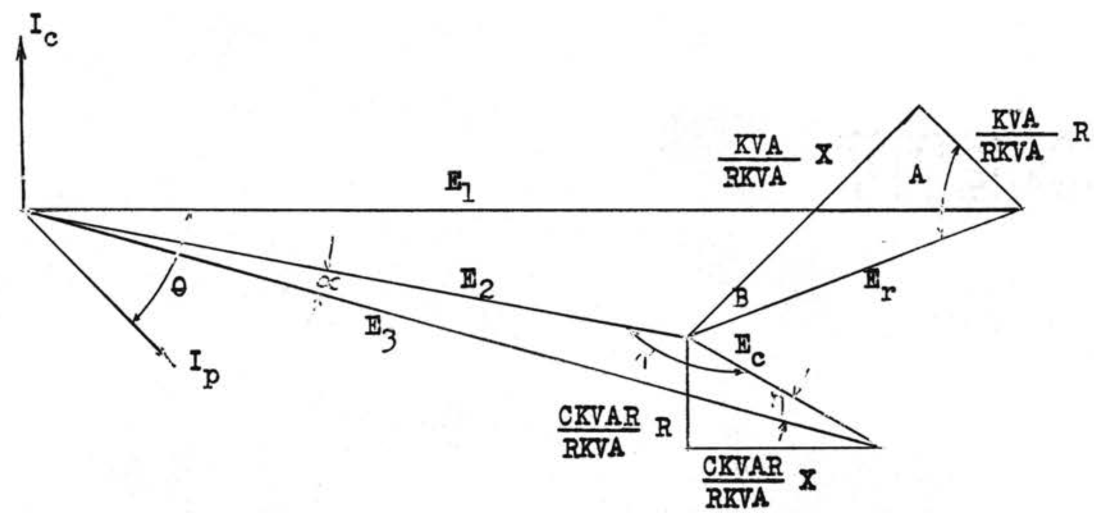
$$E_1 = E_2 + \frac{KVA \angle\theta}{RKVA} (R + jX)$$

With capacitors on the express feeder the regulator compensator circuit sees the capacitive current drawn by the capacitors and will react to it as if it were flowing through the entire length of the feeder. By superposition it can be seen that the voltage rise caused by this current flowing in the compensator circuit will be

$$\text{Voltage Rise} = \frac{CKVAR}{RKVA} (R + jX)$$

The actual voltage error will be given by the equation

$$\text{Error} = \text{Magnitude} \left[E_2 + \frac{CKVAR}{RKVA} (R + jX)\right] - \text{Magnitude} \left[\frac{CKVAR}{RKVA} (X)\right] - 120$$



Assume $\theta = -20^{o}$ for sample calculation

Power factor = 0.940 lagging

$R + jX = 4.61 + j9.36 = 10.434$

$\text{Tan } A = \frac{X}{R} = \frac{9.36}{4.61} = 2.03037 \quad A = 63.78$ degrees

$\phi = 63.78 - 20 = 43.78$ degrees

$\text{Sin } \phi = 0.69187$

$\frac{KVA}{RKVA}(E_r) = \frac{2000}{2160}(10.434) = 9.6612$

$\beta = \text{Arcsin } \frac{KVA}{RKVA} \ \frac{E_r}{E_2} \ \text{Sin } \phi$

$\beta = \text{Arcsin } \frac{9.6612}{120}(.69187) = \text{Arcsin } .055414$

$\beta = 3.17644$ degrees

$\tau = 180 - \beta - B$

$\frac{1}{2}(\eta + \alpha) = \frac{1}{2}(180 - \tau)$

$\frac{1}{2}(\eta + \alpha) = \frac{1}{2}(3.17644 + 26.2213) = 14.69885$

Using Law of Tangents

$$\frac{E_2 - E_c}{E_2 + E_c} = \frac{\text{Tan } \frac{1}{2}(\eta - \alpha)}{\text{Tan } \frac{1}{2}(\eta + \alpha)}$$

$$E_c = \frac{900}{2160}(10.434) = 4.34743$$

$$\frac{120 - 4.34743}{120 + 4.34743} = \frac{\text{Tan } \frac{1}{2}(\eta - \alpha)}{\text{Tan } 14.69885}$$

$$\text{Tan } \tfrac{1}{2}(\eta - \alpha) = (0.930076)(0.26233) = 0.24399$$

$$\tfrac{1}{2}(\eta - \alpha) = 13.71184 \text{ degrees}$$

$$= \tfrac{1}{2}(\eta + \alpha) + \tfrac{1}{2}(\eta - \alpha)$$

$$= 14.69885 + 13.71184 = 28.41069$$

Using Law of Sines

$$\frac{E_2}{\text{Sin}} = \frac{E_3}{\text{Sin}}$$

$$E_3 = \frac{.49087}{.47579}(120) = 123.803 \text{ volts}$$

$$E_1 = E_2 + \frac{\text{CKVAR}}{\text{RKVA}} X = 120 + 3.9 = 123.9 \text{ volts}$$

$$\text{Error} = E_1 - E_3 = 123.9 - 123.803 = .097 \text{ volts}$$

This would be the error for a 94% power factor load. The feeder center voltage would be 119.903 volts which would be one point on the curve in Figure 4.

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