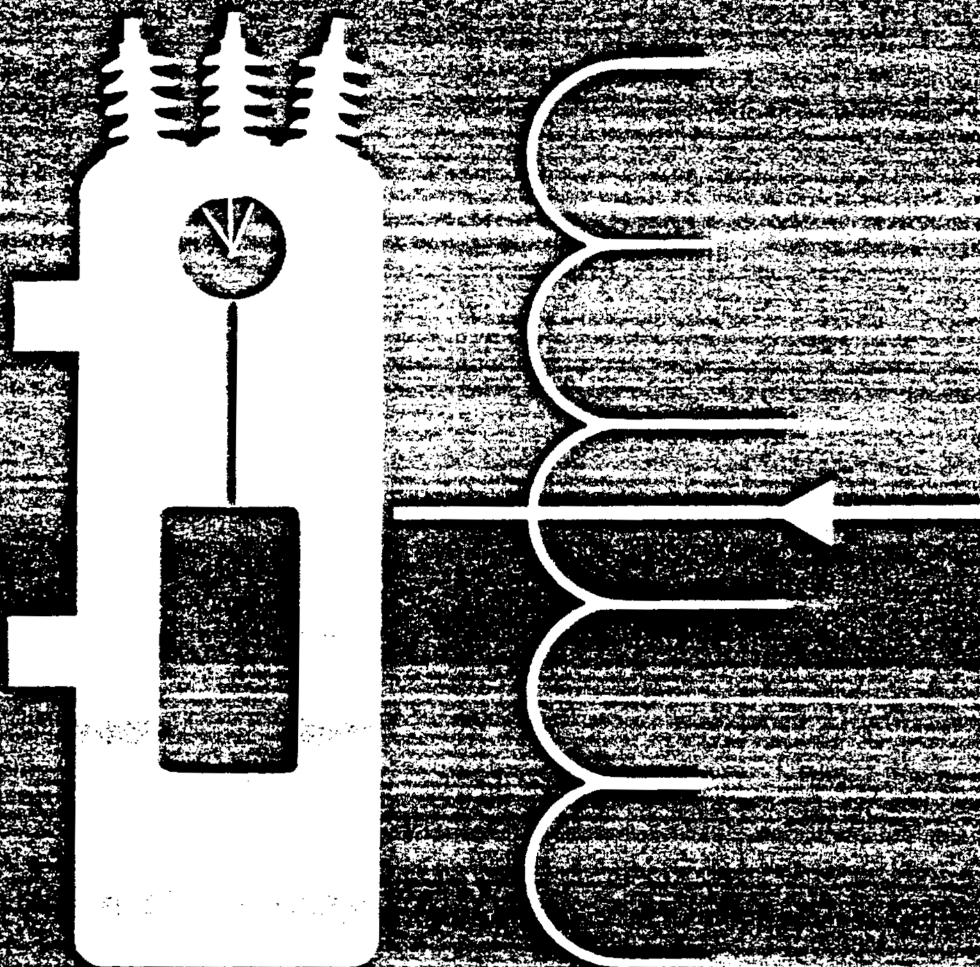
VOLTAGE REGULATOR APPLICATION

on rural distribution systems



REA

U.S. DEPARTMENT OF AGRICULTURE
RURAL ELECTRIFICATION ADMINISTRATION

FOREWORD

The level of voltage maintained at a consumer's service entrance is one of the most important indicators of the quality of electric service which is being provided. The consumer is entitled, at all times, to a level of service voltage which will make it possible for equipment receiving power from the system to operate effectively and efficiently.

The voltage levels recommended by REA are given in Bulletin 169-4, "Voltage Levels on Rural Distribution Systems." These levels are based on American National Standard c84.l-l970, "Voltage Ratings for Electric Power Systems and Equipment (60 Hertz)."

Both voltage regulators and shunt capacitors have a place in voltage control for a distribution system. Capacitors are more efficient in correcting chronically low voltage, especially where this can be realized as a side benefit to the capacitor's principal function of improving power factor. Voltage regulators provide a more effective correction of voltage swing caused by fluctuations in load or in the supply voltage.

You should study not only this Bulletin (169-27) but also Bulletin l69-l, "The Application of Shunt Capacitors to the Rural Electric System" in evaluating the proper application of these devices to best suit your needs.

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UNITED STATES DEPARTMENT OF AGRICULTURE
Rural Electrification Administration

January 1973
Supersedes March 1954

REA BULLETIN 169-27

SUBJECT: Voltage Regulator Application on Rural Distribution Systems

I. Introduction:

Demands on an electric distribution system today are such that voltage levels throughout the system must be held within certain prescribed limits. Consumers will no longer tolerate wide voltage variations at the point of service anymore than they will tolerate service interruptions. Consumers are demanding and are entitled to high quality electric service. The use of voltage regulators has long been recognized as a primary means of maintaining system voltage levels, but regulators are often not used to their full capability. It is the purpose of this bulletin to explore the application of voltage regulating devices so that the maximum benefits from sound voltage regulator application can be achieved.

II. Voltage Spreads and Voltage Drops:

In many states the limits of voltage spread permitted at the consumer's meter are fixed by the state regulatory commission. In states where borrowers are not subject to such controls REA recommends the limits established by the American National Standards Institute.

A. American National Standard Institute (ANSI) Voltage Limits

The revised American National Standard, C84.l-1970, "Voltage Ratings for Electric Power Systems and Equipment (60 Hertz)," approved January 1970, establishes the voltage limits shown in Table 1.

	MINIMUN			MAXIMUM
RANGE	Utilization Voltage		Service Voltage	Utilization & service voltage
	Non-lightning loads	Loads includ-ing lighting		
A	108	110	114	126
B	104	106	110	127

Table l. Voltage Ranges (120 Volt Base)

- Range A defines the limits within which service voltages should be held.
- Range B defines the limits that service voltages may vary from the limits of Range A for limited durations due to system design or operation.

B. REA Recommendations on Voltage Levels

REA Bulletin 169-4, "Voltage Levels on Rural Distribution Systems" recommends that rural electric distribution systems be designed and operated to meet the voltage level requirements of "Range A" in ANSI C84.1-1970 as described in Table 1. The optimum utilization of regulators as an integral part of the operation and design of the electric system is the basic approach to meet these requirements.

The effects of the adoption of the "Range A" voltage limits on a rural distribution system are shown in Tables 2 and 3 below. Table 2 shows the voltage spreads and levels for a rural distribution system using a suitable voltage regulator with line drop compensation to meet the above voltage standards. Table 3 shows the voltage drops and percent voltage drops permitted in each segment of a rural distribution system in meeting the above recommendation.

Location On System	Voltage Levels		Voltage Spread
	Minimum	Maximum	
Regulated Substation Bus	122	126	4
Primary Side of Distribution Transformer			
Close to Substation	122	126	4
At End of Line	118	122	4
Service Connection (Meter Socket)			
Close to Substation	118	126	8
At End of Line	114	122	8
Point of Utilization			
Close to Substation	114	126	12
At End of Line	110	122	12

Table 2. Voltage Levels and Voltage Spreads for Rural Distribution System Design (120 Volt Base)

Section of Rural Distribution System	Voltage Drop (Volts)	Voltage Drop (Percent)
Substation Bus to End of Primary Distribution Line	8	6.67
Distribution Transformer and Service Conductors to Metering Point	4	3.33
Consumer's Service Point to Utilization Point	4	3.33

Table 3. Vo1tage Drops for Rural Distribution System Design (120 Volt Base)

III. Voltage Regulators:

A. Types

There are two general types of voltage regulators, the induction regulator and the step-type regulator. The step-type regulator has by far the wider application in the electric distribution system. A description of the two types of regulators is given below to facilitate an understanding of the difference between the two. The definitions are quoted from American National Standard C57.15-1968, "Requirements, Terminology and Test Code for Step-Voltage and Induction-Voltage Regulators."

1. Induction - Voltage Regulator

"An induction-voltage regulator is a regulator having a primary winding in shunt and a secondary winding in series with a circuit for gradually adjusting the voltage or the phase relation, or both, of the circuit by changing the relative position of the exciting and series windings of the regulator."

Figure l shows a schematic diagram of an induction-type regulator with the primary or exciting winding connected in shunt and the secondary or regulating winding connected in series. It can be seen from the figure that the induction-type of voltage regulator is similar to an electric motor.

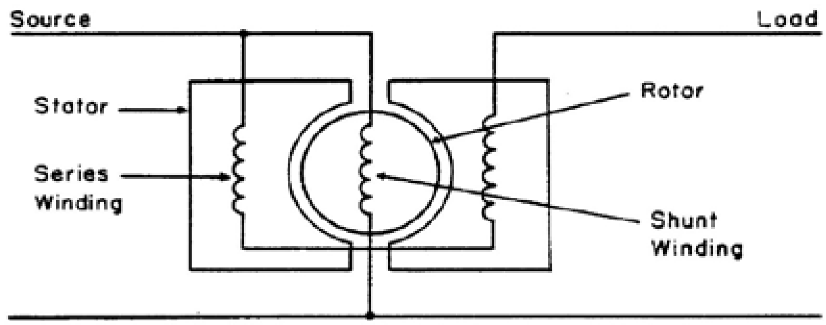


Figure I. Schematic Diagram of Induction Voltage Regulator

When a voltage is impressed on the primary (shunt) winding, the magnetic flux linking the secondary or series winding wil1 produce a voltage across the series winding. The magnitude of this voltage is dependent upon the amount of magnetic flux linking the series winding. By rotating the primary winding, the amount of flux linking the secondary' winding can be regulated; and hence, the voltage induced in the secondary winding is also regulated. Rotation in one direction will result in additive voltages while rotation in the opposite direction will result in subtractive voltages with respect to the primary voltage.

2. Step - Voltage Regulator

"A step-voltage regulator is a regulator having one or more windings excited from the system circuit or a separate source and one or more windings connected in series with the system circuit for adjusting the voltage, or the phase relation, or both, in steps, without interrupting the load."

A step-type voltage regulator is essentially an autotransformer consisting of a primary or exciting winding connected in parallel with the circuit and a secondary or series winding connected in series with the circuit. Taps of the series winding are connected to an automatic tap-changing mechanism. Voltage and load sensitive controls are used to operate a driving motor which in turn operates the tap-changing mechanism.

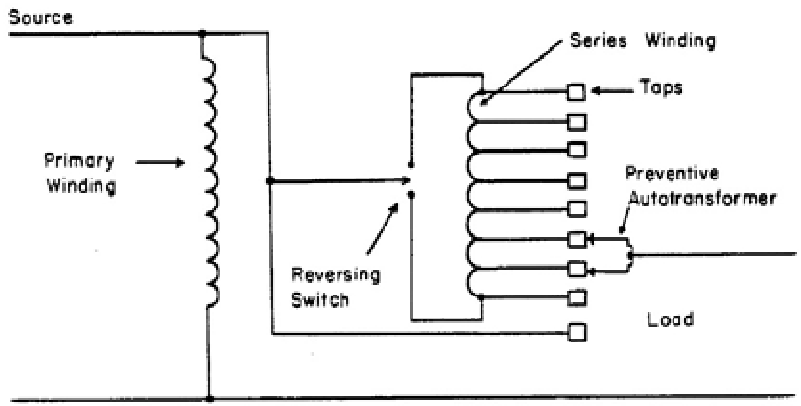


Figure 2. Schematic Diagram of Step-Voltage Regulator

Figure 2 is a schematic diagram of a step-type voltage regulator. Again, as with the induction regulator, when a voltage is impressed upon the primary, winding the magnetic flux linking the secondary or series winding will induce a voltage in the series winding. By use of a reversing switch the polarity of the induced voltage can be made to add to or subtract from the primary voltage. The amount of additive or subtractive voltage induced in the secondary winding is controlled by providing this winding with taps, thus regulating the amount of induced voltage. The purpose of the preventive autotransformer is twofold. First, through the use of dual contacts, the discontinuity associated with the tap-changing mechanism, as it changes from one tap to another tap of the series winding is avoided - since one of the dual contacts is always in contact with a tap of the series winding. Second, the impedance of the preventive autotransformer avoids shorting out turns of the secondary winding when the dual contacts are bridging adjacent taps of the series winding. Since the preventive autotransformer is center tapped, it also provides an output voltage halfway between the voltage of adjacent taps of the series winding.

Referring to Figure 2, it can easily be seen why this regulator is called a step-type. The output voltage is increased or decreased by equal steps as the tap position on the series winding is changed from one position to the next.

To this basic step-type regulator are added the necessary controls to sense and regulate the output voltage and to adjust the bandwidth, voltage level, time delay, and line drop compensation. Each of these regulator control devices is discussed in detail in a later section.

B. General Description

1. KVA Ratings

The rating in kVA of a regulator is the product of its rated load amperes and its rated range of regulation in kilovolts. The kVA rating of a 10 percent 7620 volt regulator capable of carrying a rated load current of 100 amperes would be:

$$kVA = 7.620 \times .10 \times 100 = 76.2\ kVA$$

In those cases where the range of regulation is different for the "raise" position than for the "lower" position, the larger percent regulation is used in determining the regulator kVA rating. Since most users are interested in current carrying capabilities of regulators, this leads to the odd regulator sizes of 19.1 kVA (25 amperes), 38.l kVA (50 amperes), and 114.3 kVA (150 amperes) generally found in 7620 volt regulators.

The ratings for regulators generally are based upon operation at 60 Hz with a range of regulation of 10 percent "raise" and 10 percent "lower" without exceeding the specified temperature rise at the given operating voltage.

a. Extended Range of Ratings

One of the inherent features of today's step-type regulator is the fact that regulator losses decrease as the regulator moves from the extreme tap positions (boost or buck) closer to the neutral point.

Recognizing this fact, and realizing that in the application of regulators, the range of regulation required need not always be a full 10 percent allows for an extended range of regulator operation.

In those instances where less than the full 10 percent regulation is satisfactory, the load carrying capabilities of the regulator can be extended. This is shown in the tabulation below for single-phase step regulators rated 19.9 kV and below.

Range of Voltage Regulation (Percent)	Amperes as Percent of Rated Current *
± 10	100
± 8.75	110
± 7.50	120
± 6.25	135
± 5.00	160

* Maximum Current 668 Amperes

For three-phase step-voltage regulators rated 13.8 kV and below, the extended range of regulation is as follows:

Range of Voltage Regulation (Percent)	Amperes as Percent of Rated Current**
+ 10	100
+ 8.75	108
+ 7.50	115
+ 6.25	120
+ 5.00	130

** Maximum Current 600 Amperes

It can be seen from the above tabulations that if regulators are applied to circuits requiring only 5 percent regulation their current carrying capabilities can be extended to provide additional capacity - up to l60 percent in the case of single-phase regulator.

2. Terminal Designations for Step-Voltage Regulators

The terminal designations of step-type voltage regulators are as follows: The terminal connected to the load is designated L, the terminal connected to the source is designated S, and the common terminal is designated SL. For three-phase regulators these identifications are Sl, S2, S3, Ll, L2, L3 and SoLo. This is illustrated in Figure 3.

3. Regulator Standards

Regulators for use on REA borrowers' systems must meet the requirements set forth in REA Specification S-2, "Specification for Substation Regulators."

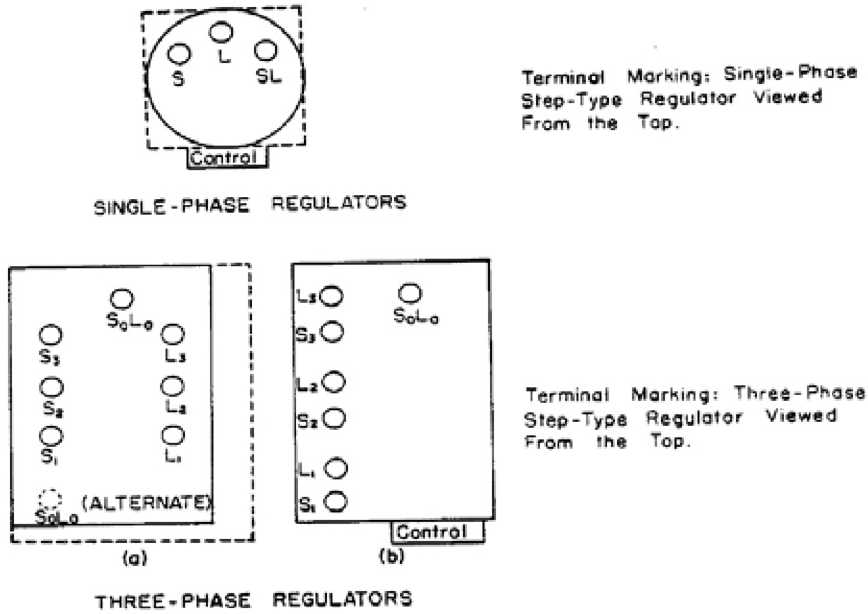


Figure 3. Terminal Marking for Step-Voltage Regulators

These specifications apply to step-type single- or three-phase, substation or pole-mounted, outdoor, oil-immersed, self-cooled regulators.

In addition to the REA specification, all regulators must comply with the American National Standard C57.l5-1968, "Requirements, Terminology, and Test Code for Step-Voltage and Induction-Voltage Regulators."

a. <u>Short-Circuited Strength</u>

Regulators used on REA borrowers' systems must be capable of withstanding rms symmetrical short-circuit currents of 25 times the regulator full-load current for two seconds and 40 times the regulator full-load current for 0.8 seconds without injury.

Regulators are connected in series in a circuit and as such are subjected to very high short-circuit requirements. Care must be exercised in regulator application to insure that the short-circuited capabilities of the regulator are not exceeded. The following procedure should be observed in applying regulators on a rural distribution system:

(1) Determine the short-circuit duty at the proposed location in terms of the available fault current and the clearing time of the over-current protective device.

(2) If the short-circuit duty on the regulator exceeds its capabilities, then one of the following steps should be taken:

- Install larger regulators to obtain greater short-circuits withstand capabilities.

- Install the regulator at a distance far enough from the substation to limit the duty at the regulator to safe values.

- Install current limiting reactors at the substation to limit the available fault current.

C. Regulator Controls

1. General

Regulators are equipped with a number of devices and controls which allow the operator to use the regulator effectively. These include means for setting or adjusting the:

- Voltage level
- Bandwidth
- Time delay
- Line drop compensation
- Range of' regulation

Since a change in the setting of any one of these devices will directly affect the operation of one or more of the other devices, they are all treated as a unit comprising what is known as the regulator control system. In earlier regulators, the components of this control system were of the electro-mechanical type, but regulators made since about 1963 are equipped with static-type devices featuring solid state components. The setting of the individual devices in the newer control systems is based upon the same principles. They are, in general, easier to set than the older mechanical type.

Adjustments of the various devices used in the control system are almost all made at the control panel. The control pane1 can be mounted directly on the regulator or remote from the regulator. Remote mounting is used to provide a more convenient panel location when regulators are installed on poles or platforms.

The following is a brief description of the control devices and the settings recommended by REA. These are discussed in more detail in Sections V C 1 through V C 5 of this bulletin.

a. Voltage Level

The voltage level adjustment is made at the control panel, and usually can be set at any value between 105 and 135 volts in 1 volt increments. The voltage level control for regulators on REA borrowers' systems should be set to yield 122 volts (on a 120 volt base) at the output terminals as indicated in Table 2.

b. Bandwidth

The bandwidth is the area above and below the voltage level setting (122 volts) within which the voltage may fluctuate. The bandwidth on most regulators is adjustable from plus or minus 3/4 volt to plus or minus 3 volts. In general, the narrower the bandwidth, the more effective the regulator will be in maintaining a relatively constant voltage. REA recommends the bandwidth be either plus or minus l volt or plus or minus 3/4 volt.

In never regulators, the bandwidth is adjusted by means of a knob on the control panel. In older models, the stationary "raise" and "lower" contacts of the voltage regulating relay are adjusted to just close when the test voltage applied to the relay is 1 vo1t below and 1 volt above, respectively', the voltage level setting. This adjustment also requires an indicating voltmeter of suitable design and properly calibrated across the test terminals to read the applied voltage.

c. Time Delay

The time-delay device in the regulator control system serves the function of interjecting a pre-determined "waiting period" into the control system operation. This delay prevents the regulator from responding to momentary excursions outside the bandwidth - caused by loads being added or removed from the line. It is not possible for a regulator to respond to these short-time variations nor is it desirable for it to try as this would result in an inordinate number of regulator operations and hence shortened contact life.

Most regulators have provisions in the control panel for adjusting the time-delay setting. REA recommends substation regulators be adjusted for 30 seconds delay with associated line regulators adjusted for a somewhat longer period than the substation regulator. This longer delay on the line regulator setting allows the station regulator to respond to changes in supply voltage before the line regulator and thus eliminate unnecessary back-and-forth operations.

d. Range of Regulation

The range of regulation is changed by adjustment of the limit switches which stop the travel of the tap-changer in either direction. These limit switches are located in the position indicator, and it is a simple matter to adjust them. The range of regulation is the only adjustment to the regulator control system that is not made in the control panel itself - being made at the position indicator mounted on the regulator.

In addition to its indicating hand (which shows the regulator tap position at time of reading) the position indicator has two drag hands which show the maximum regulation - both "raise" and "lower" - the regulator has been called on to deliver since the last time the drag hands were reset. Periodic observation and resetting of the hands will provide vital information about the operation of the regulator.

e. Line Drop Compensator

Of all the devices in the regulator control system, none is more important and at the same time less understood than the line drop compensator (LDC). Because of this lack of understanding the LDC often is not used at all, or when used, is improperly applied, thus wasting one of the most important features of' the regulator control system.

When the LDC is not used, the regulator reads the voltage at its own output terminals and compares this with its reference voltage level and bandwidth settings. If the output voltage is high or low (outside the band.-width) the regulator automatically responds to bring the output voltage in line with the voltage level setting. This is the normal operation of a regulator without LDC; and thus, any transformer close to the regulator will have a fairly constant voltage level. It can easily be seen that although the output voltage of' the regulator is held constant, the voltage drop along the line - and hence the input voltage to transformers along the line - will still be a function of load current.

The regulator, therefore, can hold reasonably constant voltage at only one point along the line and, without LDC, that point is at the regulator's own location. This is not likely to be the best point in terms of providing good voltage all along the line. In an ideal situation every consumer would be supplied constantly with 122 volts at the primary side of' the distribution transformer. With a moderate drop in the transformer, service and house wiring the voltage at the point of utilization always would be between 115 and 120 volts. This is an ideal situation and cannot be attained, but the objective should be to supply every consumer with a voltage as close as possible to 122 volts at all times of the day and night. To do this the point on the line at which voltage is held constant should be not at the regulator, but at a point nearer the "center of population" of the consumers served by the regulator.

The line drop compensator allows the regulator to hold a flat voltage at some point out on the line. This point is generally thought of as a "load center" for which the regulator will hold a constant voltage. Knowing the peak load current expected on the line and the size and length of line to this arbitrary load center, the voltage drop at the load center due to resistive and reactive components can be calculated. Since line current passing through the regulator can be easily monitored, it is now a matter of introducing resistive and reactive elements into the LDC device to simulate the resistive and reactive elements of the line out to the "load center." This is exactly what a LDC does.

The LDC consists of adjustable resistive and reactive elements along with a current transformer to monitor line current. The current from the secondary of the current transformer creates a drop in the resistive and reactive elements in the LDC which in turn lowers or raises the voltage in the voltage sensing circuit. The regulator then responds to this condition and in effect is reading the voltage at the distant "load center" point and adjusting its output voltage accordingly.

The adjustment the regulator makes in responding to load current is an overriding adjustment; that is, the voltage level setting (122 volts discussed in section a. above) is overridden at the regulator and appears not at the regulator output but at the load center. Thus, the l22 volts set at the regulator become 122 volts plus the line drop compensation - or 126 volts at peak load for a fully loaded line.

The actual LDC settlings are made at the control panel by means of R and X adjustment dials. These dials are set to correspond to the amount or resistive and reactive voltage drop expected at peak load at the arbitrary "load center." Some long, lightly loaded lines may have a leading current which produces a voltage rise instead of a voltage drop along the line. In such cases the LDC can, by sensing the voltage rise at the control point, respond to correct this condition by reducing the voltage level of the regulator output.

The setting of the R and X dials of the LDC causes the regulator to respond as follows:

- At estimated peak load - maximum line current - it causes the regulator to respond with its maximum adjustment over the voltage level setting - 4 volts if set according to REA recommendations. {NOTE: If the estimated peak load is exceeded, the amount of line drop compensation will be greater than 4 volts.)

- At light load - minimum line current - it causes the regulator to respond with minimum or very little adjustment to the voltage level setting.

- At intermediate loads - it causes the regulator to respond with an adjustment somewhere between the voltage level setting (122 volts) and the maximum adjustment (126 volts). This adjustment is just enough to offset the voltage drop out to the "load center."

2. Control System Accuracy

The individual components utilized in the regulator control system are accurate devices, and as such, they enable the regulator to obtain a level of efficiency sufficient to meet Class I accuracy requirements. Class I accuracy means that the sum of errors in the control circuit taken individually' cannot total more than plus or minus l percent. A plus error would be one causing the regulator output to be higher than the reference value; while a minus error would be one causing the regulator output to be lower than the reference value.

Because of this accuracy and more importantly, because of its function in maintaining system voltage levels, the voltmeters and other instruments used in conjunction with regulators should be as accurate as the regulator. To utilize measuring equipment any less efficient than this deprives the system of the regulator's full capabilities. (See REA Bulletin 161-7, "Guide for Making Voltage Measurements on Rural Distribution Systems.")

D. Single-Phase Versus Three-Phase

The most fundamental application of voltage regulators to a distribution system is in the load side of the distribution substation, where they are used to control substation voltage levels from periods of light to peak loads. Generally, the initial substation design includes regulators. Normally, the low voltage substation bus will be regulated rather than the individual feeders leaving the substation. The extra cost of individual feeder regulation can only be justified when there are extreme variations between individual distribution feeder peak load times.

Substation regulators should be capable of providing a range of regulation of plus or minus 10 percent. In addition, the substation regulator must also be capable of maintaining a bandwidth not greater than plus and minus l volt.

In selecting equipment for controlling voltage in the distribution substation there are three choices: single-phase regulators, three-phase regulators, and load tap changing (LTC) equipment built into the power transformer. Several factors influence the selection.

For the sizes of substation used most frequently by rural electric systems, single-phase regulators are usually less expensive than either of the other methods. They also are more able to maintain balanced phase voltages under conditions of unbalanced loading. Single-phase regulators are also more adaptable to line use because of the relative ease of pole mounting.

In large distribution substations the choice of three-phase regulators may be based on costs or on the non-availability of single-phase regulators of the required size. Three-phase regulators require somewhat less space than three single-phase regulators although this is not generally a major factor in selection.

Load tap changing power transformers are being used more and more in distribution substations. They consist essentially of a three-phase regulator built into a three-phase power transformer. The relative cost of this combination compared to a separate transformer and single-phase regulators varies depending on the size of the substation. Aside from the base cost of the equipment, the LTC method generally will result in a saving in space, buswork and supporting structures.

Because their controls sense only one phase of a three-phase circuit and since some unbalance may be expected among the phases, the voltage correction of three-phase regulators and LTC transformers will be less precise than that of single-phase regulators.

IV. The Regulator and System Voltage Levels

A. System Voltage Profiles

When a distribution line is initially energized, the maximum drop along the line is generally less than the full 8 volt drop permitted primary lines. This allows for future load growth to develop in a normal manner. When such a line is supplied with a constant (regulated) bus voltage at its source, its voltage profile resembles that of curve A of Figure 4 below. With increasing time and inevitable load growth, the voltage drop along this line will increase - causing line voltages below the allowable minimum as shown by curve B. Continued load growth beyond this point will result in excessive line voltage drop, greater than 8 volts on the primary, for some sections of the line. This is shown by curve C. Curve B demonstrates why voltage regulators that regulate system voltage without respect to system loading are not in themselves sufficient for maintaining proper voltage levels.

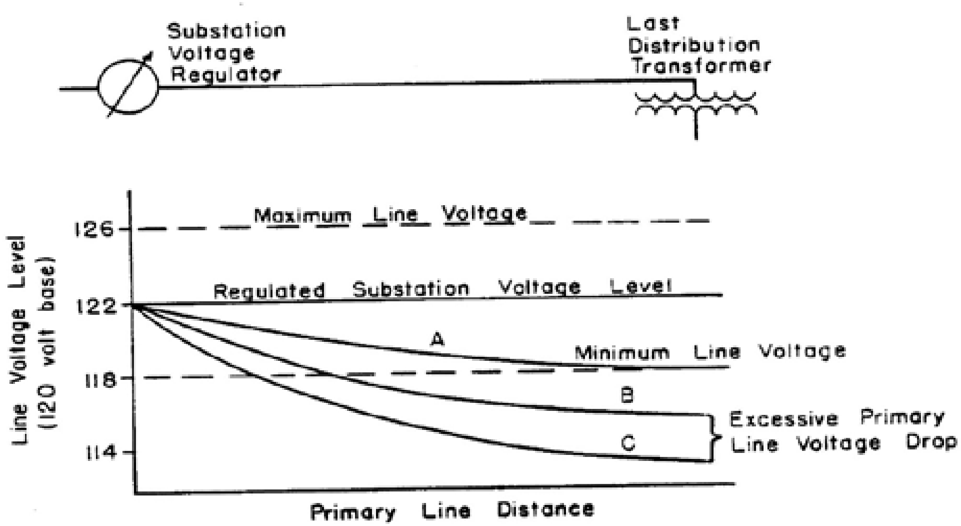


Figure 4. Line Voltage Profile

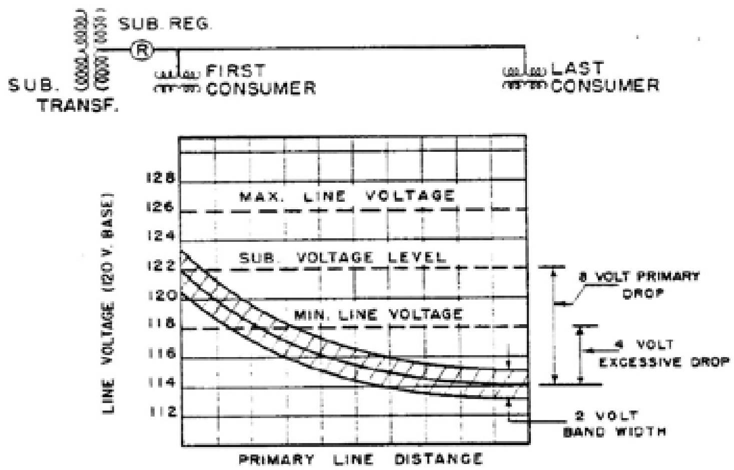
Although the voltage drop as represented by curve B is not greater than the full 8 volts drop permitted primary lines, the voltage level for some segments of the line may still be below the minimum recommended line voltage. Distribution transformers served from these portions of line will have insufficient input voltage to their primary terminals and the consumers probably will have low voltage at their point of utilization. This results from the fact that at peak loading times the full 8 volt primary drop is from a fixed substation bus - regulated independently of loading.

To be effective, system voltage regulators must do more than provide a constant source voltage. They must regulate the source voltage such that it will provide for normal distri - bution line drop at peak loading times as well as light loading times - without either being too high or too low.

1. <u>Effects of Line Drop Compensator</u>

   The line drop compensator (LDC) is the nerve center of the voltage regulator control system, and as such, it enables the regulator to respond in a manner directly proportional to changes in load. When this capability is coupled with the regulator's ability to maintain a constant output (voltage level), we then have a device capable of maintaining proper system voltage levels throughout all types of loading patterns.

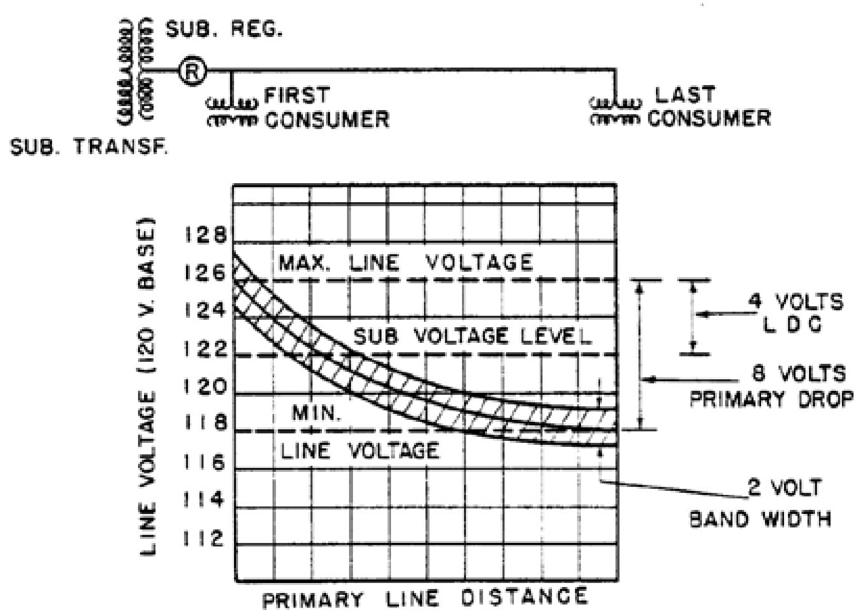
Figure 5 below shows the voltage profile of a regulated line at peak loading times without line drop compensation. The regulated substation output voltage has been held to a constant 122 volts with a bandwidth of plus or minus l volt as indicated. The maximum and minimum primary line voltages recommended by REA to meet the ANSI Voltage Standard have also been indicated. It can be seen that restricting the primary voltage drop to 8 volts maximum at peak load, while holding the substation output voltage constant, does not prevent segments of the line from receiving less than the minimum recommended line voltage (118 volts).



LINE VOLTAGE DROP AT PEAK LOAD USING SUBSTATION REGULATOR WITHOUT LINE DROP COMPENSATION

FIG. 5

Figure 6 shows the same line except in this instance the load sensing capabilities of the line drop compensator are being utilized to monitor the line loading and to provide the necessary voltage adjustment to the regulator output. This adjustment is in proportion to the amount of line voltage drop caused by the loading.



LINE VOLTAGE DROP AT PEAK LOAD USING SUBSTATION REGULATOR WITH LINE DROP COMPENSATION

FIG. 6

In this instance (peak loading conditions) the adjustment is in the form of an increase in regulator output voltage at the substation bus. In effect, the regulator has increased its normal voltage level output from 122 volts to 126 volts - or in other words 4 volts line drop compensation has been added to the regulator output. This compensation, or increase in substation voltage level, allows the primary line to experience a full 8 volt drop from a 126 volt base, without going below the minimum recommended line voltage level - even at the input to the last distribution transformer on the line.

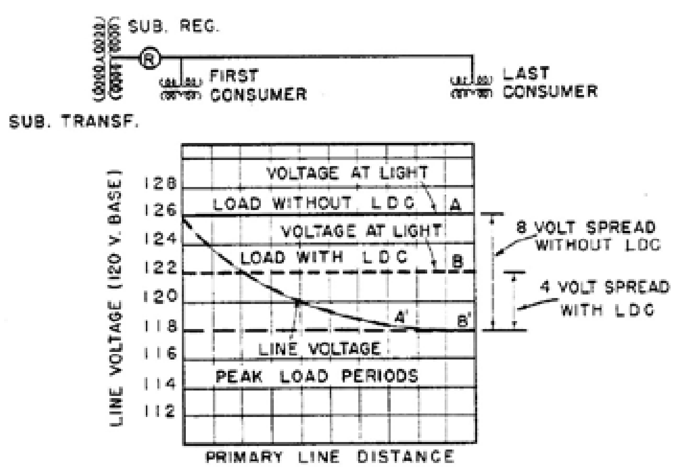
The load sensing capabilities of the line drop compensator coupled with the regulator's ability to maintain a constant output voltage allows the distribution system to operate within the voltage limits of the ANSI Standard as shown in Table I.

It should be noted that operation within the limits of the ANSI Voltage Standard does not in itself imply that all consumers are receiving the best possible service. Wide swings of voltage over the course of a day can be annoying to the consumer, even though the ANSI limits are not exceeded.

B. The Regulator and System Voltage Swings

One of the inherent advantages gained by using the line drop compensator to adjust regulator output voltage levels in proportion to load is the minimizing of voltage swings throughout different parts of the distribution system.

This can be seen in curve A of Figure 7 below. The substation voltage regulator has been adjusted to provide a constant output voltage of 126 volts without line drop compensation. At peak loading times (curve A') this 126 volt setting will allow for an 8 volt primary drop without going below the minimum recommended line voltage of 118 volts at the input to any transformer on the line. At light loading times, there will be little line voltage drop, and the input voltage to the last transformer will be close to the 126 volt substation setting. Thus, from peak loading to light loading, consumers served from the far end of the line can experience up to an 8 volt change (or spread) in their voltage.



VOLTAGE SPREADS AT INPUT TO LAST TRANSFORMER WITH LINE DROP COMPENSATION AND WITHOUT LINE DROP COMP.

FIG. 7

Consumers served from segments of the line closest to the substation will have nearly a constant voltage level - the 126 volt substation setting. Thus, without line drop compensation it is still possible to supply adequate voltage levels throughout the distribution system, but with annoying voltage swings. Under this method of operation, some consumers are supplied near constant voltage while others experience maximum spreads in their service voltage.

These spreads are automatically held to reasonable limits and at the same time are more evenly distributed among consumers when line drop compensation is properly applied.

This is shown in the B curves of Figure 7. During lightly loaded periods, very little - if any, line drop compensation is added to the normal regulator output of 122 volts. It is not necessary to increase substation output levels during this period because line drop is at a minimum (curve B). At peak loading periods, the line drop compensator senses a voltage below 122 at the system load center and introduces an additive voltage correction to the normal 122 volt level setting of the regulator. This correction is directly proportional to load - being 4 volts (from 122 to 126) at peak load (curve B'). Thus, it can be seen that not only does the line drop compensator maintain adequate voltage levels - within the recommended ANSI voltage limits - it accomplishes this while restricting the deviation from the ideal voltage of 122 volts to a minimum.

In the first case (without LDC-curve A} the maximum deviation from the ideal substation voltage level setting of 122 volts would be 4 volts above and 4 volts below, or an·8 volt spread from peak to light load. All of this spread is experienced by consumers at the far end of the line. When LDC is properly employed, this deviation still remains 4 volts except the 4 volts above is experienced at the substation end and the 4 volts below is experienced at the far end of the line. Thus, what was a maximum spread of 8 volts at one end of the line has been redistributed to a 4 volt spread at each end of the line.

The ability of the LDC to monitor system loading and respond in a manner to offset any line drop caused by this loading inherently controls voltage swings while maintaining overall system voltage levels within the ANSI Standards.

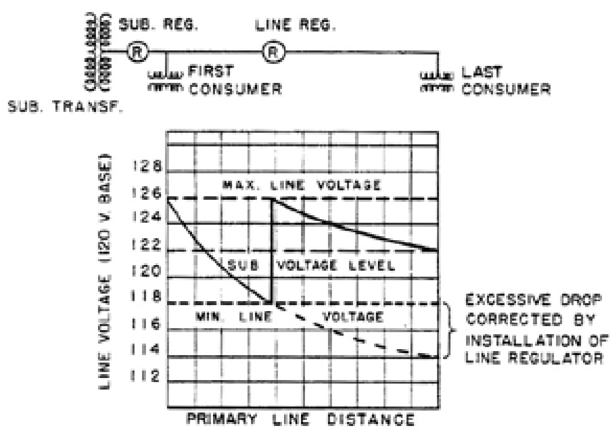
From Figure 7 it can be seen that at peak load the voltage profile along the line is the same regardless of whether LDC is used. At all other times - certainly the greater portion of the day - the use of LDC holds line voltages closer to the recommended level of 122 volts.

C. <u>The Role of the Line Regulator</u>

The concepts of maintaining and controlling voltage levels and voltage swings are not limited to substation application. They apply equally well to regulators installed out on the distri- bution lines.

It has been shown previously how a properly applied substation regulator utilizing line drop compensation can maintain system voltage levels within the ANSI Standard, while at the same time keeping voltage swings to a minimum. What happens when the 8 volt primary drop occurs before the end of a line and the voltage 1evel at the end of the line is no longer within the limits of the Standard? Such a situation is shown in Figure 8.

Because of load growth and line extensions, the reach of the substation regulator may no longer be adequate to maintain proper voltage levels over the entire length of line. Such a situation is represented by the dotted line below the minimum line voltage level in Figure 8. Consumers served from this section of line will in all probability experience low voltage conditions during peak loading periods. If an additional regulator were to be added to this line, at a point on the voltage profile where the 8 volt drop occurs, the below-normal line voltage from this point to the end of the line could be corrected. The effect of the installation of such a regulator is shown in Figure 8.



LINE VOLTAGE PROFILE AT PEAK LOAD USING BOTH SUBSTATION AND LINE REGULATORS

FIG. 8

The addition of a line regulator at this point provides the same voltage control for the end of the line as the substation regulator originally provided for the entire line. The line regulator, like the substation regulator, will maintain an output of 122 volts at light load and will increase this output to 126 volts, through its LDC, at peak load. Thus, the excessive line drop at the far end of the line can be corrected by the proper installation of a line regulator. The full 8 volt primary line drop from the substation is recovered at the location of the line regulator. This means theoretically that at peak loading a full 8 volt primary drop can take place from the substation to the line regulator and another 8 volt drop from the line regulator to the end of the line. In practice though, these drops are limited to somewhat less than this to provide for future load growth.

The utilization of a line regulator in effect extends the length of line for which proper system voltage levels can be maintained. It also defers replacement or heavy-up of feeders that are limited by voltage drop. The exact location of a line regulator is an important consideration from the standpoint of future load growth, relationship to critical loads and branch circuits, as well as accessibility. These aspects will be discussed later.

V. Application

The relationship between system voltage levels, voltage swings, and the role regulators play in maintaining and minimizing these factors has been discussed. The questions now are: When to install a line regulator? Where? And with what settings?

A. When is a Line Regulator Required?

The obvious answer to, "When is a line regulator required?" would be: when the system voltage is low or in other words, outside of the ANSI Standard - as outlined in Section I. To determine system voltage levels one should begin with an analysis of the data gathered in a system monitoring program. (For a detailed discussion of system monitoring see REA Bulletins 161-7, 161-8, and 161-9.) Suspected problem areas or feeders should then be given detailed voltage profile analyses, taking into account the effects of projected load growth. From these analyses regulator requirements are determined.

When the voltage profile indicates that the primary line voltage is approaching or has dropped below the recommended limit, the time to take corrective action is at hand. The effects of future load growth on the voltage profile should be evaluated, and a regulator location selected that will provide for both present and future conditions.

In making the voltage profile study, it is most important to use high accuracy voltmeters - 1 percent accuracy or better (see Bulletin 161-7). To use instruments with a degree of accuracy less than that of the regulator, (1 percent), can lead to incorrect decisions on existing voltage conditions - resulting in less than effective regulator application.

B. Where to Install the Regulator?

A distance from the regulated substation that provides for 75 to 80 percent of the allowable primary voltage drop should be considered for regulator location.

1. Location Considerations

Equally important along with the voltage profile location of a regulator is its physical location on the system. The actual location on the system must be evaluated in terms of its relative position with respect to the following:

- Critical loads - voltage sensitive or critical loads should receive maximum benefit from regulator location. Can the regulator be placed so as to minimize voltage variations at these loads? Is the load such that loss of regulation would have adverse effects on a consumer's critical manufacturing processes?

- Long taps - should the regulator be placed before or after long branch lines? How is the load growth on these branches with respect to the entire line?

- Sectionalizing - what effect will sectionalizing devices have on regulator location? Is the location subject to a high degree of recloser or sectionalizing device operations?

- Accessibility - the regulator location selected must provide for ease of accessibility in order to adjust the regulator control settings as well as provide normal maintenance.

C. Regulator Control Settings

Once the need for a regulator has been established, the site selected - in terms of physical and electrical location, the next thing to determine is the regulator's control settings. Settings will have to be provided for:

- Voltage level
- Bandwidth
- Time delay
- Range of regulation (size)
- Line drop compensation

Normally, the voltage level and bandwidth will be the same for all regulators installed on the system. Once determined, these settings become more of a function of system operation rather than individual application - as is the case with the time delay, range of regulation, and line drop compensator settings which vary with each individual application.

1. Voltage Level Setting

   The voltage level setting should be as close to the ideal system voltage as possible. It is the voltage with which all other voltages on the system are compared. In reality, the voltage level is determined by the limits set for voltage delivered to the consumer's meter – 114 to 126 volts as set forth in the ANSI Standards. Allowing for distribution transformer and service connection drops, the corresponding limits of 118 to 126 volts are established for the primary line.

   Selecting the mid-point of this range, 122 volts, provides every consumer essentially the same voltage service at light loads. There is minimum line current at this time, and hence, little line voltage reduction. A voltage level setting of 122 volts is recommended for overall system operation.

   The value to be set at the voltage level adjustment knob in the control panel is 122 volts. This setting should be verified with an accurate (l percent or better) voltmeter which has been recently calibrated. The voltage level should be adjusted to give a reading of 122 volts on the voltmeter. (NOTE: If the ratio of the potential transformer used in the regulator is other than on a l20 volt base, a different voltage level setting may be required. See Section III, C, l, a.)

2. Bandwidth Setting

   The bandwidth represents the variation above and below the voltage level setting at which point the regulator will respond by either raising or lowering its output voltage - thus maintaining the 122 volt system left. The bandwidth setting is the one control setting not affected by other control settings, but it will have an influence on the values selected for the other control settings.

The narrower the bandwidth, the smaller is the deviation from the preferred voltage level the regulator will permit without a tap change to correct the over- or under-voltage. A narrow bandwidth, therefore, improves the quality of the voltage regulation. On the other hand, setting too narrow a bandwidth may cause an excessive number of tap changes.

REA recommends a bandwidth setting of 2 volts, l volt above and 1 volt below the voltage level setting. There is rarely any need for a bandwidth setting other than this for either substation or line regulators.

3. Time Delay

The time delay relay, set in the control panel, provides a predetermined response time for the regulator. Unless the output voltage of the regulator is outside of the bandwidth for a time in excess of this response time, the regulator will not make a tap change. In essence then, the time delay relay provides a predetermined "waiting period" for the regulator before it will respond to voltage variations. If the voltage stays outside the bandwidth for longer than the time delay setting, the tap changer will operate to correct it. If, on the other hand, the voltage returns to a value inside the bandwidth before the end of the response time, the tap changer will not operate, and hence no voltage correction will be initiated.

The time delay relays used on today's regulators are of the integrating type. That is, the timer sums up the time the voltage is outside of the band and subtracts the time it is inside the band. When the net time outside the band exceeds the response time, the regulator will make a tap change.

a. Substation Regulators

A time delay of 30 to 40 seconds, depending upon the characteristics of the loading area, will provide a satisfactory level of operations for most rural substations. If excessive regulator operations are encountered with a 30 to 40 second setting a longer response time up to a maximum of 60 seconds should be considered.

b. Line Regulators

Response times for line regulators should always be longer than those for substation regulators. This allows the substation regulator time to correct source voltage variations before line regulators operate. When more than one line regulator is used, (which we do not normally advocate except on a temporary basis) time delay settings should increase as you move away from the source. This allows the regulators to respond in an orderly progression (substation to end of line) thereby eliminating excessive operations by regulators farthest out on the line.

c. Controlling Regulator Operations

The number of tap changing operations which a regulator performs has a bearing on both the life of the regulator and on the interval between scheduled inspection and maintenance. The number of operations which a regulator will make during a given period is determined by the characteristics of the supply voltage and. of the load, and by the bandwidth and time delay settings of the regulator. A regulator operated under typical conditions will probably make - on the average - between 100 and 200 tap changes per day. If the daily average number of operations falls much below 100 the regulator is possibly not being used as effectively as it could be. If the average is much above 200 more frequent maintenance will be required.

Both an increase in time delay or an increase in bandwidth will tend to reduce the number of regulator operations. Of the two methods, an increase in time delay will reduce operations with the least sacrifice in voltage control. This is shown in the series of sketches (Figure 9) where the change in regulator output voltage can be seen for various settings of time delay and bandwidth.

As can be seen with cases II and III the number of regulator operations decreases with increasing time delay. In Case IV the output voltage is obtained by the same time delay as in Case II, but the bandwidth has been increased 50 percent. A comparison of Cases III and IV shows the same number of regulator opera- tions, but because of the greater bandwidth in Case IV, there is a significant sacrifice in voltage quality.

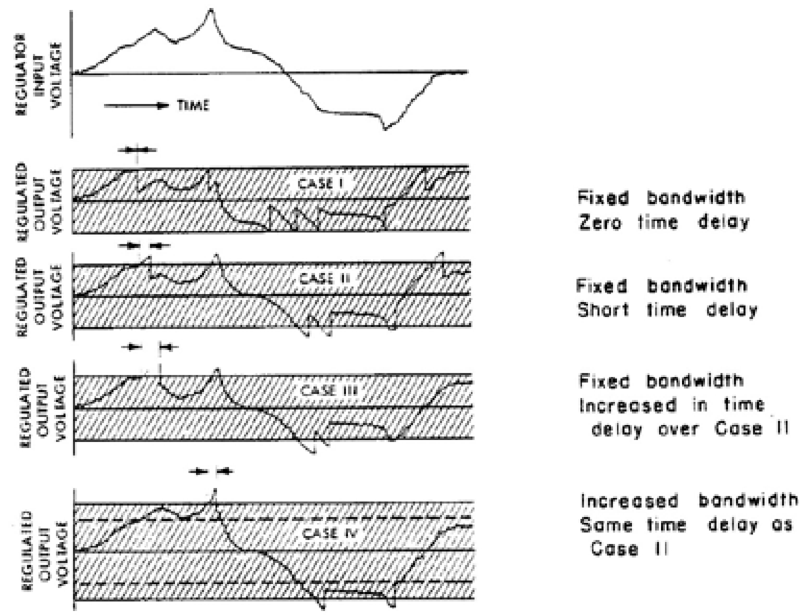


Figure 9. Regulated output as affected by bandwidth and time delay adjustments.

Thus, the proper approach to controlling regulator operations is by use of the time delay relay and not by increasing the regulator's bandwidth.

4. <u>Range of Regulation</u>

   a. <u>Setting the Range</u>

   The range of regulation is the only component of the regulator control system not adjusted in the control cabinet. Adjustment of the range of regulation is made at the regulator position indicator which is generally mounted on the regulator tank.

   The range of regulation is changed by adjustment of the limit switches which stop the travel of the tap changer in either direction. These limit switches are located in the position indicator of the regulator, and their adjustments to provide the desired range of regulation is a simple matter - differing somewhat among different brands of regulators.

b. Selecting the Regulator Size

As previously outlined in Section III B, the load carrying capability of a regulator is directly related to its range of regulation. At nameplate rating, the regulator will deliver rated current while either boosting or bucking the incoming voltage 10 percent. Reducing this regulation to 5 percent, will allow the regulator to carry more than rated current with no overheating or expected loss of life.

This extended range of load carrying capabilities at reduced regulation can play an important role in selecting what size regulator to use in a particular application. For new substations that will not reach their projected full load for a number of years, and so will not require full range of regulation initially, a smaller size regulator can provide first-cost savings while still providing excellent line regulation.

Assume a new 5000 kVA substation is planned and that the outgoing feeders will require no more than 5 percent regulation for a number of years. Using 3-167 kVA regulators would provide 5000 kVA of regulation at the maximum 10 percent level; but since only 5 percent regulation would be required·, 3-114 kVA regulators could be used initially. When additional regulation is required the 114 kVA regulators could be replaced with the larger l67's and then relocated for other substation or line use. In this manner the higher cost of the larger regulators can be postponed while at the same time a higher level of regulator utilization can be obtained.

c. Shifting the Range of Regulation to Increase Substation Loading

Sometimes in substation application, it is desirable to have the regulators bucking the substation transformer voltage during medium to light loading periods. Such a practice can effectively be used to increase the loadability of a substation that has become voltage limited. If' the taps on a substation transformer are lowered, to raise the normal output voltage, the substation's regulators will buck the higher voltage at light loading times and boost it at peak loading time. It is not necessary to be concerned with the regulator bucking voltage in the 5 to 10 percent range; because this mode of operations is during light loading periods and hence should not overload the regulator.

In instances where corrective measures such as transformer changeout cannot be completed before another peak seasonal loading period would occur, this procedure can be utilized to maintain system voltage levels as well as provide good voltage regulation.

5. The Line Drop Compensator

a. General

Of all the components in the regulator control system, the line drop compensator has traditionally been considered the most difficult to understand - and hence the most difficult to properly adjust. This does not need to be the case. A basic understanding of the functions of the LDC will eliminate any apprehension about its use, as well as any apprehension about how to adjust the compensator for maximum benefits.

b. What Does the Line Drop Compensator Do?

It provides a method of monitoring the actual load current IL passing through the regulator; this is done by means of a current transformer, C.T. in Figure 10 below.

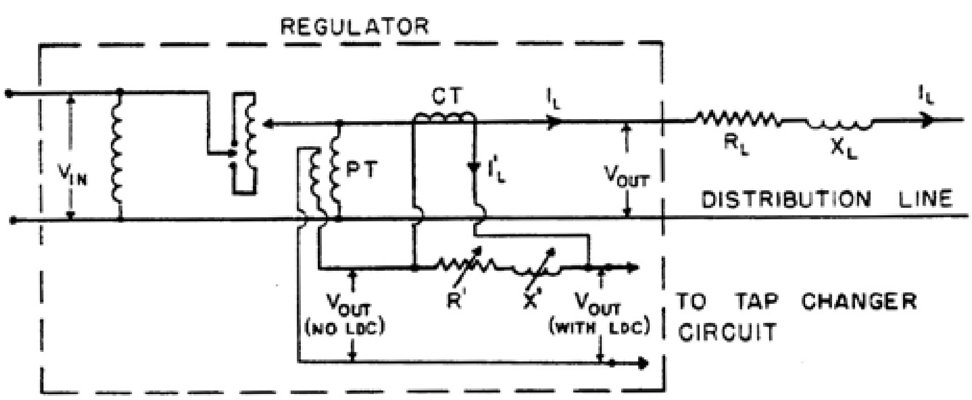


Figure 10. Line Drop Compensator Circuit

Since this current is the same current that flows in the distribution line, it can be utilized by means of the C.T. to produce a proportional voltage drop in the regulator control circuit. This voltage drop is created by the addition of R' and X' to the control circuit; these impedances correspond to the actual distribution line impedances RL and XL. By making the control circuit impedances R' and X' variable, they can then be adjusted to readily simulate the distribution line impedances RL and XL.

It can be seen in Figure 10 that the output at the regulator terminals without line drop compensation is maintained by means of a potential transformer (P.T.). This output is then compared with the desired system voltage as set by the voltage level adjustment. This comparison allows the regulator to respond by making tap changes up or down to always maintain the desired system voltage level as determined by the voltage level setting adjustment. With the addition of R' and X' to the control circuit, a voltage drop or rise can be superimposed on the regulator output voltage by passing the current from the C.T. through R' and X'. In this manner, the output voltage of the regulator as monitored by the P.T. is altered to reflect the line drop caused by the actual line current and line impedances. Comparing this altered output with the desired voltage level setting will enable the regulator to increase or decrease its output level in a manner to compensate for the actual line voltage drop caused by the load current.

It now becomes a matter of determining the R' and X' values that will correspond to the actual value of line impedance RL and XL. Since the function of the line drop compensator is to provide for voltage drop along the line, the actual values set on the control panel dials tor R' and X' are expressed in volts and not impedance (ohms) values. That is, they correspond to how much voltage drop is caused by the line current flowing through the line resistance and line reactance - hence line drop compensation is set in volts.

This is the function of the line drop compensator; how successful it is in actual practice is up to the user. A properly applied regulator utilizing line drop compensation is basic to maintaining quality system voltage with minimum voltage swings.

c. Setting the Line Drop Compensator

The voltage boost produced by a line drop compensator is a function of the settings of R and X controls on the control panel and of the amount of the line current flowing through the regulator. The control settings, depend not only on the number of volts boost desired, but also on the peak load current. Some of the several methods of determining the proper settings are discussed below:

(1) Recommended Method

We would like the LDC to produce a rise, at time of annual peak load, of 4 volts above the 122 volts of the voltage level adjustment. When the load current is equal to the current rating of' the regulator, any settings of the R and X controls which add vectorially to 4 volts will produce the desired rise.

In most cases it is desirable to maintain a ratio between the Rand X control settings which is about the same as the R to X ratio on the actual distribution line. This ratio varies with the size of conductor used but for most distribution circuits a ratio of 5 to 3 will be satisfactory. Breaking down the 4 volts vectorially on this basis gives us approximately 3.5 volts for R and 2 volts for X. This is the setting we should use it the annual peak load current is equal to the current rating of the regulator. Since this is not often the case, it is necessary to calculate R and X for the estimated peak current. This is done in the following steps:

- Find the current rating of the regulator. This is shown on the nameplate as the current transformer primary rating.
- Estimate the peak load current expected during the time until the next regulator control adjustment will be made. (This is often done on an annual basis but if there is a pronounced seasonal peak or if load is growing rapidly, semi-annual or even quarterly adjustments are advisable).

- Divide the current rating by the peak load current. Multiply the result by 3.5 to obtain the R setting and by 2 to obtain the X setting.
- Example: 150 ampere rating, estimated peak current 80 amperes.

l50/80	= 1.87	
l.87x3.5	= 6.6 volts	= R setting
l.87x2	= 3.75 volts	= X setting

(since X is usually adjustable only in l volt steps, use 4 volts for X setting)

(2) Load Center Method

When it is desired to hold a constant voltage at some specific spot on a distribution line (such as at a small town or industrial load) the settings are based on the actual resistance and inductance of the distribution line between the regulator and the load. This is done in the following steps:

- Calculate the R and. X of the distribution line by multiplying the per mile values for the appropriate conductor (see values in REA Bulletin 45-l or REA Bulletin 61-2) times the number of miles between regulator and load.
- From the nameplate of the regulator find the current transformer primary rating and the potential transformer ratio.
- Divide the current transformer primary rating by the potential transformer ratio. Multiply the result by the line R calculated above to find the R control setting. Repeat for the X setting.
- Example: 6.2 miles of three-phase, No. 2 copper equivalent line. Current transformer primary rating 150 amperes; potential transformer ratio 60:l.

From Bulletin 45-1 R per mile = .885,
X per mile - .756
(6.2) (.885) = 5.5 ohms= R
(6.2) (.756) = 4.7 ohms= X
l50/60 = 2.5

(2.5) (5.5) = 13.7 volts = R control setting
(2.5) (4.7) = 11.8 volts = X control setting

(NOTE: This method is applicable only when the regulator serves only the line for which the calculations are made. It should not be used for setting substation regulators serving more than one circuit).

(3) Voltmeter Method

This is a simple method which can be used when the load on the regulator is at or very near the anticipated peak.

With the R and X control settings at zero, connect an accurate voltmeter to the voltage test terminals of the regulator control panel. Verify that the output voltage is 122 volts. Slowly raise the R and X control settings (in an approximate ratio of 5 for R to 3 for X) until the voltmeter reads 126 volts.

With proper care, this method may be used with less than peak load on the regulator if the ratio of present load to peak load is known. For example, if the present load is one-half the anticipated peak load, the R and X controls should be set to give a voltmeter reading of 124, which is a boost of 2 volts or one-half the desired peak load boost of' 4 volts.

d. Special Considerations

While the 5 to 3 ratio between R and X settings will be suitable for most circuits, there are exceptions where other ratios should be used.

In a high load density area where large primary conductors (larger than No. 4/0 aluminum) are used in distribution lines a smaller ratio such as l to l may be substituted.

Where there is a leading power factor (such as on long cable circuits or on very long, lightly loaded overhead lines) the regulator with LDC can be useful in preventing overvoltage at the load end of the line during light load periods. Here the X setting of the LDC may be fair critical and may have to be adjusted by trial and error to obtain a suitable setting.

On circuits were switched capacitors are used, the change in power factor caused by capacitor switching may affect the boost provided by the LDC. This change is less pronounced if the X setting is left at zero and the R setting alone is used to obtain the desired boost.

When the LDC is being used, the output voltage of the regulator is influenced by the load current passing through it. High voltage at the regulator output will result when the load current exceeds tha.t for which the LDC was set. This may be caused by:

- Normal load growth over a long time.
- Addition of large new loads.
- Emergency feeding of lines or loads normally supplied through another regulator.

When any of these events occur the LDC should be reset to reflect the larger load current. For a moderate cost an accessory can be added to a regulator to pre-vent its output voltage from exceeding a preset level (say 126 volts) regardless of the load current.

D. <u>Lightning Protection</u>

Voltage regulators, like other elements of the distribution system, require protection from lightning and other high volt-age surges. Because voltage regulators are constructed like autotransformers, having one of the windings in series with the primary line, additional protection is required for this series winding. Regulators are normally factory equipped with by-pass arresters across this series winding; these arresters may be connected internally or externally depending upon the manufacturer. The by-pass arrester limits the voltage developed across the series winding during surges to within safe values. <u>CAUTION:</u> By-pass arresters protect only the series winding of the regulator and do not eliminate the need for distribution class arresters to protect the regulator itself.

E. <u>Reversibility</u>

Voltage regulators are normally designed to regulate in the direction of power flaw only. When the direction of power flow is reversed, the regulator will not operate as desired.

regulator will respond to a low voltage condition by further lowering the voltage – thus aggravating an already poor voltage condition.

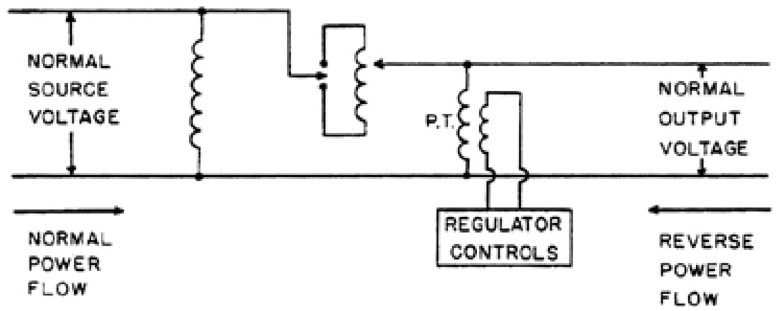


Figure 11. Effect of Reverse Power Flow Through Regulator

This can be seen in Figure 11, where the normal power flow through the regulator has been reversed. If the input voltage to the regulator in this reverse power mode is low, the potential transformer monitoring the normal output voltage of the regulator will sense this and instigate action to increase the normal output voltage by increasing the turns in the series winding. This increase in series turns will result in a lowering of the output voltage across the normal primary winding. If the voltage in the reverse power mode is high, the potential transformer will sense this and take action to reduce the number of turns in the series winding - again compounding the problem by increasing the output voltage.

If a regulator is to be subjected to a reverse power flow, one of the following procedures should be observed:

- Disconnect the regulator from the circuit.
- Set and lock the regulator in the neutral position.
- Reconnect the regulator for operation in the reverse power mode.

Regulators can now be purchased with accessories that automatically sense reverse power and adjust the regulator to respond accordingly.