Basic Considerations for the Application of LTC Transformers and Associated Controls

1.0 ABSTRACT

This Application Note provides a discussion of fundamental topics related to the theory of voltage regulation, control equipment commonly used in conjunction with load tapchanging (LTC) transformers, and step-voltage regulators and criteria for establishing the proper settings for such equipment.

2.0 ISSUES

Power systems which include tapchanging under load transformers will vary significantly in degree of complexity. This Application Note is structured to start with the most fundamental considerations and build, step-by-step, into the more involved situations. It is recognized also that there are many very special situations, usually of particular interest only to the concerned user, which must be treated on an individual basis and are beyond the scope of this Application Note.

3.0 CONSIDERATIONS

3.1 Voltage Regulation Principles

Step-voltage regulation is today most commonly accomplished using LTC transformers or regulators which provide for the output (secondary) voltage to be regulated about the range of 90% to 110% of the voltage at the input (primary). This regulation is accomplished in 32 discrete steps, so that each step represents

$$\frac{20\%\ \text{voltage total range of regulation}}{32\ \text{steps}} = 0.625\%\ \text{voltage / step}$$

$$\text{or } \frac{5}{8}\%\ \text{voltage per step.}$$

Since all modern controls sense the output of a 120 V ac potential device, a one-step change of the LTC is seen to result in a voltage change of 0.75 volt at the control potential input.

This mode of voltage regulation is commonly referred to as 1) bus or 2) feeder regulation, being indicative of aspects of the system for which the regulation is oriented.

1. **Bus regulation:** A single bus voltage is regulated by an LTC transformer, three-phase step-voltage regulator or three single phase step-voltage regulators. The objective is to regulate the voltage of the substation low voltage bus assuming this will satisfy the voltage requirements of all feeders fed from the regulated bus. There will commonly be several (perhaps four or more) three-phase distribution feeders emanating from the regulated bus.

2. **Feeder regulation:** Each feeder is separately regulated by single phase step-voltage regulators out on the distribution feeders, or in the substation.

3. Combinations of 1 and 2 may be used if feeders are long.

The overall circuit of interest may take the form of Figure 1a or 1b, or a combination of the two.

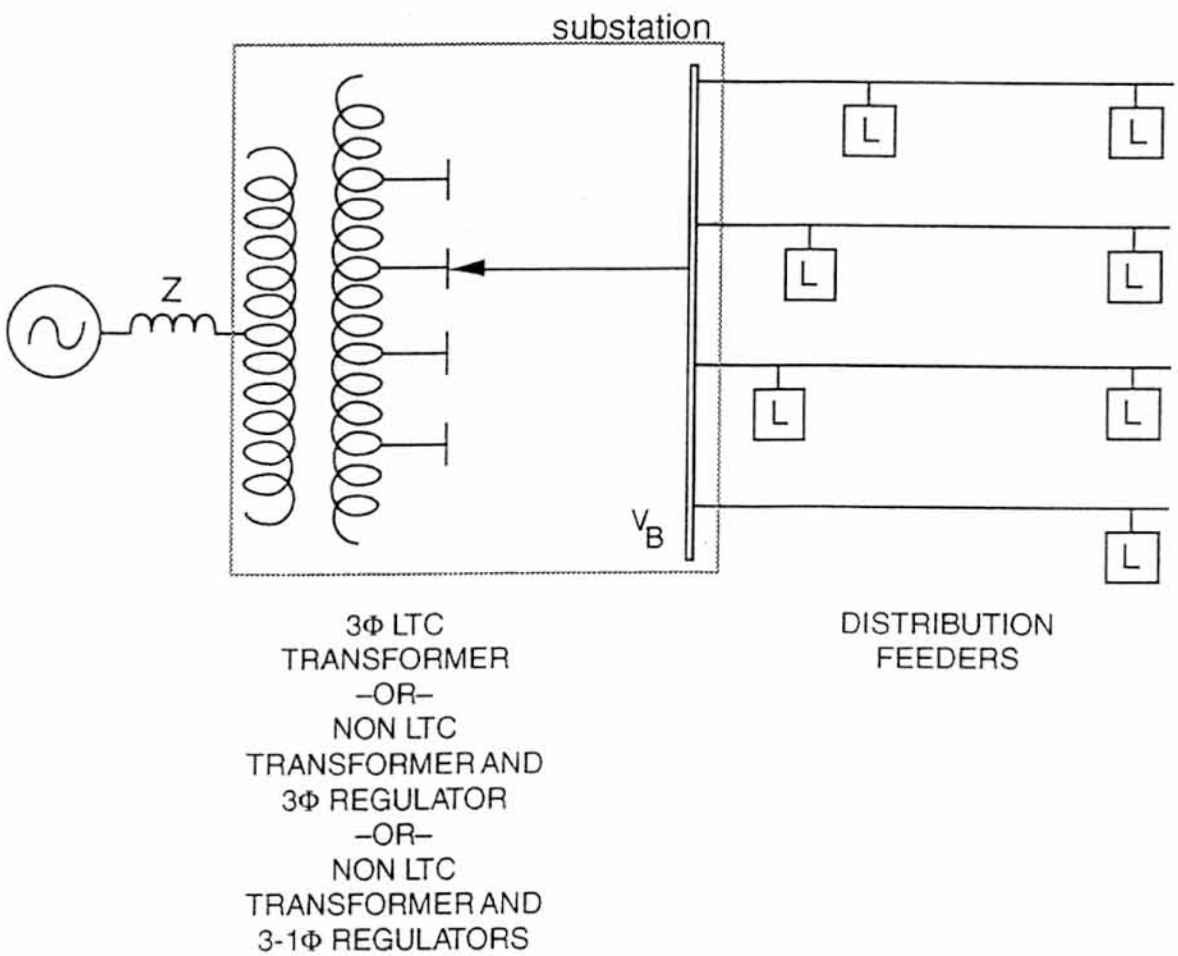


FIGURE 1a Typical System One-Line Diagram, Bus Regulation

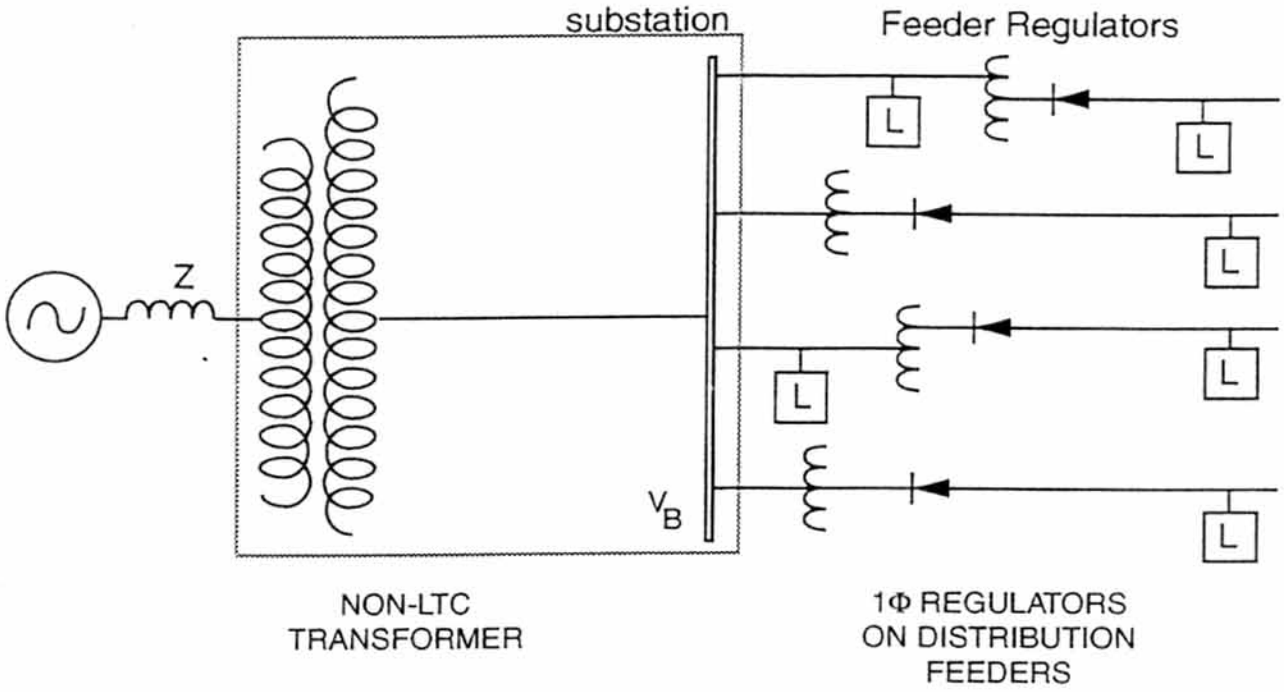


FIGURE 1b Typical System One-Line Diagram, Feeder Regulation

Figure 1a shows that the system includes a power source, a transmission system represented by its impedance Z and a substation with any of three means of providing voltage regulation at the bus (to hold V_B steady). Figure 1b shows a non-LTC transformer with four distribution feeders, each with distributed loads, which employ single phase step-voltage regulators.

3.1.1 Factors which cause V_B to change

Review of Figure 1 reveals that there are four simple factors which, when changed, will cause the voltage at the substation secondary bus to change.

1. Transmission system voltage
2. Impedance (R and X) looking back from the bus
3. Load, and load power factor, on distribution feeders
4. The tap position of the LTC transformer/regulator(s), for bus regulation case.

It is because each of the first three items is continually changing by virtue of factors beyond consideration in this Note, that the LTC is in fact used in order to mitigate the combined effect of the three.

3.1.2 Objective #1: Hold Bus Voltage (V_B) at Desired Level

The most fundamental objective for implementation on the bus regulating LTC is simply to hold the voltage on the bus at the desired level. In order to accomplish this objective there is only one system parameter which must be known to the control: the present value of V_B. This requires that a voltage transformer (VT) be added to the circuit in order to convert the bus voltage to a 120 V ac basis for use by the control.

The circuit of Figure 2 illustrates the important aspects of the system. To the system of Figure 1a has been added the VT and a control. The control allows for the operator to make three settings, those generally considered to be the minimum realistic setpoint requirements.

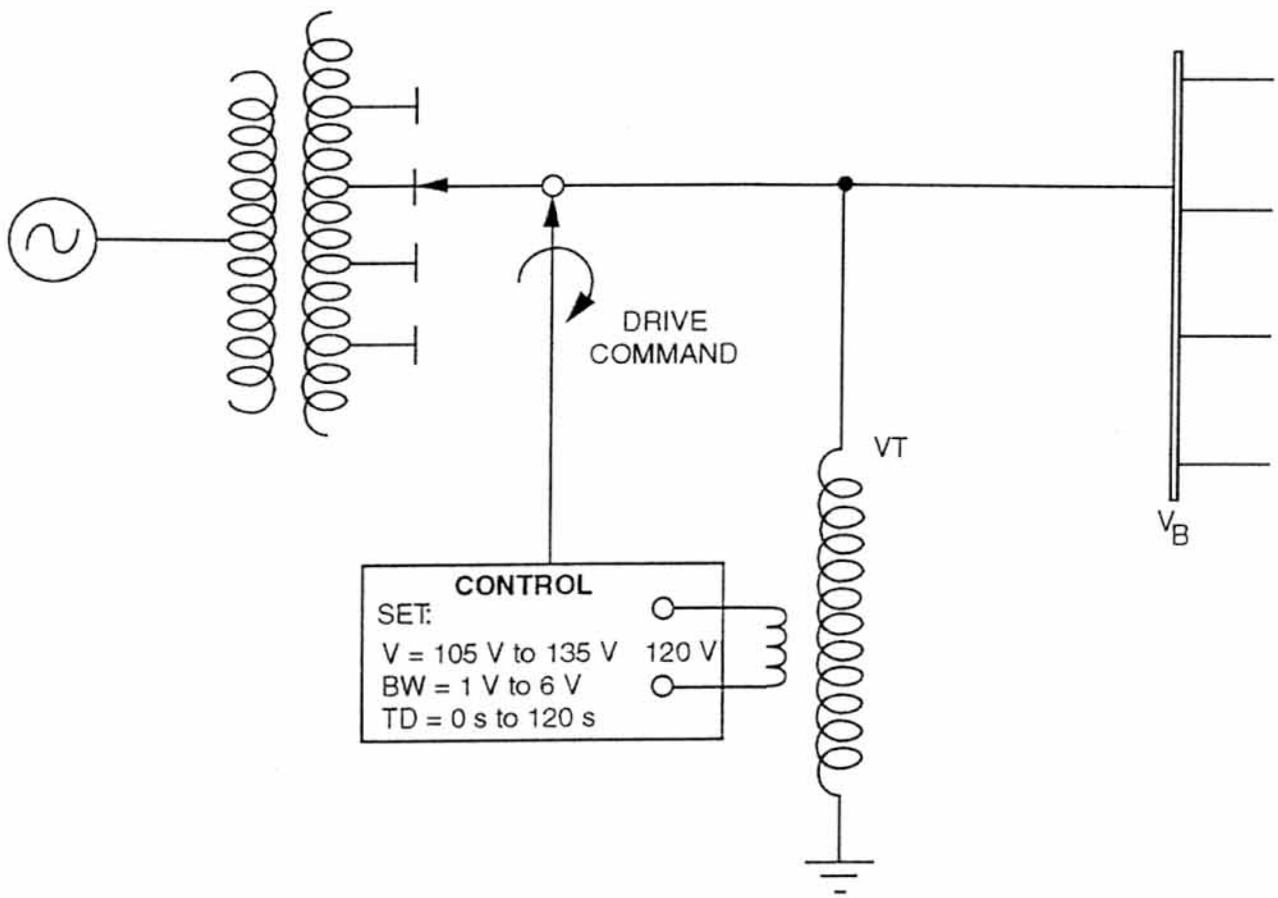


FIGURE 2 Control Circuit Required to Satisfy First Objective

1. Voltage Level

The desired voltage level at the bus. This is spoken in terms of the 120 V basis of the control. The setting used will usually be somewhat more than 120 V, perhaps 124 V to 126 V in recognition that there will be a voltage drop along the distribution feeders and a common criterion is to hold 114 V to 126 V at all loads. Controls typically allow for settings as low as 105 V due to the use in the past of reference voltages of 110 V and 115 V in now obsolete standards.

2. Bandwidth

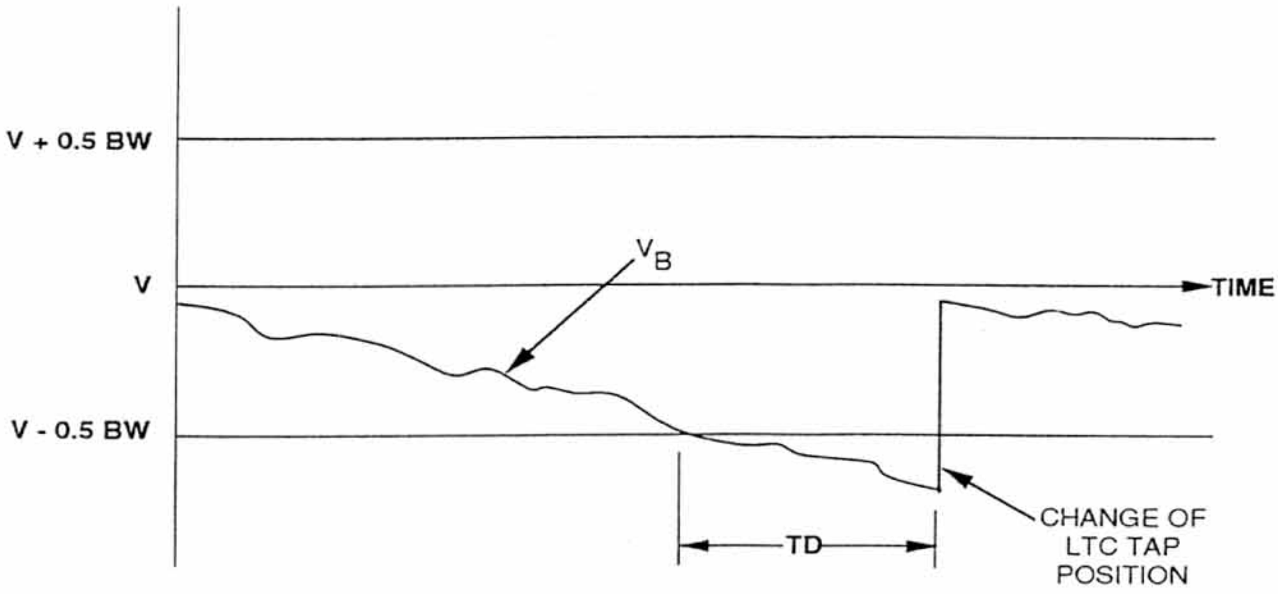
The voltage bandwidth. Due to the step change nature of the LTC output there must be some range of voltage about the voltage level setting which is acceptable to the control and will be recorded by the control as being "in-band." Thus, the bandwidth, also expressed in volts on the 120 V base is the total voltage range, one-half of which is allowed above, and one-half below the voltage level setting.* There is always a minimum acceptable bandwidth setting, usually considered to be twice the voltage change per LTC step change, or 1.5 volts in the common system. In fact, 2.0 and 2.5 volts are the most common settings with 3.0 V and higher values being used where tight regulation is not required.

3. Time delay

An intentional time delay is always included so as to avoid tapchanger operations when the voltage excursion outside of the bandwidth is of short duration. The best example is that of a large motor starting on the system. The voltage level may be pulled low, but will be expected to recover in perhaps 15 seconds. To have made a raise tapchange for the short period would not significantly help in motor starting, and would require consecutive lowering operations after the motor came to speed with attendant accelerated wear of the tapchanger. Consequently, the intentional delay is set, most often in the range of 30 to 60 seconds.

Figure 3 illustrates the relationship between voltage level setpoint, (V), (also frequently stated: "voltage centerband"), the bandwidth, illustrated as 1/2 BW to each side of the centerband, and the time delay (TD). Per Figure 3, the bus voltage V_B is sagging with time as may be due to an increase in the system load. At some point, the voltage drops below V-0.5 BW initiating the timer. When the time attains its set value, a drive command is sent to the tapchanger. Tapchanger operation results in a step-change of the voltage V_B, bringing it back "in-band," thereby satisfying the defined objective #1, to hold the bus voltage at the desired level.

* This is not universally true. In some countries the bandwidth is regarded as the voltage on each side of the centerband, thus for a stated number doubling the acceptable band.



V=Voltage Setpoint of tapchanger control

FIGURE 3 Illustration of the Interaction of Three Basic Control Settings

3.1.3 Objective #2. Hold Load Voltage V_L at Desired Level

The real objective should be to hold the voltage at the load to a desired level. To this end, controls include provision to set Line Drop Compensation (LDC) providing the control with the additional feature of modeling the impedance of the distribution feeder between the LTC and the load thereby to compensate for the voltage drop of the feeder.

The difficulty is that there is seldom a clear real-world illustration of a system applicable to the classical application of LDC, i.e., one in which there is appreciable length of distribution feeder terminated in the sole load for that feeder.

In spite of this, LDC is frequently used with the recognition that the system may not be ideally suited for it. It is therefore important to understand the underlying principle.

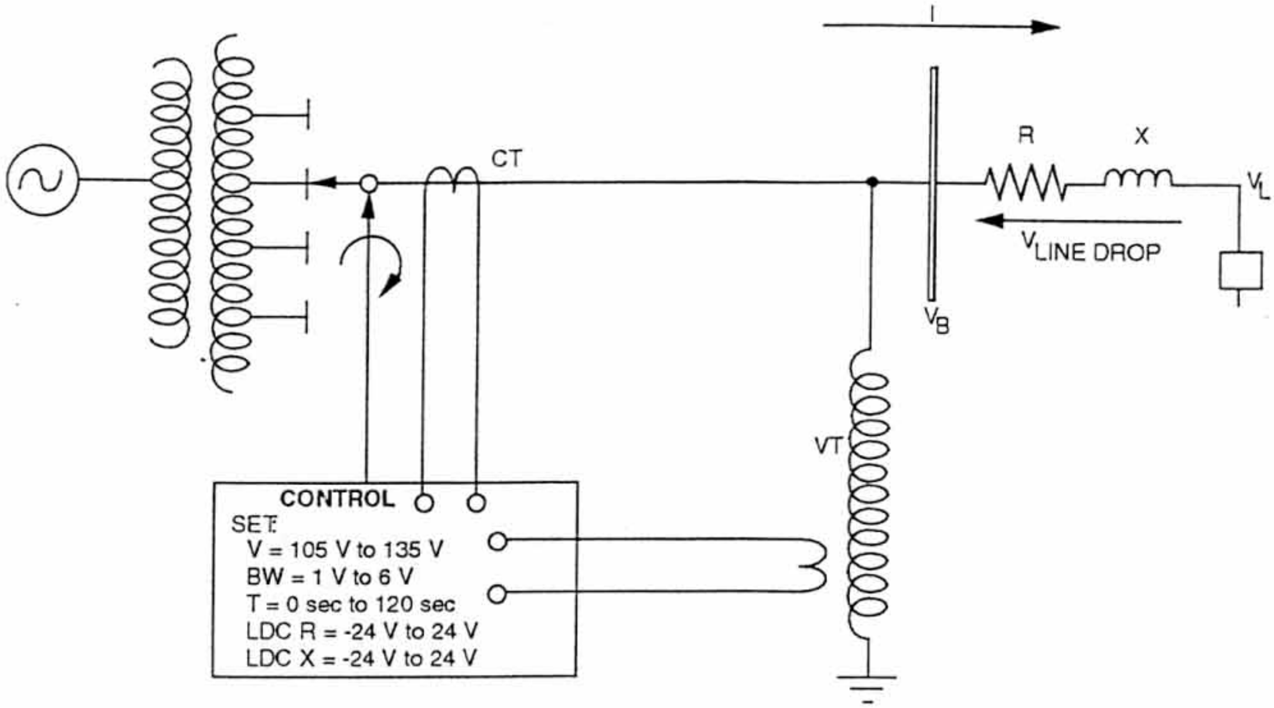


FIGURE 4 Control Circuit Required to Satisfy Second Objective

Figure 4 shows the system of interest. It is now the voltage at the load, V_L, which is to be regulated, not V_B. Unfortunately, lacking some means of remote communications, the control has no way to directly know V_L. However, looking at Figure 4 it is seen that three items are needed in order to model (or calculate) V_L. Thus, with knowledge of

1. the bus voltage V_B
2. the feeder current I and
3. the feeder resistance R and reactance X

the control can be programmed to adjust the bus voltage (V_B) to compensate for the voltage drop in the feeder line between the bus and the load. Evidently,

$$\bar{V}_L = \bar{V}_B - \bar{V}_{LINE\,DROP}$$

$$\bar{V}_L = \bar{V}_B - \bar{I}\,(R + jX)$$

when proper phasor relationships are considered, as illustrated in Figure 5.

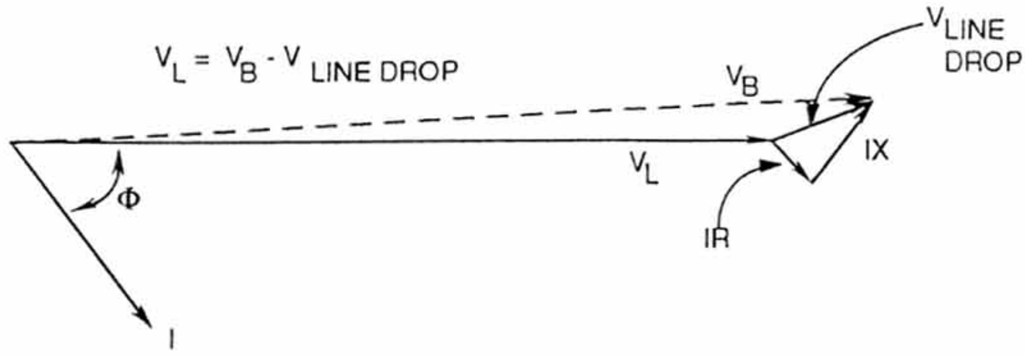


FIGURE 5 Phasor Relationships Applying to Voltage Regulation Using Line Drop Compensation

In Figure 5, it is important to note that V_B and V_L will not usually be in phase with each other, the phasing being a function of the relative magnitudes of R and X and the magnitude and power factor angle (Φ) of the load current. It is thus apparent that the control must resolve these parameters and accomplish the solution indicated by the equations above.

Now, in order to establish proper control panel settings it is necessary to consider

1. Desired voltage level at the load. The desired voltage level at the load will typically be about 120 V. It is this value which is to be set on the control panel.

2. Bandwidth-same as described in Section 3.1.2.

3. Time Delay-same as described in Section 3.1.2.

4. Line Drop Compensation. Line Drop Compensation is set using individual R and X values. These values are calibrated on the control in volts (not ohms) where the setting is representative of the line drop, in volts on a 120 V base, when the line is carrying the rated primary current of the CT. Most controls accommodate setpoint ranges for LDC R and LDC X of -24 V to +24 V, (the reason for the negative R and X settings will be described later).

3.1.3.1 Setting LTC Control LDC R and LDC X

As noted, the control must "know" the values of Resistive and Reactive Voltage Drop applicable to Line Drop Compensation. This requires knowledge of the distribution feeder configuration: To calculate the R and X values the following procedure can be used.

1. Determine Equivalent Conductor Spacing "D"

   Regardless of the physical orientation of the phase conductors, a distance D is calculated as

$$D = \sqrt[3]{D_{AB} \times D_{BC} \times D_{CA}}$$

where D_{AB}, D_{BC} and D_{CA} represent the spacings, in inches, between phase conductors.

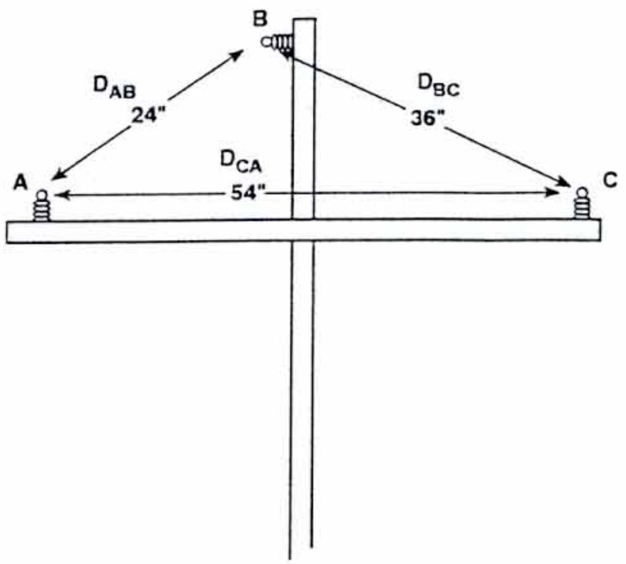


FIGURE 6 Example Distribution Feeder Orientation

For example shown:

$$D = \sqrt[3]{24 \times 36 \times 54} \cong 36 \text{ inches.}$$

2. Using knowledge of size and material of the phase conductors involved and D, read from Table I or Table II the feeder resistance, r, and inductive reactance, x, (ohms per conductor per mile).

ALUMINUM CONDUCTOR, STEEL REINFORCED									
Con-ductor Size	Resist-ance at 50° C	60 Hz Reactance (Ohms per conductor per mile at equivalent "D")							
MCM		18"	24"	30"	36"	42"	48"	54"	60"
1272.0	0.0851	.421	.456	.483	.505	.524	.540	.555	.567
954.0	0.1128	.439	.474	.501	.523	.542	.553	.573	.585
795.0	0.1373	.450	.485	.512	.534	.553	.569	.584	.596
556.5	0.1859	.469	.504	.531	.553	.572	.588	.603	.615
477.0	0.216	.479	.514	.541	.563	.582	.598	.613	.625
397.5	0.259	.490	.525	.555	.574	.593	.609	.624	.636
336.4	0.306	.500	.535	.562	.584	.603	.619	.634	.646
266.8	0.385	.514	.549	.576	.598	.617	.633	.648	.660
AWG									
4/0	0.592	.630	.665	.692	.714	.733	.749	.764	.776
3/0	0.723	.670	.705	.732	.754	.773	.789	.804	.816
2/0	0.895	.690	.725	.752	.774	.793	.809	.824	.836
1/0	1.12	.705	.740	.767	.789	.808	.824	.839	.851
2	1.65	.691	.726	.753	.775	.794	.810	.825	.837
4	2.57	.708	.743	.770	.792	.811	.827	.842	.854
6	3.98	.722	.757	.784	.806	.825	.841	.856	.868

TABLE I Distribution Feeder Resistance and Reactance for Aluminum Conductor, Steel Reinforced

COPPER, HARD DRAWN									
Conductor Size	Resistance at 50° C	60 Hz Reactance (Ohms per conductor per mile at equivalent "D")							
MCM		18"	24"	30"	36"	42"	48"	54"	60"
1000	0.0685	.449	.484	.511	.533	.552	.568	.583	.595
750	0.0888	.466	.501	.529	.550	.569	.585	.600	.612
600	0.1095	.481	.516	.543	.565	.584	.600	.615	.627
500	0.1303	.492	.527	.554	.576	.595	.611	.626	.638
400	0.1619	.507	.542	.569	.591	.610	.626	.641	.653
350	0.1845	.515	.550	.577	.599	.618	.634	.649	.661
300	0.215	.525	.560	.587	.609	.628	.644	.659	.671
250	0.257	.536	.571	.598	.620	.639	.655	.670	.682
AWG									
4/0	0.303	.546	.581	.608	.630	.649	.665	.680	.692
3/0	0.382	.554	.589	.616	.638	.657	.673	.688	.700
2/0	0.481	.581	.616	.643	.665	.684	.700	.715	.727
1/0	0.607	.595	.630	.657	.679	.698	.714	.729	.741
1	0.757	.609	.644	.671	.693	.712	.728	.743	.755
2	0.964	.623	.658	.685	.707	.726	.742	.757	.769
4	1.518	.648	.683	.710	.732	.751	.767	.782	.794
6	2.41	.677	.712	.739	.761	.780	.796	.811	.823
8	3.80	.714	.749	.776	.798	.817	.833	.848	.860

TABLE II Distribution Feeder Resistance and Reactance for Hard Drawn Copper Conductor

For example, presume the conductor is 266 MCM ACSR

Reading from Table 1 with D=36 inches:

r=0.385 ohms/conductor/mile

x=0.598 ohms/conductor/mile

NOTE: Because these values are in ohms per conductor per mile, the values of r and x must be increased for circuits other than three-phase wye.

- If the circuit is delta connected, multiply r and x by 1.73

- If the circuit is single phase, multiply r and x by 2.0

3. The values above are calculated for one mile of feeder length. Multiply these values by the length of the feeder, in miles, for the total line resistance and reactance.

   Example: Presume the circuit is connected in wye, and the length is 1.1 miles.

$$\begin{aligned} Z &= 1.1(r + jx) = 1.1(0.385 + j0.598) \\ &= 0.424 + j0.658 \text{ ohms.} \end{aligned}$$

4. Calculate, individually, the per unit resistive and reactive voltage drops on the feeder using the CT primary rating and the system voltage as base.

   Example: Presume the CT is monitoring one phase and is rated 600 A primary. The circuit voltage is 13.8 kV.

$$Z_{base} = \frac{13{,}800 / \sqrt{3}}{600} = 13.3 \text{ ohms}$$

$$IR_{pu} = \frac{r}{Z_{base}} = \frac{0.424}{13.3} = 0.032 \text{ pu}$$

$$IX_{pu} = \frac{x}{Z_{base}} = \frac{0.658}{13.3} = 0.050 \text{ pu}$$

5. The control operates on a 120 V ac base so

R_{set} = 0.032 x 120 = 3.8 V (or 4 volts)

X_{set} = 0.050 x 120 = 5.9 V (or 6 volts)

6. Adjustment for voltage/current phasing errors in single phase step-voltage regulators on delta systems.

The calculations above presume that the signals from the VT and CT are in-phase at unity power factor. This can always be made to be the case with proper instrument transformer connections on three-phase transformers and regulators and will hold on single phase step-voltage regulators connected in wye or in single phase applications. This will not, however, be true for single-phase step voltage regulators which are connected in delta where the current signal will lead or lag the voltage signal by 30° at unity power factor of the load.*

If there is no provision to automatically account for this shift in the control, the necessary corrections to the R and X LDC set points can be made using the following relationships.

• For a "lagging" regulator, i.e., where the CT signal lags the VT signal by 30°

$$R_{set\ new} = 0.866\ R_{set} - 0.5\ X_{set}$$

$$X_{set\ new} = 0.866\ X_{set} + 0.5\ R_{set}$$

• For a "leading" regulator, i.e., where the CT signal leads the VT signal by 30°

$$R_{set\ new} = 0.866\ R_{set} + 0.5\ X_{set}$$

$$X_{set\ new} = -0.5\ R_{set} + 0.866\ X_{set}$$

where R_{set} and X_{set} are values calculated in section 3.1.3.1 (5) and $R_{set\ new}$ and $X_{set\ new}$ are the values to be used on the controls.

Now, for the example of a lagging regulator

$$R_{set\ new} = 0.866\ R_{set} - 0.5\ X_{set}$$

$$= 0.866\ (3.8) - 0.5\ (5.9)$$

$$= 0.3\ (\text{or } 0\ \text{V})$$

$$X_{set\ new} = 0.5\ R_{set} + 0.866\ X_{set}$$

$$= 0.5\ (3.8) + 0.866\ (5.9)$$

$$= 7.0\ (\text{or } 7\ \text{V})$$

It is because of this situation that a negative value of R or X may need to be set for Line Drop Compensation.

* The current signals (relative to the voltage) will be shifted either 30° leading or 30° lagging (but all the same) for each regulator in a three-phase delta bank. For an open delta connection, one regulator will be leading and the other will be lagging. Procedures to determine the leading and lagging units are found in the instruction manuals for the regulators.

3.1.3.2 Bus Voltage Conditions When Using Line Drop Compensation

As stated, the Line Drop Compensation feature will hold a desired voltage at the load. It accomplishes this by recognizing that there will be a voltage drop between the bus and the load (Figure 5) and consequently will cause the voltage V_B to increase above that of V_L according to the relation

$$\bar{V}_B = \bar{V}_L + \bar{V}_{LINE\,DROP}$$

Three examples illustrate the situation as the load current varies

Example 1:

V_L desired = 120 V

$I_L = 600\,A = 1.0$ pu, the CT primary rating

Φ = load power factor angle = $\cos^{-1}$ pf

pf = 0.8, $\Phi = 37°$

$R_{set} = 4\,V$

$X_{set} = 6\,V$

$$\bar{V}_B = \bar{V}_L + \bar{V}_{LINE\,DROP}$$

$$\bar{V}_B = \bar{V}_L + I[R(\cos\Phi - j\sin\Phi) + X(\sin\Phi + j\cos\Phi)]$$

$$\bar{V}_B = (120 + j0) + 1.0[4(0.8 - j0.6) + 6(0.6 + j0.8)]$$

$$\bar{V}_B = 120 + 6.8 + j2.4 = 126.8 + j2.4$$

$$|V_B| = 126.82 \text{ volts}$$

Example 2:

Same as Example 1, except I=0.5 pu

$$|V_B| = 123.41 \text{ volts}$$

Example 3:

Same as Example 1, except I=1.5 pu

$$|V_B| = 130.25 \text{ volts}$$

From this it should be clear that an inadvertent overload may cause the bus voltage to go too high if line drop compensation is used without a voltage limit override (see paragraph 3.2).

3.1.3.3 Comparison Voltage Profile, Non-LDC vs LDC

Figure 7 illustrates the voltage profile of a line to reveal the benefit of use of Line Drop Compensation. In Figure 7a the voltage at the load is heavily influenced by the magnitude of the load current. For example, the voltage level setting has been established as 124 V at the substation bus in order to have 120 V at the load during period of heavy line loading. For this to be true, the load voltage is seen to be only slightly less than 124 V during light load conditions.

Figure 7b illustrates the benefit derived when LDC is used. Here, with the voltage level set point established at 120 V, that voltage is held at the load regardless of the magnitude of the load. Clearly, this is accomplished by causing the bus voltage to vary from slightly over 120 V to 124 V as the load increases.

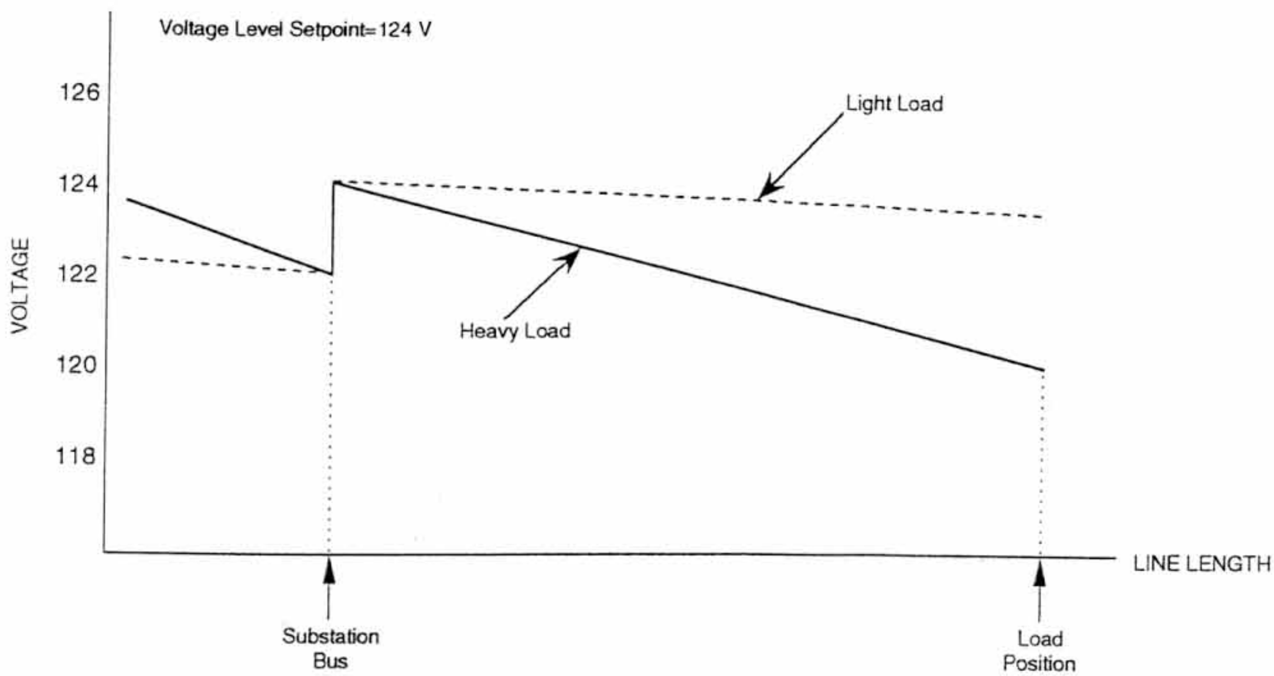


FIGURE 7a System Voltage Profile, Not Using Line Drop Compensation

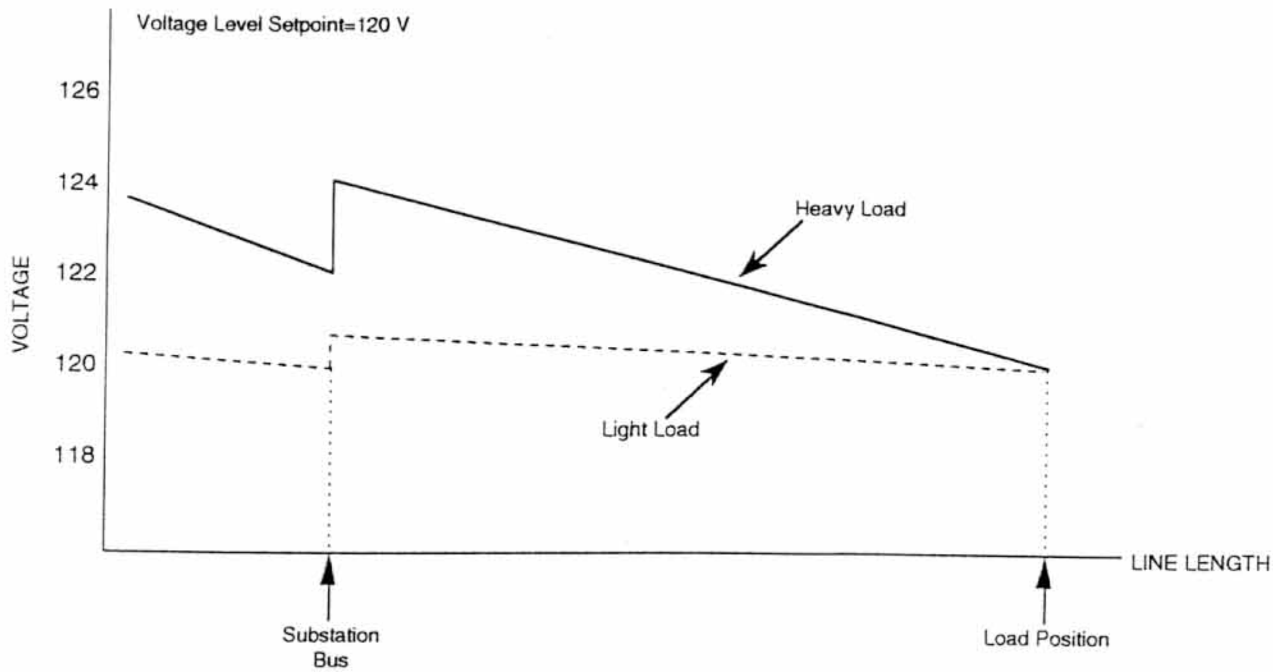


FIGURE 7b System Voltage Profile, Using Line Drop Compensation

3.2 Voltage Limit Override

As was illustrated, the use of line drop compensation may cause the substation bus voltage to go too high if the load increases above that anticipated, or no provision is made to limit the magnitude of the bus voltage, V_B.

The appropriate solution is to add an LTC Backup Control. This control, which for reliability considerations should be independent of the main control panel, will be expected to recognize the voltage V_B and act to limit that voltage to a safe level. At high load current magnitudes, this will be accomplished by effectively limiting the LDC contribution above the current which results in V_B being higher than desired.

The Backup Control is connected electrically as in Figure 8, showing the new control between the basic control and the motor drive assembly. The control needs only sensory input of V_B.

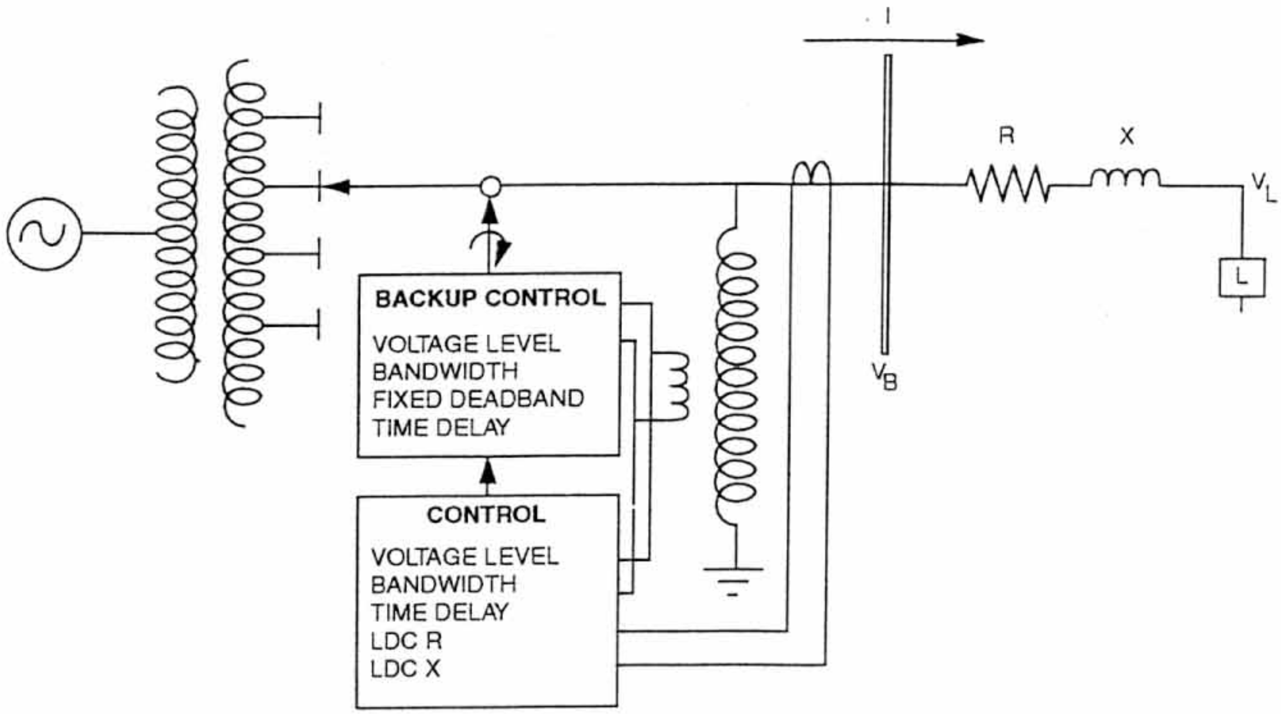


FIGURE 8 LTC Control Circuit Including LTC Backup Control

The LTC Backup Control includes four setpoints:

1. Voltage Level. This is the desired mid-point about which Backup Control action is planned. It will be set at 120 V if the desired output voltage range is, as typical, 114 V to 126 V.

2. Bandwidth. The bandwidth is the range about which the Backup Control is satisfied, i.e., no corrective action is required. A bandwidth of 12 V (with the 120 V centerband setting) means the control is "in-band" over the range of 114 V to 126 V. At 114 V, the control will take action to prevent a further lowering of the LTC tap position; at 126 V the control will prevent a further raising of the LTC. Also, at 126 V another aspect, the deadband, comes into play.

3. Deadband. A deadband, effective above the upper band-edge, is a region in which no further raise commands will be allowed to the LTC, but also, no corrective action is taken to lower V_B. When, as may be due to changes in the system source conditions, the voltage does pass above the deadband, the Backup Control will, of itself, command the LTC to lower or "run back" the voltage without regard to the status of the main control. The deadband is not a user setpoint; it is factory specified as 1 V, 2 V, 3 V, or 4 V, the 2 V setting being most common.

4. Time Delay. This setting applies to the run back aspect of the Backup Control. It will usually be set to a very short period of 0 to 10 seconds.

Figure 9 illustrates the voltage/time relationships for Backup Controls, and specifically how it may perform when used on a system for which the three examples of paragraph 3.1.3.2 apply. For this, the Backup Control is set

Voltage Level = 120 V
Bandwidth = 12 V = ±6 V
Deadband = 2 V = 126 V to 128 V.

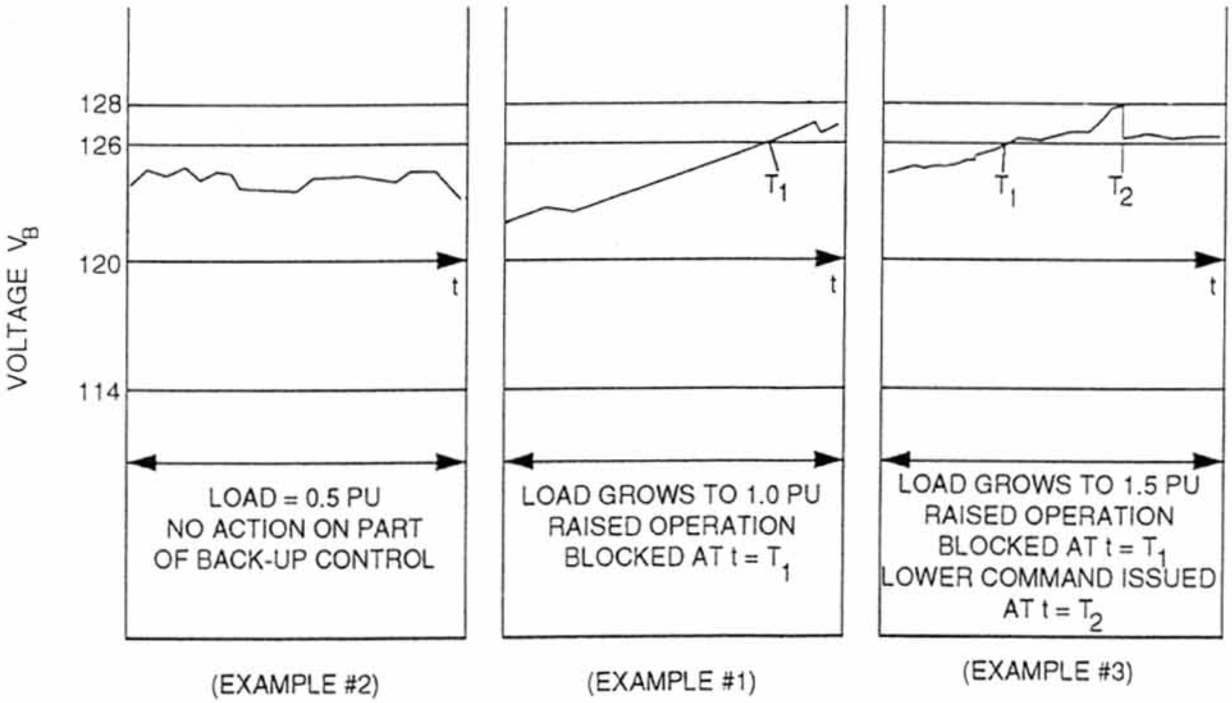


FIGURE 9 Bus Voltage as Function of Load Current When Using Line Drop Compensation/Action of LTC Backup Control (Example numbers relate to para. 3.1.3.2)

With a light load, Example #2, the voltage V_B stays in the region below 126 volts. There is no action on the part of the Backup Control. As the load grows, Example #1, V_B rises due to LDC influence. At time=T_1, V_B has attained 126 V and the Backup Control blocks further raise commands to the LTC. If the voltage at V_B continues to rise to above 128, as shown at T_2, Example #3, the Backup Control will override the basic control and command a lower tap change operation.

3.3 Control Panel Settings when Feeder Includes Capacitors

It is frequently true that a distribution feeder will include power factor correction capacitors as well as step-voltage regulators. Often, it is incorrectly assumed that the use of capacitors will necessitate the use of the negative X setting of Line Drop Compensation.

The basic problem is that the control at the transformer only knows voltage, current and the relative phasing of the voltage and current. It does not know if the load power factor is being altered by use of capacitors. Presume a capacitor bank has been installed on the load side of the transformer such that its rating matches exactly the VAr requirements of the load. Apparently, the capacitor bank might have been installed at the load, immediately at the transformer or anywhere in between; the CT in the transformer cannot recognize the difference, yet the voltage drop on the feeder which we would hope to correct using LDC, will be very different for each case.

Figure 10 illustrates the situation. In Figure 10a all of the reactive current contributes to the line drop, in Figure 10b the reactive current contributes to the drop in only one half of the line and in Figure 10c there is no line drop due to reactive current, yet the transformer CT, upon which LDC must act, sees the same current in each case. Figure 11 illustrates the feeder voltage profile based on the three conditions.

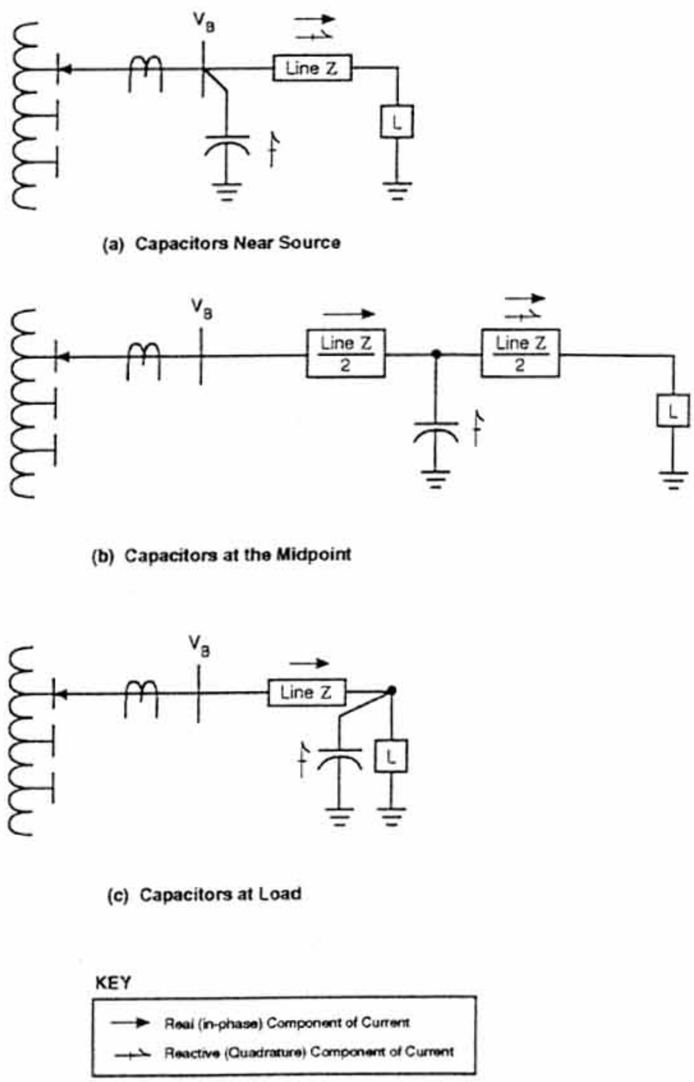


FIGURE 10 Reactive Current Contribution to Line Drop as Function of Capacitor Placement

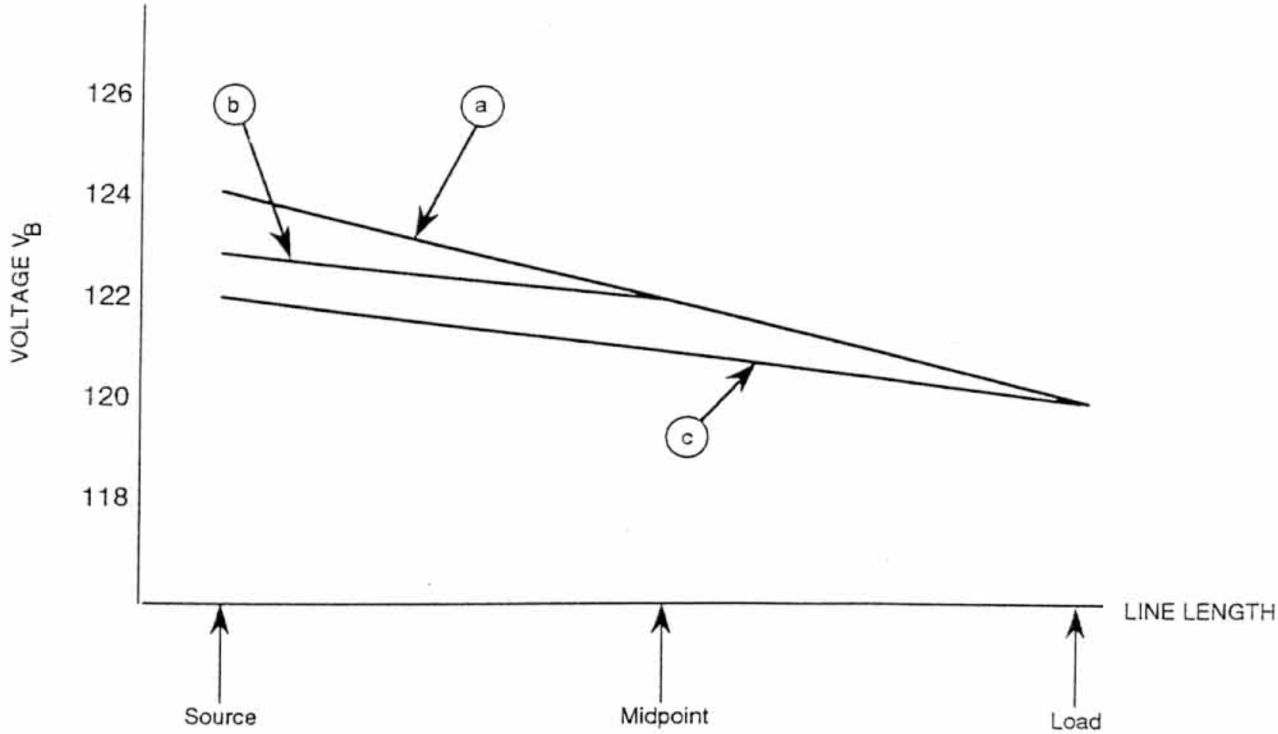


FIGURE 11 Voltage Profile of Feeders Illustrated in Figure 10

The conclusion is that LDC R and LDC X should be established based on the same premise as that described in paragraph 3.1.3.1 without regard to the presence of any capacitors on the line. The problem is that except for the case illustrated as 10c, the line drop will exceed that determined by the control LDC circuit or algorithm. When the capacitor is at any point other than at the load, the CT in the regulator does not "see" the reactive current, yet the reactive current does contribute to the line drop.

Qualitatively, it will be recognized that the regulator output voltage must be higher (because of the additional line drop) than for the case with the capacitors at the load. The questions are: How to compensate? Should the LDC setting be increased? Should the regulator voltage bandcenter be increased?

First, it is apparent that the line drop due to the capacitor current is constant so long as the load requires the vars made available by it. Thus, intuitively, it is seen that a constant voltage must be added at the regulator, which is independent of the sensed load current. What must be done is to set the regulator voltage bandcenter up to adjust for the drop in the line caused by the reactive current. If there is 1200 kVAr connected at V_B the drop in a line of four miles similar to that of paragraph 3.1.3.1 not recognized by the LDC of the control will be:

$$V_{\text{LINE DROP}} = \frac{1200\,\text{kVAR}}{13.2\text{kV}\sqrt{3}}4(0.385 + \text{j}.598)$$

$$= 125.6 - \text{j}80.8\ \text{V}$$

Of this, the quadrature component is inconsequential when added to the 7620 volt base, so the increase in the voltage bandcenter will be:

$$\frac{125.6}{7620} = 1.6\%$$

making it necessary to establish a new voltage bandcenter setting 1.6% higher or 122 volts in order to hold 120 V at the load when 1200 kVAr is connected near the regulator. Of course, this raises another problem: What is to be done when the capacitor is removed? Obviously, the voltage level setting should be reduced back to 120 V, and may be accomplished in practice by using a control voltage reduction capability actuated by a contact on the capacitor switch. Note that this problem is reduced proportionately to the length of line involved as the position of the capacitors is moved toward the load. It may also be necessary to increase the control bandwidth setting to be sure that the voltage change due to capacitor switching remains conservatively less than the bandwidth setting.

3.4 Regulators in Cascade Operation

As may occur on longer feeders, several regulators will be included at intervals of several miles in order to keep the voltage profile as desired. This introduces one new consideration, that of the time delay, in order to assure optimum operation.

Contrary to what may at first seem apparent, the time delay should increase as the distance from the source increases in order to minimize total tapchange operations. In this way, the regulator closest to the source has the first opportunity to correct the voltage.

The time delays are usually staggered such that at least 15 seconds time delay difference exists between sequential regulators in cascade.

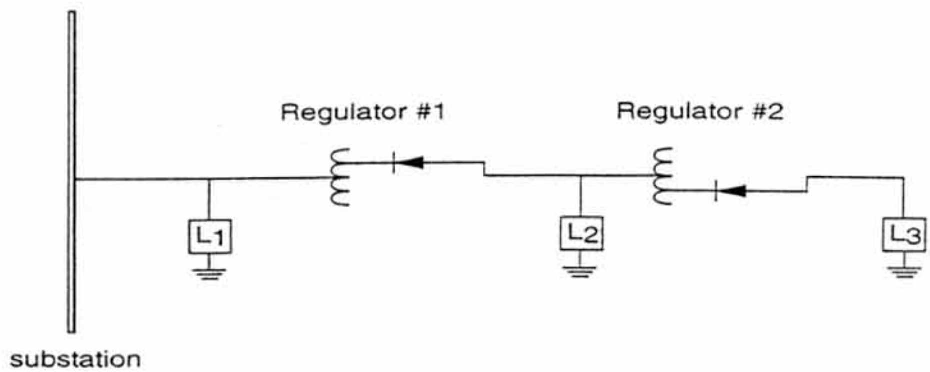


Figure 12 Regulators in Cascade Operation

By example, consider the system of Figure 12, where the time delay on regulator #2 is set (incorrectly) to a value less than regulator #1.

1. Presume a large load increase at L3 causes both regulator controls to sense an out-of-band low condition.

2. Regulator #2 makes step raise change(s) bringing its voltage in-band.

3. Subsequently, because of the longer time delay setting on the control on Regulator #1, it makes appropriate step raise change(s), bringing its voltage in-band.

4. The voltage at Regulator #2 may now be too large because of the action of Regulator #1. Consequently, regulator #2 control must again time-out causing regulator #2 to lower its tap.

The effect is that regulator #2 does more tapchanging than desired. Properly setting the Regulator #1 relay shorter than that of Regulator #2 will avoid that condition.

3.5 Reverse Power Flow Operation

Many regulators are, or can be, equipped to recognize the reversal of power flow and alter tapchanger action accordingly. Reverse power flow (RPF) operation in the classical sense is applied to feeder regulators as will be illustrated. Unfortunately, this has been improperly applied to systems with remote generation in the mistaken belief that the classical solution will apply here also.

3.5.1 Proper Application—Reverse Power Flow

The classical case for the use of reverse power flow detection and actuation is based on the system of Figure 13.

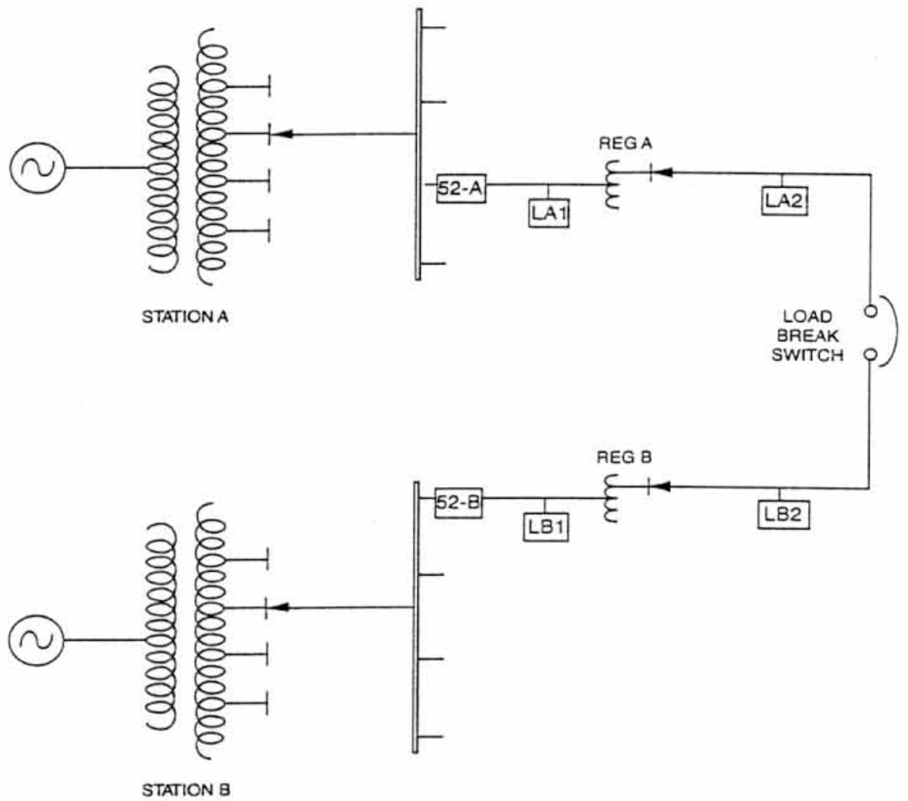


FIGURE 13 System for Proper Application of Basic Reverse Power Flow Control

In Figure 13, normally stations A and B are in service and the load break switch is open. Therefore, loads LA1, LA2, LB1 and LB2 are all served radially from these respective stations.

Presume that station B must be removed from service for maintenance. With two linemen able to communicate with each other, one lineman may close the load break switch, radio to the other who quickly (in less than about 30 seconds) opens breaker 52-B. All load service continues without interruption from station A. Note, however, that the direction of the flow of load in Regulator B has reversed to serve LB1.

This reverse power operation is characterized by two very important points:

1. The transition was quick, being accomplished in less time than required for the control on Regulator B to have timed out.

2. At the completion of the switching, the system is again operating radially, albeit with Regulator B recognizing the power flow reversal.

Here, Regulator B will be equipped to monitor the voltage on its new load side, this having previously been the source. The regulator control must also reverse its operation, commanding the tapchanger "up" to lower the voltage and vice versa.

3.5.2 Reverse Power Flow-Misapplied

Figure 13 has been restructured as Figure 13 to better illustrate the situation which occurs with sources of remote generation. The utility, which may be considered as station A serves load L1 and L2, L2 being on the load side of a regulator. A remote source of generation, station B, is introduced where B will have sufficient capacity to sell power to the utility. While the regulator will be forced into a reverse power flow situation, a conventional RPF actuation is not appropriate. This is apparent when it is seen that upon normal RPF the regulator will attempt to use VT1 and regulate per that signal. VT1 is, however still connected to the utility (A) source, which source may be very much stiffer than B. Consequently, the control senses an out-of-band condition and commands a tapchange. The voltage at VT1 does not change appreciably, being held by station A. A second, third, fourth...tapchange is commanded still without control satisfaction. In the limit, the tapchanger runs to 16R or 16L (depending on the initial out-of-band direction) with the result of drastically upsetting the desired system VAr flows.

This application requires special consideration. For example, it may be that the objective of the LTC control is not to regulate voltage, but to act so as to minimize VAr exchange.

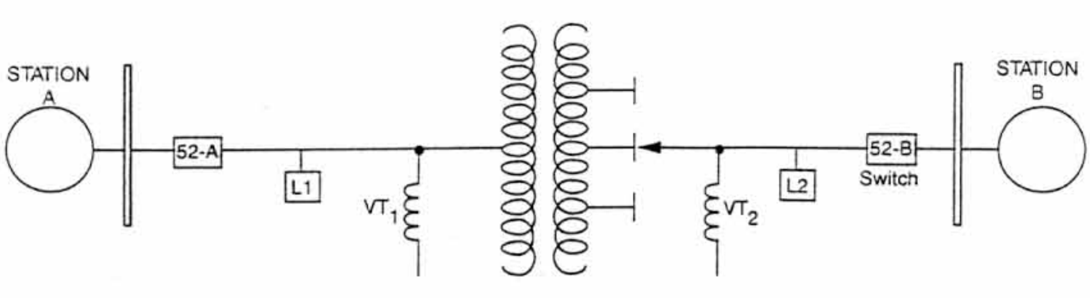


FIGURE 14 System With Remote Source of Generation

4.0 Conclusion

Load Tapchanging Transformers and/or Step-Voltage Regulators are used extensively through the utility and industrial complex. The application has perhaps become so routine that there has been a loss of recognition of some of the basic principles which apply. This Application Note reexamines those principles. With this training, it is expected that the user will be able to apply LTC apparatus with a high level of confidence in its proper operation. A related follow-on topic, that of Parallel Operation of LTC Transformers, draws from the basics of this note, but justifies individual description. Beckwith Electric Company Application Notes #11 and #13 are available for this purpose. WDBN}AN #17ising

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