PRINCIPLES OF VOLTAGE REGULATION

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**TYPICAL SYSTEM**

All electrical systems are composed of the same basic equipment. Experience has shown it is most economical to generate power in large bulks, transmit it at very high voltage to minimize line losses, and transform it to low voltages for safe feeding to individual customers in small quantities.

A typical system has a generator (probably rated 13.8KV) which generates a large quantity of power. The power is stepped up (perhaps 115 KV) and sent over a transmission line. In the individual substations the power is stepped down (15 KV or less) and fed out on distribution feeders.

The last transformation occurs in the distribution transformers hanging along these distribution feeders. Here the power is transformed to 120/240 volts and fed into the houses of the individual customers. On a wye secondary, it may be 120/208 volts or in the case of industrial load it may be 277/480 volts. In a perfect system the voltage at every point along the line remains constant. But the ideal is impossible to achieve because every electrical machine and element is subject to internal voltage drop. This means the output voltage, or the voltage that appears across the output terminals of any such electrical device, changes with the load.
A generator is a device which converts mechanical energy into electrical energy. It has a field winding and an armature winding. A voltage \( E_g \) is generated when the field is excited and there is relative movement between the two windings. The generated voltage varies directly as the speed of relative motion, or frequency, and as the strength of the field. When a generator is operated at no load, the terminal voltage equals the generated voltage. However, as the generator is loaded, the load current flows through the impedance of the armature winding causing a voltage drop which vectorially subtracts from the generated voltage.

Under load the terminal voltage of a generator differs from the generated voltage, depending upon the impedance of the winding and the power factor of the load. Since most loads are lagging, the output of a generator usually drops as load is added. Using a generator voltage regulator, the field strength is varied to vary the generated voltage. The generated voltage is adjusted under load conditions to maintain a constant terminal voltage to feed into the system.

\[
\begin{align*}
\text{At no load} & \quad V_t = E_g \\
\text{Under load} & \quad V_t = E_g - I_L (r + jx)
\end{align*}
\]
The output voltage of transformers varies with load conditions too. When a transformer is excited with rated primary voltage, the secondary left open, and a voltmeter placed across the secondary terminals, rated voltage is read on the secondary side. However, as soon as load current flows through the resistance and reactance of the windings, causing an impedance drop, the voltmeter reads other than rated voltage.

\[ E_{ip} = n E_{is} \]

At no load

\[ V_s = E_{is} \]
\[ V_s = \frac{V_p}{n} \]

Under Load

\[ V_s = E_{is} - I_L (r + jx) \]
\[ V_s = \frac{V_p}{n} - I_L (r + jx) \]
SHORT FEEDER

Lines have series impedance, too. A line has resistance and reactance, both capacitive and inductive, distributed all along its length. When lines are short, the capacitive effect is small and considered negligible. When a sending end voltage, $V_S$, is impressed and there is no load on that feeder, the receiving end voltage, $V_R$, equals the sending end voltage. However, as soon as load current, $I$, flows the line the current causes a reactance and a resistance drop which subtract from the sending end voltage, giving a resultant voltage on the receiving end smaller than the sending end voltage. As the load increases, the impedance drop increases and the receiving end voltage is even smaller.

$$Z = R + jx$$

$$V_S = V_R$$

$$V_S$$

$$I$$

$$I_R$$

$$I_X$$
LONG FEEDER

When a line is sufficiently long, the capacitive effect becomes appreciable. As the line is loaded, the load current adds vectorially with the charging current taken by the line, giving a resultant current which is smaller than, and ahead of, the actual load current. This resultant current causes an impedance drop and a low voltage condition results as before. However, under light load conditions where the actual load current is smaller than the charging current of the line, the vectorial addition of the two currents yields a resultant current which leads the sending end voltage. Leading current causes an impedance drop in such a way that the receiving end voltage is higher than the sending end voltage. This is a high voltage condition. A feeder of sufficient length can be subject to both high and low voltage conditions even though the loads on that feeder are lagging loads.

Since every component on the system is subject to regulation, the variation at the input terminals of the individual consumer is a vectorial summation of all of the variations that occur from generator to consumer.
REDUCE RESISTANCE OR REACTANCE

As a feeder is loaded, the load current causes an impedance drop which subtracts from the voltage impressed on the feeder, resulting in low voltage condition, VR, shown in the upper schematic. This is the voltage at the customer's terminals and is the voltage at which he is buying power. It is advantageous to minimize this voltage drop in the line so that the voltage at the load is rated or as near rated as possible.

The first method in minimizing voltage drop which logically comes to mind is a reduction in the series resistance on the line. A reduction in the resistance is accomplished by stringing larger conductor. A reduction in resistance (shown pictorially in the middle vector diagram) does not affect the reactance drop but diminishes the impedance drop. Consequently, the receiving end voltage is higher than it was. Hanging larger conductor means taking down the old conductor, stringing the new conductor, and the probable strengthening or replacement of poles and crossarms to carry the additional weight.

A similar correction can be obtained by reducing the series reactance of the line (shown pictorially in the lower vector diagram). A reduction in the reactance drop decreases the total impedance drop and increases the resultant voltage at the load center. The reactance of the line can be reduced by changing the configuration of the line, by going from overhead lines to underground cables, or by installing series capacitors in the line.

Changing the configuration of the line may not provide much gain because there are minimum clearances for each voltage level. Going from overhead lines to underground cables is very costly. The application of series capacitors to a line is somewhat difficult since it is not easy to determine the proper location on the system for the capacitors to do the most good. Also, they are somewhat difficult to properly insulate. They do have the advantage of holding the voltage up during motor starting, thereby reducing light flicker.
REDUCE CURRENT AND POWER FACTOR CORRECTION

A reduction in the current causes a subsequent reduction in both resistance and reactance line drops, thereby, increasing the receiving end voltage. The line current can be decreased by multiphasing singlephase circuits, changing delta feeders over to four-wire feeders, and by going to higher voltage levels. For a given amount of KVA, the current decreases proportionately with an increase in voltage.

A low voltage condition can be corrected by improving the power factor as shown in the lower vector diagram. Power factor is improved by adding shunt capacitors to the feeder. These capacitors supply a leading current, IC, which when added to the load current, I, yields a resultant current which is smaller in magnitude and ahead of the load current in phase relation. Shunt capacitors when properly applied release system peak capacity and yield linear voltage improvement at the same time.

In other words, the voltage rises from the operation of the capacitors linearly along the line in the same way that the voltage drops from the load currents flowing through the series impedance. To maintain rated voltage at all times, the amount of capacitance must be increased or decreased to follow the requirements of the load. Switching capacitors requires proper application of current or voltage relays and oil switches. If the capacitors are not switched off during periods of light load they may cause high voltage.
REGULATING EQUIPMENT

The last general method is the in-phase voltage control method. If the low voltage, $V_R$, is fed into a regulating device, it can be raised to whatever value desired. The top schematic shows a pictorial representation of a regulating device applied to the line and the vector diagram shows how this regulating device corrects the voltage, $V_R$, to the value $V^1_R$ shown equal to the sending voltage. Regulating devices are voltage sensitive and are usually automatically controlled and adjusted to maintain some constant output voltage. In this general classification of equipment are transformers with load-ratio-control, regulating transformers and feeder voltage regulators.

Voltage regulating devices work equally well on high voltage or on low voltage conditions. The device takes over the voltage and lowers it to the appropriate value. The application of the unit to the feeder is shown in the schematic and its operation is pictorially shown in the vector diagram.
COMPENSATION

Regulators are usually located remote from the load center. Even though the regulator automatically holds its output voltage constant at rated value, load current flowing through the line from the regulator to the load causes an additional drop in voltage. This drop is proportional to the load current. A voltage regulator can be made to correct for this drop in voltage between regulator and load center by the proper setting of the line drop compensator circuit.

The operation of the compensator can be seen a little easier by a slight rearrangement of the circuit. The control circuit is actually a miniature of the line itself. The control output voltage, $V_{OP}$, is proportional to and in phase with the regulator terminal voltage, $V_L$. The compensator current, $I_C$, is proportional to and in phase with the line current, $I_L$. When the voltage relay was adjusted, the voltage drop, due to the coil current's flowing through the compensator resistance and reactance, was balanced out. With no resistance or reactance turned in on the compensator, the regulator maintains an output voltage just equal to the control voltage.

By the addition of the proper amounts of compensator resistance and reactance, $R_C$ and $X_C$, the current, $I_C$, exactly duplicates the action of the line current $I_L$. With a properly adjusted compensator, the regulator raises its output voltage sufficiently to make up for the drop due to load. The load center voltage held is in phase and proportional to the control voltage or, in other words, a voltage is maintained at the customer's terminals equivalent to the value at which the control is balanced.
REGULATORS

All three-phase regulators are internally connected wye. A three-phase regulator gives only bus regulation. That is, all phases are regulated exactly the same.

Three-phase power can also be regulated using single-phase regulators. The big advantage in using single-phase regulators in such an application is that each phase is given individual attention.

Two single-phase regulators can be connected in an open delta bank to regulate three-phase three-wire feeders. With two regulators thus connected, two of the phases receive individual attention obtaining plus and minus 10% regulation. The third phase tends to read the average of the other two. The installation is shown here schematically.