



VOLTAGE REGULATION OF THE DISTRIBUTION GRID

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Voltage Regulation and Power Quality Track
Monday and Tuesday Sessions



SESSION 1 – Why there is a voltage drop and the apparatus that addresses it.

Disclaimers

- You get what you pay for (this is a free class)
- I am a salesperson, I am a member of the sales union, I am required to lie, I am required to lie at least 25% of the time, I am not required to tell you when I am lying
- No two utilities run their grid in exactly the same manner
- What might work for one utility may not work for another
- This tutorial is meant to make you think but not all of it will be useful for your application
- While I know Volt/Var and voltage regulation you have many experts at your company that know your system

Voltage and ANSI C84.1

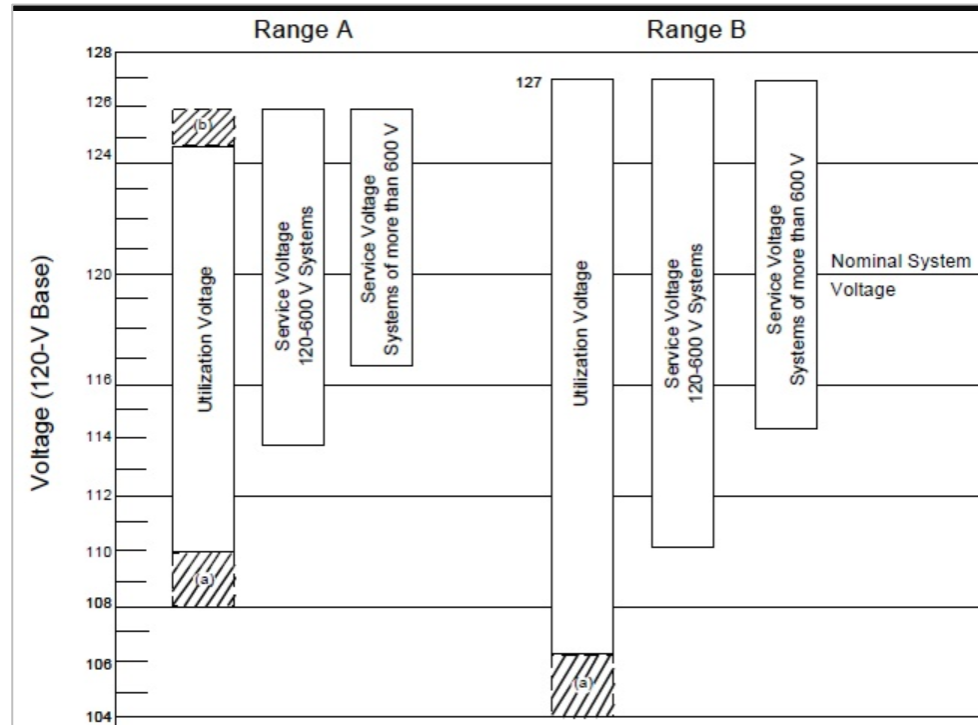
What about voltage?

1. Utilities are to keep the voltage of the entire distribution system +/- 5 percent of nominal (ANSI C84.1-1995).
2. If voltage is too high, damage can be done to appliances and lighting.
3. If voltage is too low, motors can stall or draw additional load. (90% nominal voltage increase motor load by 10-50%.)

Voltage and ANSI C84.1

What about voltage

1. ANSI C84.1 Defines the allowable acceptable voltages.
2. All voltages are specified at the point of the revenue meter.
3. Range A is for normal operate and Range B is for emergency conditions over short durations.



What about voltage?

1. Voltage magnitudes will decrease as the distance from the source increases due to impedance of circuits.
2. Customers closer to the source will have higher voltages than customer at the end of the line.
3. Equipment can be installed in the substation or on the feeder circuits to flatten this voltage profile.

What causes voltage drop?

1. Lower voltage distribution systems increase voltage drop (due to increased current for the same load).
2. Poor power factors increase voltage drop.
3. Unbalanced loading increases voltage drop.
4. Cable impedance, the smaller the cable the more voltage drop.
5. Length of circuit, the longer the circuit the more voltage drop.

Two Areas of Concern

1. Customers at the end of the circuit can have low voltages under heavy loads.
2. Customers at the beginning of the circuit (close to the substations) can have high voltages at low loads.

Three Types of Load

- **Constant Power** – The real and reactive power stay constant as the voltage changes. As voltage decreases, this load draws more current, which increases voltage drop. A constant power model is good for induction motors.
- **Constant Current** – The current stays the same as the voltage changes, and the power increases with voltage. As voltage decreases, the current draw stays the same, so the voltage drop does not change.
- **Constant Impedance** – The impedance is constant as the voltage changes, and the power increases as the square of the voltage. As voltage decreases, the current draw drops off linearly; so the voltage drop decreases. The constant impedance model is good for incandescent lights and other resistive loads.

Normally, circuits are modeled as something like 40%-60% constant power and 40%-60% constant impedance.

Impedance

1. As current flows through impedance losses are create in the form of heat and this causes a voltage drop.
2. There are two types of Impedance:
 - a. Real - Mainly from the cable and some customer loads.
 - b. Reactive – Mainly from transformers and customer motor loads and also some from the cable.

X/R Ratio

1. X/R ratio is the percentage of the total impedance that is reactive (X) versus resistive (R).
2. Most distribution feeders have X/R ratios between 2 – 6. This means reactive current causes 2-6 times more voltage drop than real current.
3. Most secondary networks have X/R ratios between 0.8 – 1.2. This means the voltage drop is about the same for real versus reactive current.

Voltage Drop

1. Voltage drop on the distribution system occurs in two places:
 - a. On the primary due to cable impedance.
 - b. On the secondary due to distribution transformers, cable impedance and customer load.
2. Most utilities allow for 2-3% voltage drop on the primary and 2-3 % voltage drop on the secondary for a total of 4-6% drop across the distribution grid.

Voltage Regulation

- Because the voltage drop is dynamic in nature the utility must have a means of dynamically controlling the voltage.
- The voltage on a distribution circuit is dynamic in nature due to:
 - Changes in load on the circuit.
 - Changes in the voltage level on the transmission grid which will be seen through the distribution substation.
 - Possible generation on the distribution system:
 - Larger generation connected directly to the distribution circuits on the primary.
 - Residential generation connected to the secondary.
 - Reconfiguring the distribution system due to switching or faults:
 - This causes a change in impedance and a change in load.

Static Regulating Devices

- There are two primary means to change the voltage on a static basis, one correcting voltage drop due resistive and reactive current flow and one to address only reactive current flow:
 - Fixed Tap transformers – Both substation and distribution transformers can be ordered with fixed taps:
 - Fixed taps typically provide 2.5% and 5% voltage boost or buck.
 - These taps can only be changed when the transformer is de-energized.
 - Fixed taps on the substation transformer will impact all customers below the transformer and will impact all three phases.
 - Fixed taps on the distribution transformer will only impact the customers being served off the transformer.
 - Fixed Capacitor Banks – Fixed capacitor banks will provide a voltage rise when Closed and a voltage drop when open.
 - To close a fixed capacitor a lineman must close in the fuses and open the bank a lineman must open the fuses.

Dynamic Regulating Devices

Types of Controlled Regulation

1. Inside the substation:
 1. LTCs.
 2. Bus Regulators.
 3. Feeder Regulators.
 4. Substation Capacitor Banks.
2. Outside the substation:
 1. Line regulators.
 2. Pole-top capacitor banks.
 3. Distribution STATCOMs.
 4. DER-Based Inverters.

Differences Between Regs and Caps

1. Regulators and LTCs are uni-directional devices. They impact the voltage on the load side of the device but have little impact on the source side of the device.
2. Capacitors are bi-direction in that they will impact both the upstream and downstream voltage.
3. Regulators are a series device and a voltage source.
4. Capacitors are a shunt device and an impedance-based current source.
5. Regulators impact the voltage the same amount no matter the location.
6. Capacitors impact on the voltage is made up of two components, the size of the bank and the amount of reactive impedance between the capacitor bank and the source. The more impedance, the greater the voltage change. Another way of stating this is the weaker the system the more voltage rise.

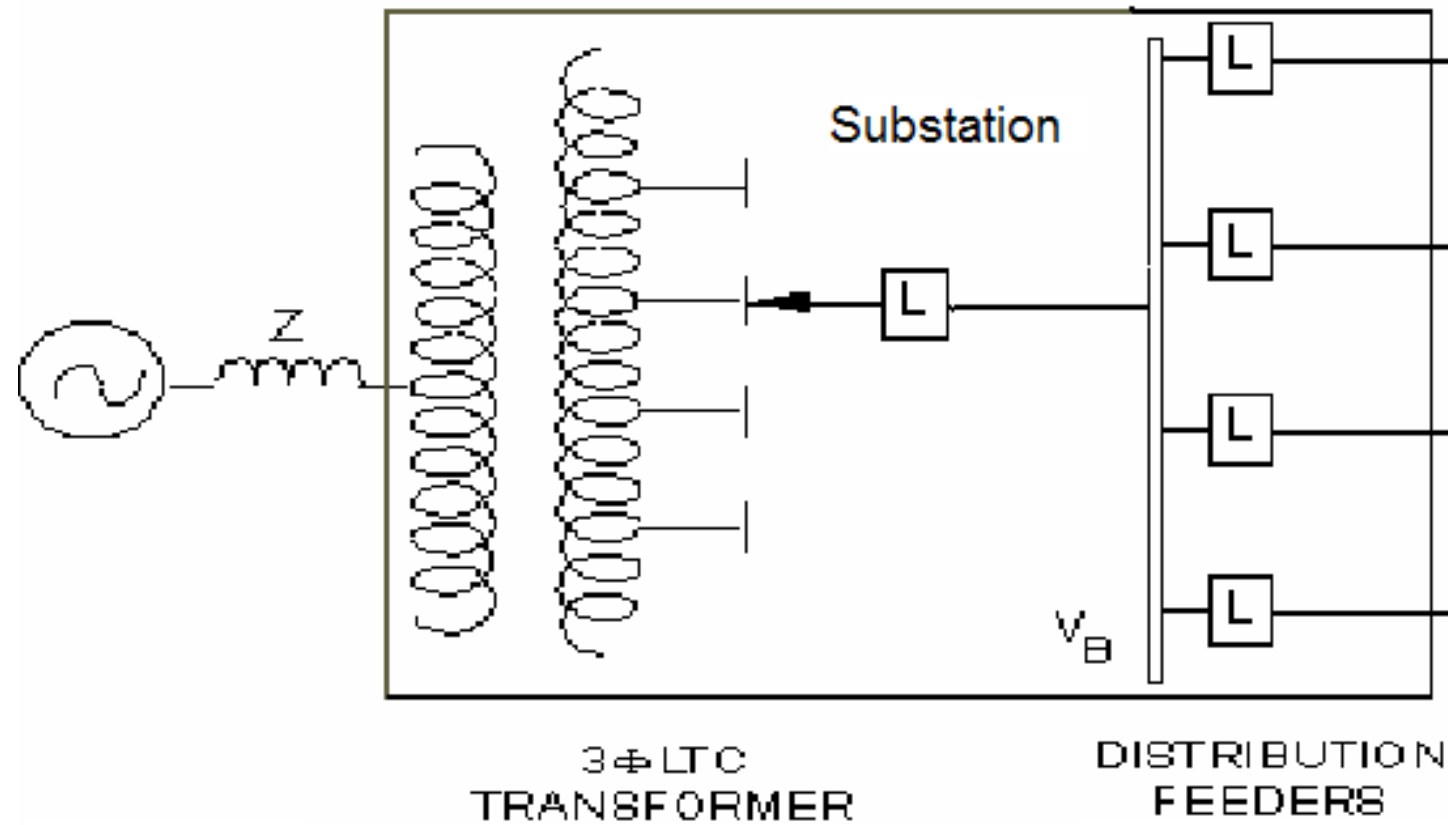
Load Tap Changers

LTCs

- Transformers with typically 33 taps that can be changed under load conditions.
- One neutral tap that does not impact the voltage.
- 16 lower taps that lowers the outgoing voltage.
- 16 raise taps that increases the outgoing voltage.
- Each tap typically increases/decreases the outgoing voltage by 0.75 volts on a 120 volt base.
- A controller typically is used to dynamically raise/lower taps as the voltage varies but the LTC can also be controlled remotely.

Load Tap Changers

Substation with LTC



Load Tap Changers

Advantages

- Cost effective for circuits with 3 or more feeders. A LTC for transformers within distribution substations typically costs 75 – 100 K depending on the size of the transformer (20.MVA – 60 MVA).
- Saves space which is important in areas where land is expensive.
- Applies changes on all three phases at the same time so it can't cause voltage imbalances.
- Requires only one controller.
- Can regulate voltages under higher load conditions.

Load Tap Changers

Disadvantages

- Monitors only one phase – This means that the load must be fairly balanced so the voltage drop is the same on each phase.
- Controls all three phases as one.
- Attempts to regulate all the load on the transformer which may have 2-8 circuits. This means the voltage drop across each circuit must be similar or other devices outside the substation must be used to make each have the same voltage drop.
- Failures affect all circuits attached to transformer.
- Harder to obtain flatter voltages as the zone of regulation is much larger.
- To perform maintenance the transformer must be taken out of service or have no regulation.

Load Tap Changers

LTC Compartment



Bus Regulation

- They come in two varieties: Three-Phase and Single Phase.
- Three phase regulators are typically the same as an LTC, only removing the LTC from the transformer.
- Single Phase Regulators are three separate regulators, one for each phase.

Bus Regulation – Three Phase

Three Phase Bus Regulators

Advantages:

- Can accommodate higher currents than single phase regulators.
- Have only one control.
- Can be maintained without taking the transformer out of service.
- Can't cause a voltage imbalance between phase.

Disadvantages:

- Require more real estate than LTCs.
- Requires loads to be balanced between phases.
- Failures impact all customers below the regulators.
- More expensive than an LTC.
- They sit in the bus differential zone so a failure can cause a fault that may be harder to detect.
- Still one larger regulating zone making VR and CVR harder.

Bus Regulation – Single Phase

Single Phase Bus Regulators

Advantages:

- Each phase is individually regulated so they can accommodate imbalanced loads.
- A fault only impacts a single phase.
- Makes the regulating zone slightly smaller.
- Less expensive than LTC or a Three Phase Regulator.
- Can be maintained without impacting the transformer.

Bus Regulation

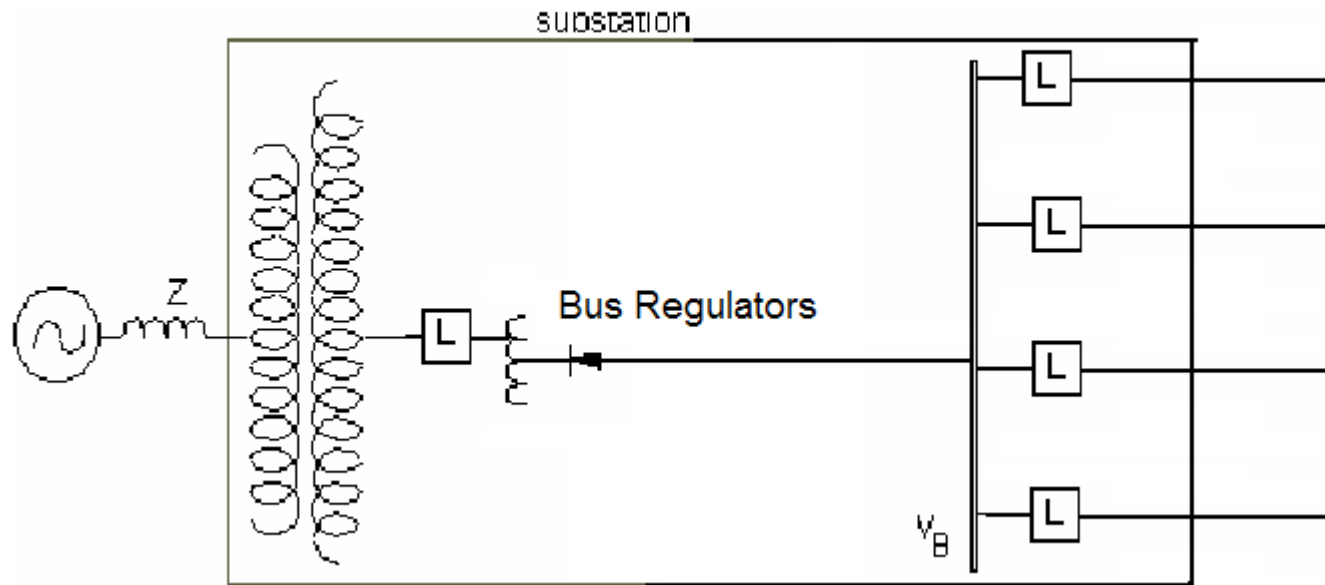
Single Phase Bus Regulators

Disadvantages:

- Require more real estate than LTCs.
- They sit in the bus differential zone so a failure can cause a fault that may be harder to detect.
- A failure of one phase can create voltage imbalances.
- Requires three controllers (although some newer controllers can support all three phases with one controller which can protect against the voltage imbalance issue).
- Limited to small transformers (typically 15 MVA and below).

Bus Regulation

Substation with Bus Regulators



Bus Regulation



Feeder Regulation

Feeder Regulation

- The first two options, LTC and Bus regulators, regulate the voltage on the substation low-side bus.
- With feeder regulators the substation bus is left unregulated and each feeder circuit is regulated independently before it leaves the substation.
- Three single phase regulators are required for each circuit.

Feeder Regulation

Advantages:

- Can accommodate unbalanced loads.
- A failure impacts the least amount of customers (one phase on one feeder).
- Can be maintained without impacting the transformer.
- Provides the smallest regulating zones from the source making it easier for VR and CVR applications.
- Can be the cheapest approach if there are only two feeders per transformer.

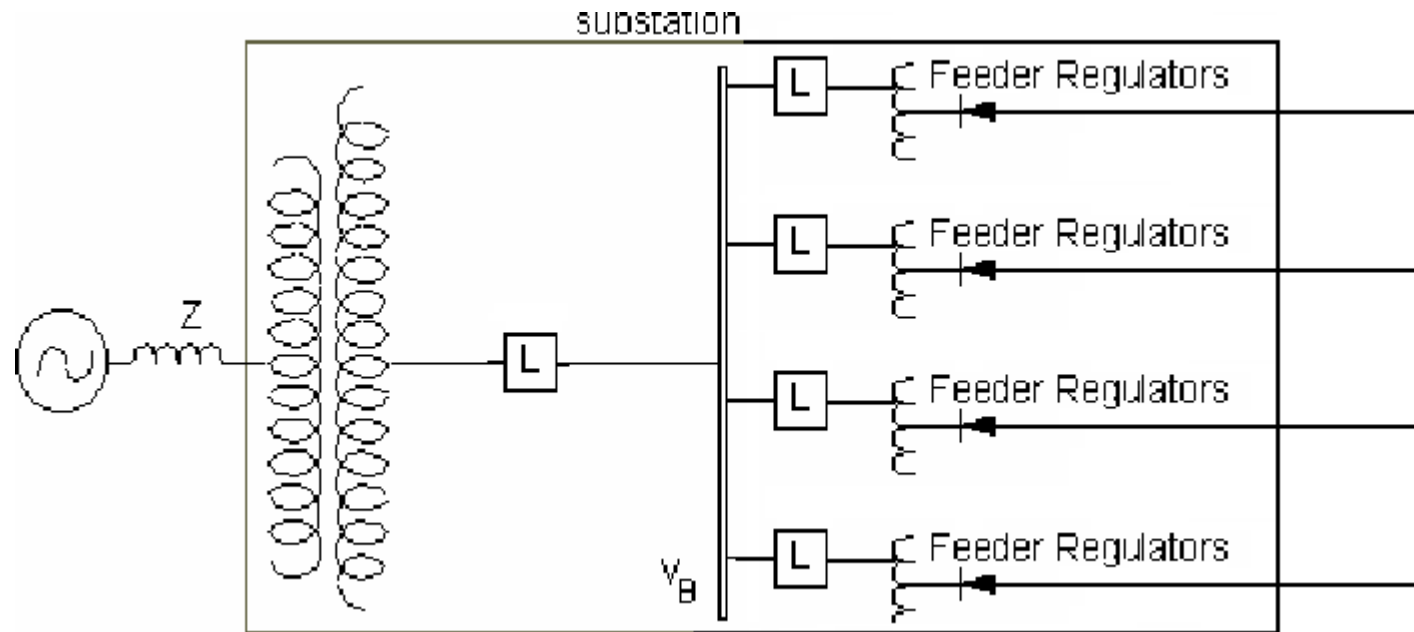
Feeder Regulation

Disadvantages:

- Requires the most real estate.
- Can be most expensive (the more feeders per transformer the more expensive this approach is).
- Requires a separate control for each phase of each feeder circuit (4 feeders would require 12 regulators and 12 controllers).
- Can create voltage imbalances with a failure on one phase.

Feeder Regulation

Substation with Feeder Regulators



Feeder Regulation



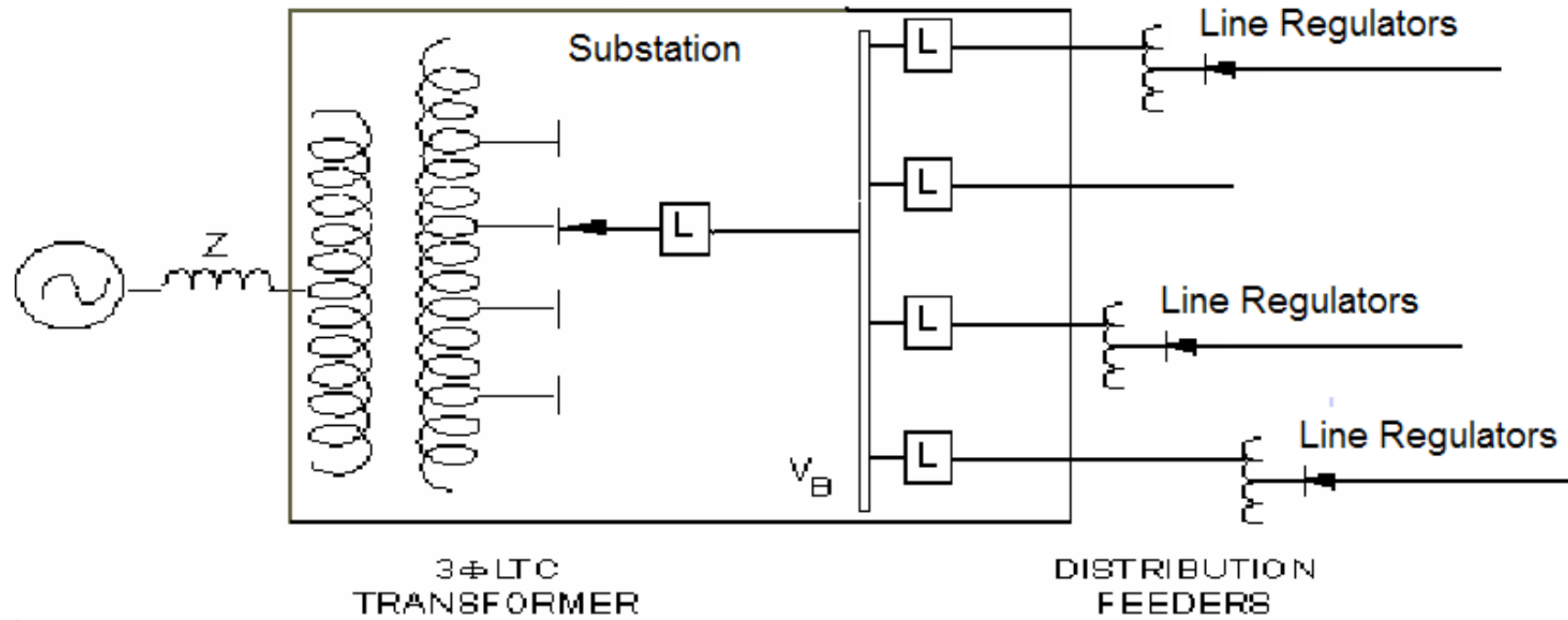
Line Regulation

Line Regulators

- The first three options, LTC, Bus regulators and feeder regulators are all located inside the distribution substation.
- These devices can only supply 10% boost/buck.
- On longer circuits the voltage drop may be greater than 12 volts so additional downline regulation is required.
- On LTCs, one feeder may have 3-4 volts more drop than the others. The LTC can only regulate the bus and can't tell that one feeder is running 4 volts lower than the bus. Again, downstream regulation maybe required.
- Feeder regulators are mounted on the feeder circuits outside of the substation.
- They are typically smaller and less expensive than feeder regulators as the load going through them will be less.
- A Single one can be deployed for long single-phase laterals.

Line Regulation

Sub with LTC and Feeder Regulators



Line Regulation



Substation Capacitor Banks

Substation Capacitor Banks

- Used to provide voltage support on the substation bus.
- Typically come in stages. Each stage can be open or closed.
- Can be used to cancel out the Vars required for the inductance of the substation transformers.
- Some utilities use them for power factor correction at substations that are penalized for power factor.
- If placed on a bus with an LTC, operating the substation capacitor bank typically adds 3-5 operations on the LTC.
- Can be controlled with a local controller or remotely via SCADA commands.

Photos of Substation Capacitor Banks

Open Air



Metal-Enclosed



Switched Capacitor Banks

Line Capacitor Banks

- Smaller than substation banks.
- Typical sizes are 300 KVar, 600 KVar, 1200 KVar and 1800 Kvar.
- Can be installed as Fixed or Switched.
- Are typically switched in and out with all three phases, not per phase.
- Can be polemounted or padmounted.

Fixed Capacitor Banks

Fixed Capacitor Banks

- Relatively inexpensive.
- Can be switched in and out only locally so while installed cost is low, running cost can be high.
- Typically placed on circuits requiring base KVar support. This should be KVar requirements at no to very low load conditions.
- Typically, no more than one fixed bank per circuit.

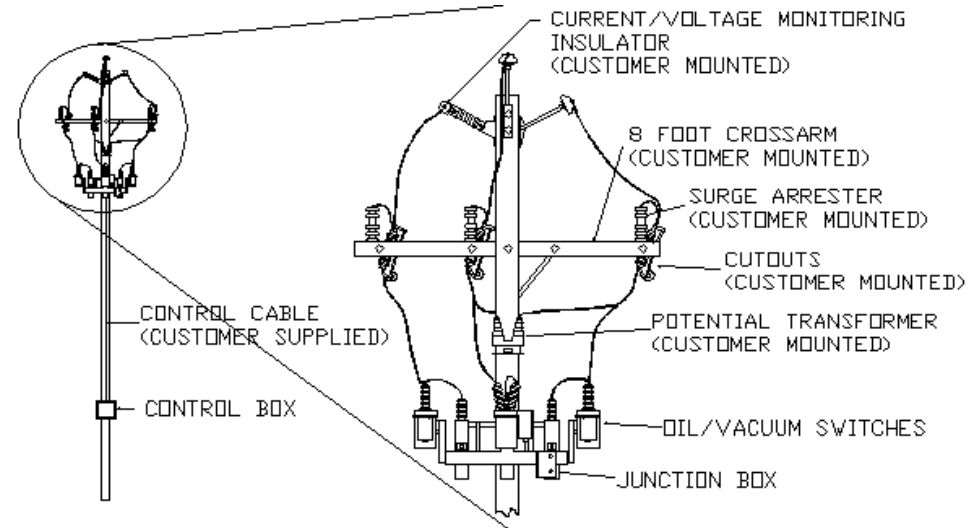
Switched Capacitor Banks

Switched Capacitor Banks

- Typically adds an additional 5-7K per site.
- Requires motor-operated or solenoid driven switches and some type of control along with a PT to power the switches and control.
- Capacitor Bank can be switched remotely via SCADA or locally via an intelligent control.
- Controllers can use as the sense:
 - Time of Day.
 - Temperature.
 - Voltage.
 - Current.
 - Vars.

Switched Capacitor Banks

Photo of Switched Cap Bank



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