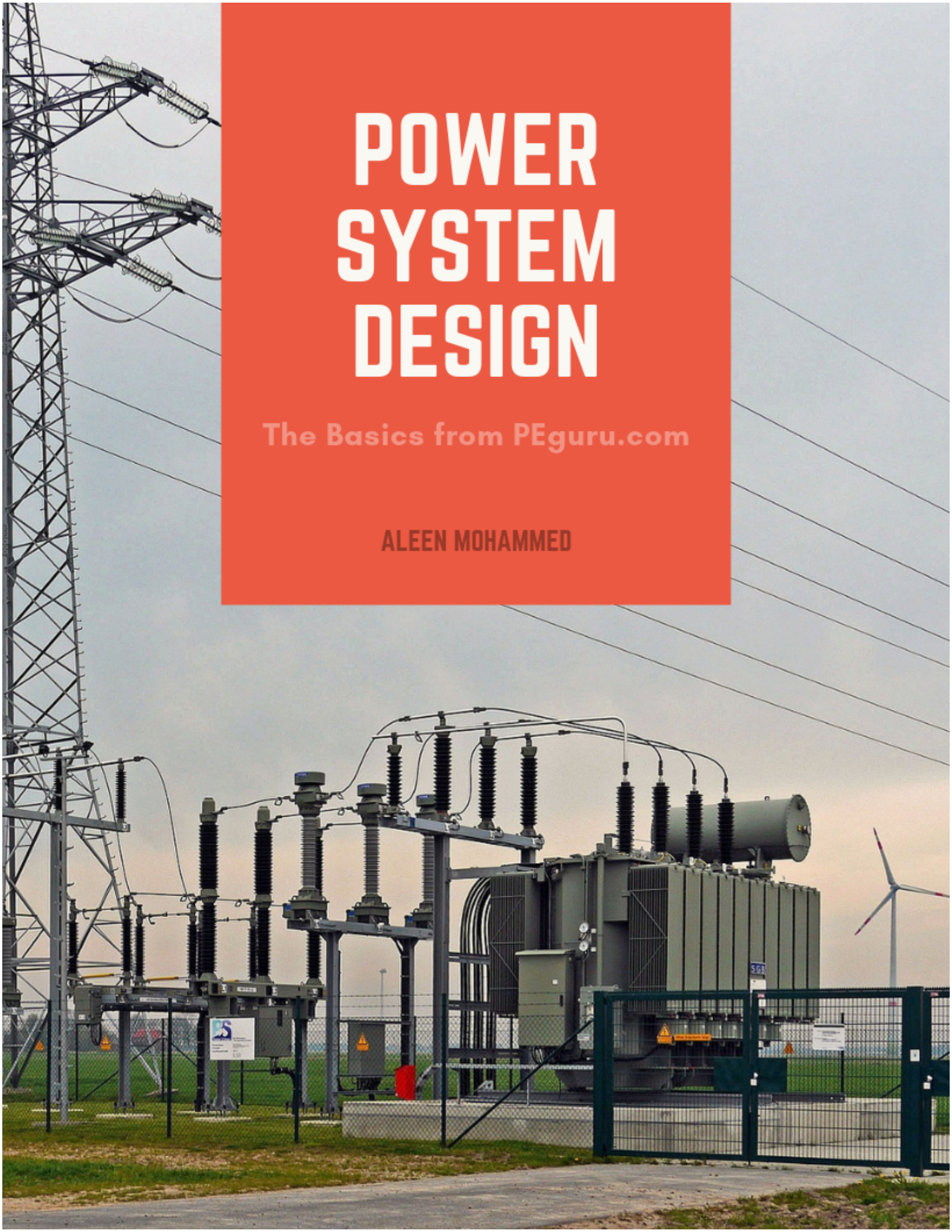
POWER SYSTEM DESIGN

The Basics from PEguru.com

ALEEN MOHAMMED



Why We Need Electrical Power Substations

We build substations for the following reasons:

Practical Considerations

To satisfy load growth

When people or businesses move to a new location that has little to no power supply infrastructure, it might make a case for building a substation close to the community. Supplying this new load from distant substations is inefficient because a little amount of power will be lost as heat on the distribution lines.

To accommodate new generation

Say you want to build a wind farm or a solar farm. You will need a collector substation to tie all the generators and connect them to the power grid.

To maintain reliability requirements

At times new transmission lines are constructed by developers or public utilities to address any deficiency in the reliability of the power grid. This deficiency occurs when you are operating the T-line at its thermal capacity. Therefore, when building new transmission lines, effort is made to connect it to an existing substation. When that is not possible, a new substation is built.

Technical Considerations

To step up or step-down AC voltage using transformer(s)

Remember higher voltages mean lower currents. Lower currents yield to lower I^2R (copper) losses. Thus, more energy can be delivered to do useful work. Voltages at the distribution end need to be stepped down for utilization by customers.

Substations provide the necessary real-estate to install a transformer for power transmission and distribution.

To break the power flow

Quite often a fault (such as a tree touching a live wire) requires complete isolation of the line until the fault is removed. Breaking the power flow by merely placing some switches on the line will not work. To safely interrupt thousands of amperes you will need circuit breakers that can handle such high current magnitudes. Almost all substations contain circuit breakers in some form that trip and isolate transmission lines connected to it.

Provide support to the power flow

Unlike DC power flow, AC power flow needs to overcome not only the resistive impedance but also the impedance offered by the inductive nature of various equipment (like motor loads, transmission lines, reactors etc.) connected to the system. For this reason, substations have capacitor banks connected to all the three phases of the lines to ease the power flow. Doing so also improves the power factor of the electrical system.

There are several other reasons for building a substation. However, the ones listed above are the important ones.

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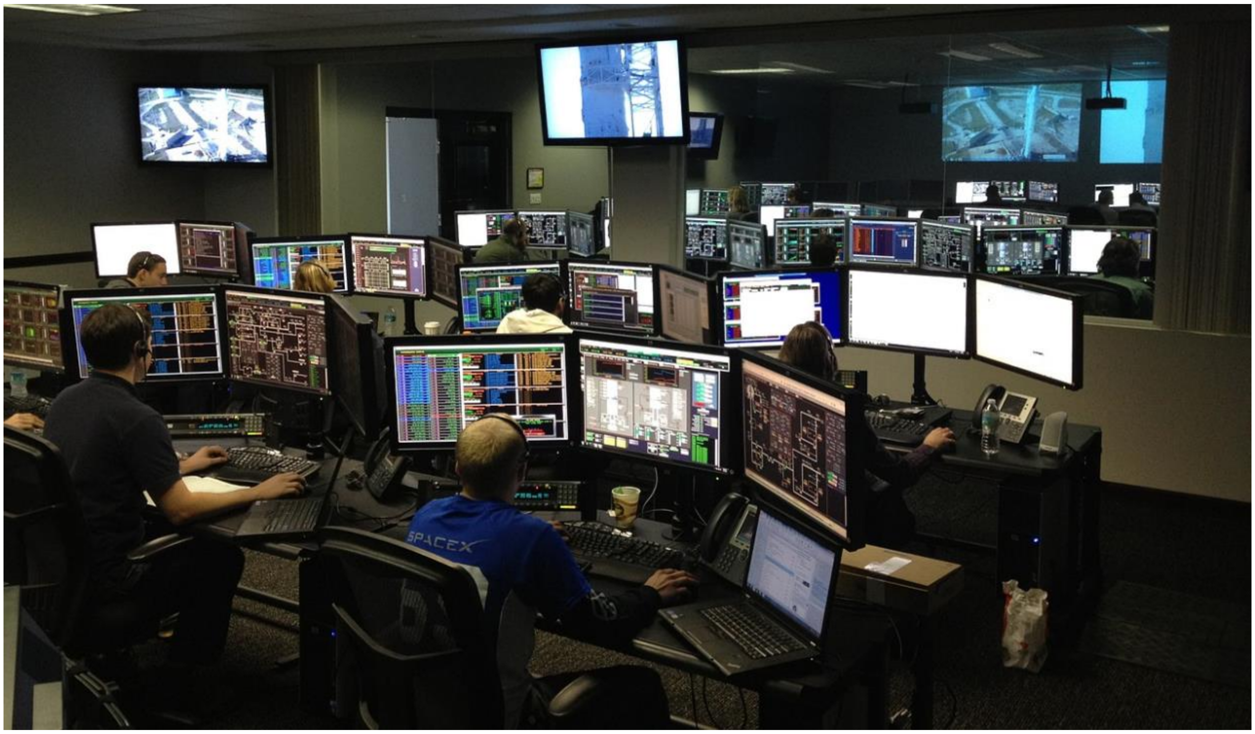
Who Controls the Power Grid in USA?



Have you wondered what goes on behind the scenes of electric power delivery in America? This post explains who is controlling the flow of power on the grid and who is policing to ensure the reliability requirements are met.

First a quick look of the power-grid

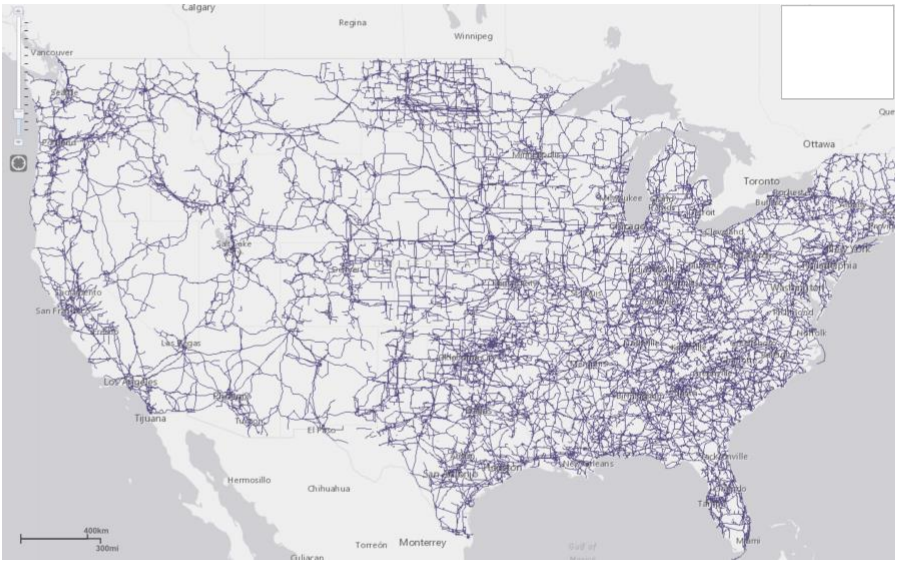


FIGURE 1: TRANSMISSION WIRES 138,000 VOLTS AND ABOVE

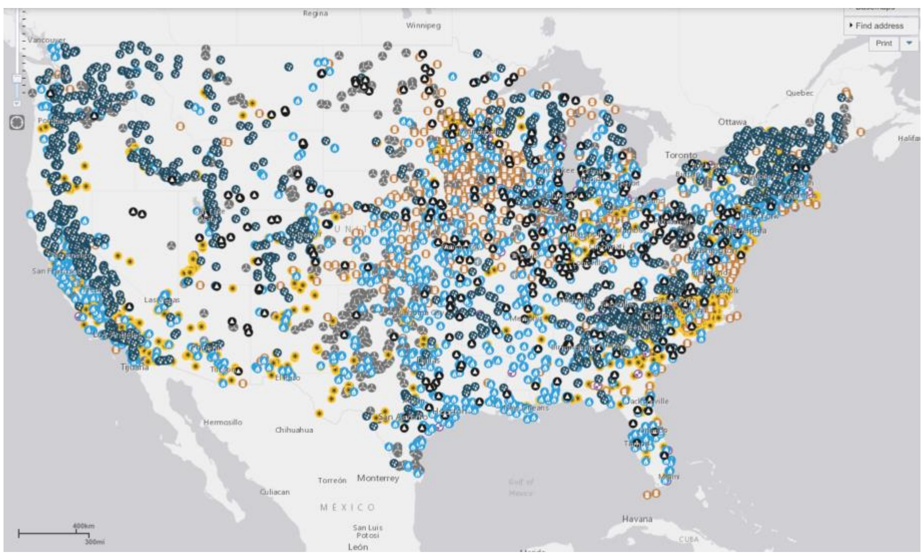


FIGURE 2: POWER GENERATORS (NON-RENEWABLE & RENEWABLE). Not all are directly tied to the HV t-lines.

So, who is dispatching the megawatts and megavars from generators that gets sucked up by reactive and active loads in the grid? Below maps shows the balancing authorities.

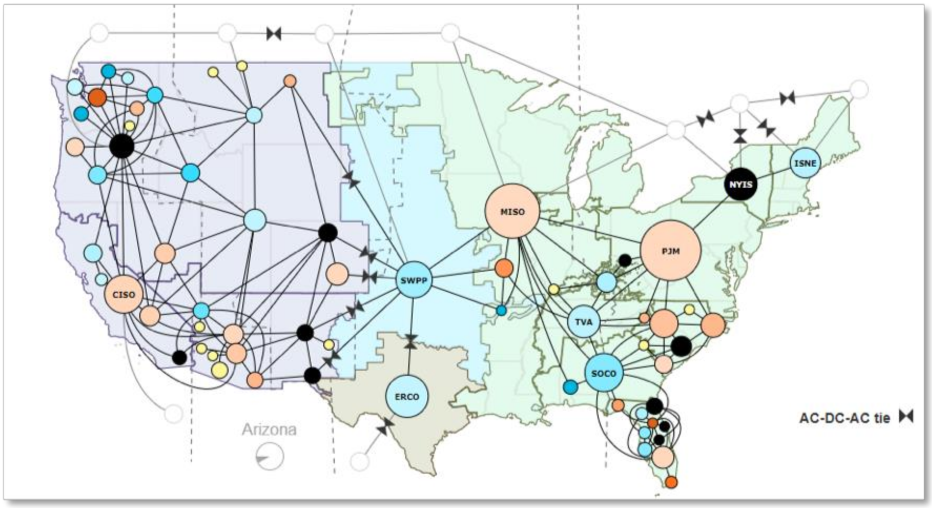


Figure 3: Organizations that take power from the generators in Figure 2 and transmit using wires shown in Figure 1 to distribution substations

Figure 3 illustrates the power grid operators. In most cases, the owners of generation and transmission facilities hand-over the controls to these operators. They do this to avoid monopoly by any one entity. Some of the big operators and the customers it serves are (as of June 2018):

PJM: 65 Million people
MISO: 42 Million people
CISO: 39 Million people
ERCOT: 24 Million people
SWPP: 18 Million people
Information on the remaining operators can be found here.

Who regulates the power grid for electric reliability in USA?

Federal Government Entities:
Federal Energy Regulatory Commission (FERC) imposes mandatory reliability standards on all generation and transmission owners that tie into power grid shown in Figure 1 above. FERC has authorized North American Electric Reliability Corporation to implement its standards.
North American Electric Reliability Corporation (NERC) delegates its authority to 8 regional reliability councils (as of June 2018). These councils are shown in Figure 4. These councils audit all participants (transmission owners, generation owners, and power grid operators) in their region to assure the standards are being followed.

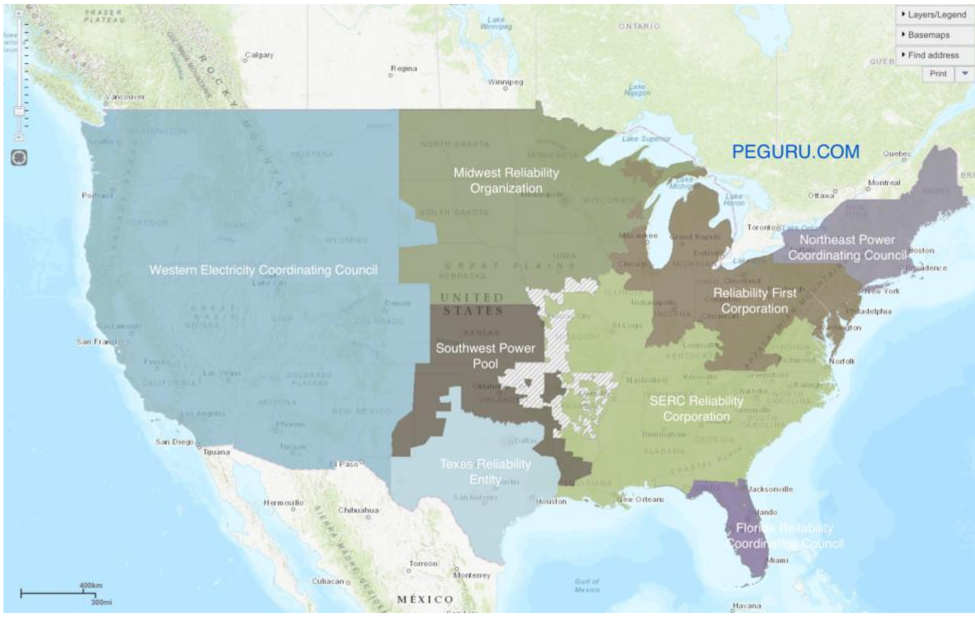


Figure 4: Reliability Councils Authorized by Federal Government to Maintain Electric Reliability of The Power Grid (As of June 2018)

State Government Entities:
Every state in USA has a commission that ensures the Owners are delivering safe and reliable electric power to its constituents. This oversight is in addition to the federal oversight.

You can view who the governing entities are for every state, here.
Unlike federal standards, the state standards tend to apply to the distribution system. However, some standards could apply to higher voltages. For instance, click here to view Washington state’s set of standards. The 480-100-373 rule mandates the voltage on the primary distribution feeder to *not* be more than 5% or less than 5% nominal voltage. Rule 480-100-368 mandates the power frequency to stay at 60HZ under normal conditions. Other states may list these technical specifications that may or may not be as conservative as Washington’s requirements.

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Power Circuit Breaker – Operation and Control Scheme

Understanding the breaker scheme is important if you plan on designing a substation. Quite often, it is overwhelming to make sense of the entire scheme at a glance. Therefore, the figure below depicting a circuit breaker scheme will be used to simplify and explain various elements of the breaker's design and its control.

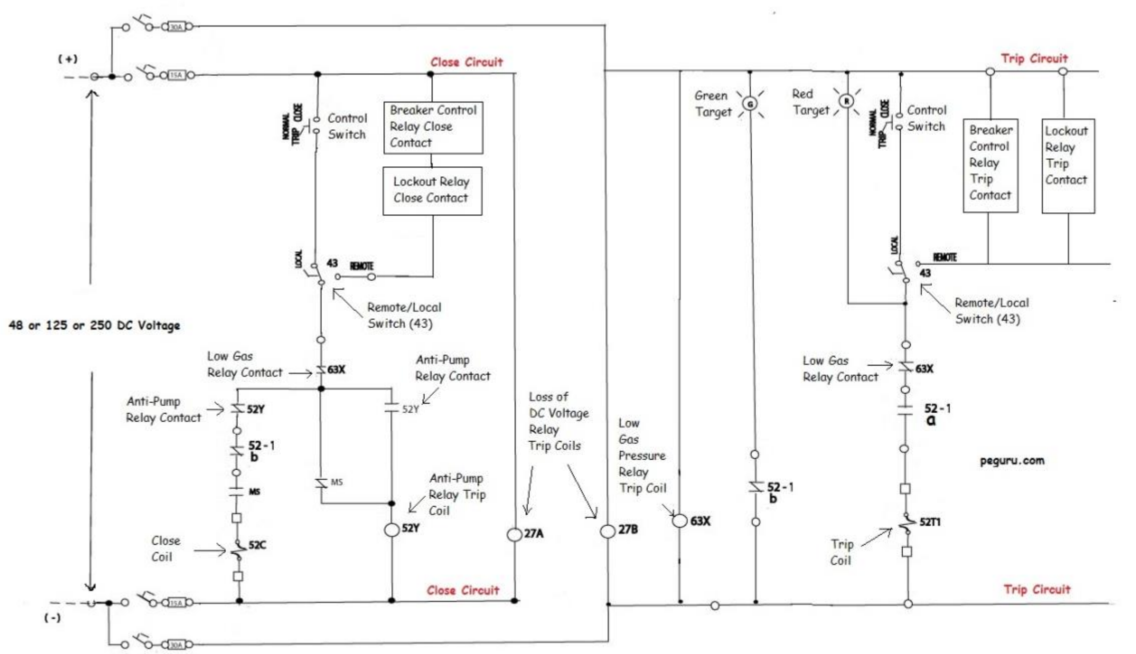

Figure 1: Close and Trip Circuit of a Breaker

Forms of Contact

Before explaining what each device in the scheme does, understanding the different forms of auxiliary contact is necessary. Every breaker comes fitted with an auxiliary switch. It is mechanically linked to the breaker's trip-close mechanism. Within the auxiliary you can have either form '**a**' contact (a.k.a. 52a per ANSI) or form '**b**' (a.k.a. 52b).

A form '**a**' contact represents a Normally Open (N.O.) contact. Thus, when the breaker is open, its 52a contacts are open. When the breaker is closed, the 52a contacts are closed. The 52a contact *follows the status of the breaker*.

A form '**b**' contact represents a Normally Closed (N.C.) contact. It operates *exactly opposite of what an 'a' does*. When the breaker is open, the 52b contacts are closed. When the breaker is closed, the 52b contacts are open.
Apart from breaker auxiliary switch contacts, you will see relays such as anti-pump relay 52Y, low gas relay 63X, under voltage relay 27 etc. in the breaker scheme. The contacts from each of these relays are interlocked with other relays (including 52a-52b) in such a way that they either permit or not permit the breaker operation.

Circuit Breaker Trip Scheme

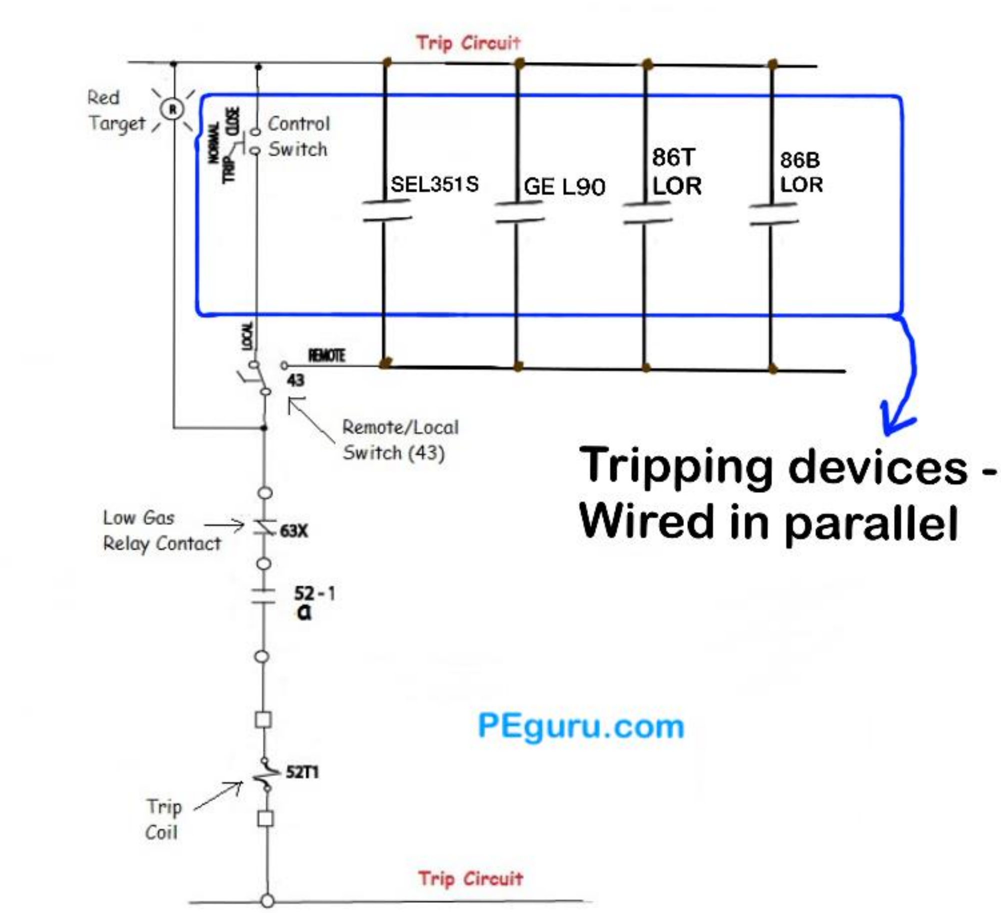

Figure 2: Trip Control Scheme

For the trip circuit you must wire the tripping relays' 'a' contact in parallel. See **Figure 2**. Therefore, when any one relay or switch contact closes, thus completing the circuit, the breaker trips. Only exception to the parallel wiring of contacts is the low-gas auxiliary relay contact (63X in the figure). This one is wired in series. Why?

Modern power circuit breakers employ Sulfur Hexa-Flouride (SF6) gas to extinguish an arc. Without adequate gas i.e. reduced interrupting capability, a flash-over can occur inside the tank. To prevent flash-overs due to low gas, breakers are fitted with ANSI ’63’ relay. Tripping of breaker is cut out by this relay’s contact.

Most modern circuit breakers are specified with two trip coils. Energizing either one trips the breaker. Since a good amount of redundancy is built into the protection and control of a power system, it is not uncommon to see all primary relaying in the system tripping trip coil 1 and the back-up tripping trip coil 2.

At this point, I hope the reader has grasped the strategy of series-parallel placement of relay contacts.

Let’s look at other relays and switches from the trip circuit of our breaker. The 27B under-voltage relay trip coil is connected across the same DC source as the one feeding the trip circuit. When this supply is interrupted, the 27B relay coil is de-energized, operating its contacts. In our breaker we are not blocking trip for this abnormal condition. It is typical in the industry to only annunciate locally and forward the alarm to a remote operator via SCADA. The breaker is also fitted with a 43 switch that toggles between local trip and remote trip. Positioning it in local allows the persons at the breaker junction box to trip the breaker by closing the Control Switch (CS). Switching it to remote position permits the relays in the control house to trip the breaker.

Target Devices

Target lamps are used in circuits to convey certain conditions. With the breaker closed and energized, the red lamp illuminates to indicate a live breaker. When the breaker opens the green lamp illuminates – the circuit complete with 52b contact switching from open to close.

Now, you may notice the red target lamp is connected in a way that will essentially short out the tripping relays and trip the breaker. Not surprisingly, this is not the case. The target lamps shown in the scheme have enough resistance in them (~200 ohms for a 125VDC circuit), limiting the current that can energize the coil.

Circuit Breaker Close Scheme

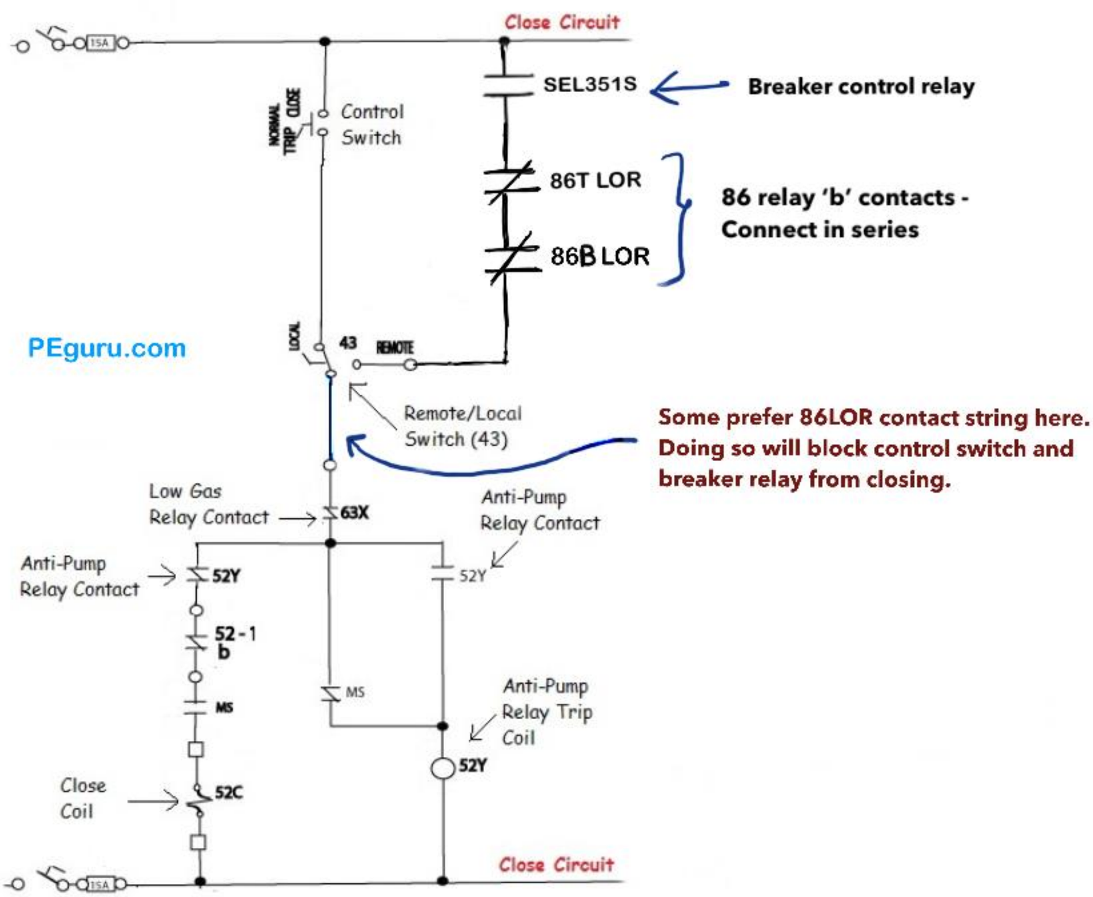

Figure 3: Close Control Scheme

For this circuit you must wire breaker control relay's 'a' contact in series with a string of 86 lockout relay 'b' contacts before you hit the anti-pump relay in the close circuit. Why? Well, would you want to close a breaker into a faulted circuit? See **figure 3**. In this example you have 86T (transformer LOR) and 86B (bus LOR) 'b' contacts in series with 'a' contact of SEL351S breaker control relay. Therefore, when either a transformer or a bus fault occurs, its corresponding LOR will block the SEL351S from completing the circuit.

Modern breaker control relays are programmed to check for synchronism. That is, before the breaker is closed, the relay checks the phase angle of source and load side voltage of any one phase. If the angles are out of sync, the relay logic will not allow its close control contact to operate.

The close circuit also has contacts from the Motor Switch (MS). The motor is used to charge the spring that trips-closes. The motor switch contacts don't allow the breaker to close until it finishes it job.

Anti-Pump Relays

To prevent inadvertent multiple closing operation, breakers are fitted with anti-pump relay (52Y ANSI designation). Assume a scenario where a fault persists on a line and a person is attempting to close a breaker on it. Although the person presses the close button for a second or two, for the breaker which operates in cycles, this duration is an eternity. With the close button pressed, the breaker attempts to open and close multiple times. Since the motor in the breaker is not rated for continuous duty, serious damage can occur.

On a final note, keep in mind that not all relays back in the control building can handle the momentary inrush current from the breaker. Case-in-point the SCADA control relays. Interposing relays like those manufactured by Potter-Brumfield are typically installed to act as the middle-man. So in our case the SCADA relay trips an interposing relay and this relay trips the breaker.

Most modern microprocessor relays especially ones made by Schweitzer can handle inrush currents upto 30Amps and thus can be wired directly to the breaker coils.

Summary

- Breaker scheme is a web of interlocked relays and switches.
- Breaker operation is controlled by relays and switches.
- Trip contacts are wired in parallel.
- Close contacts are wired in series i.e. breaker control relay 'a' contact followed by a series of LOR 'b' contacts.

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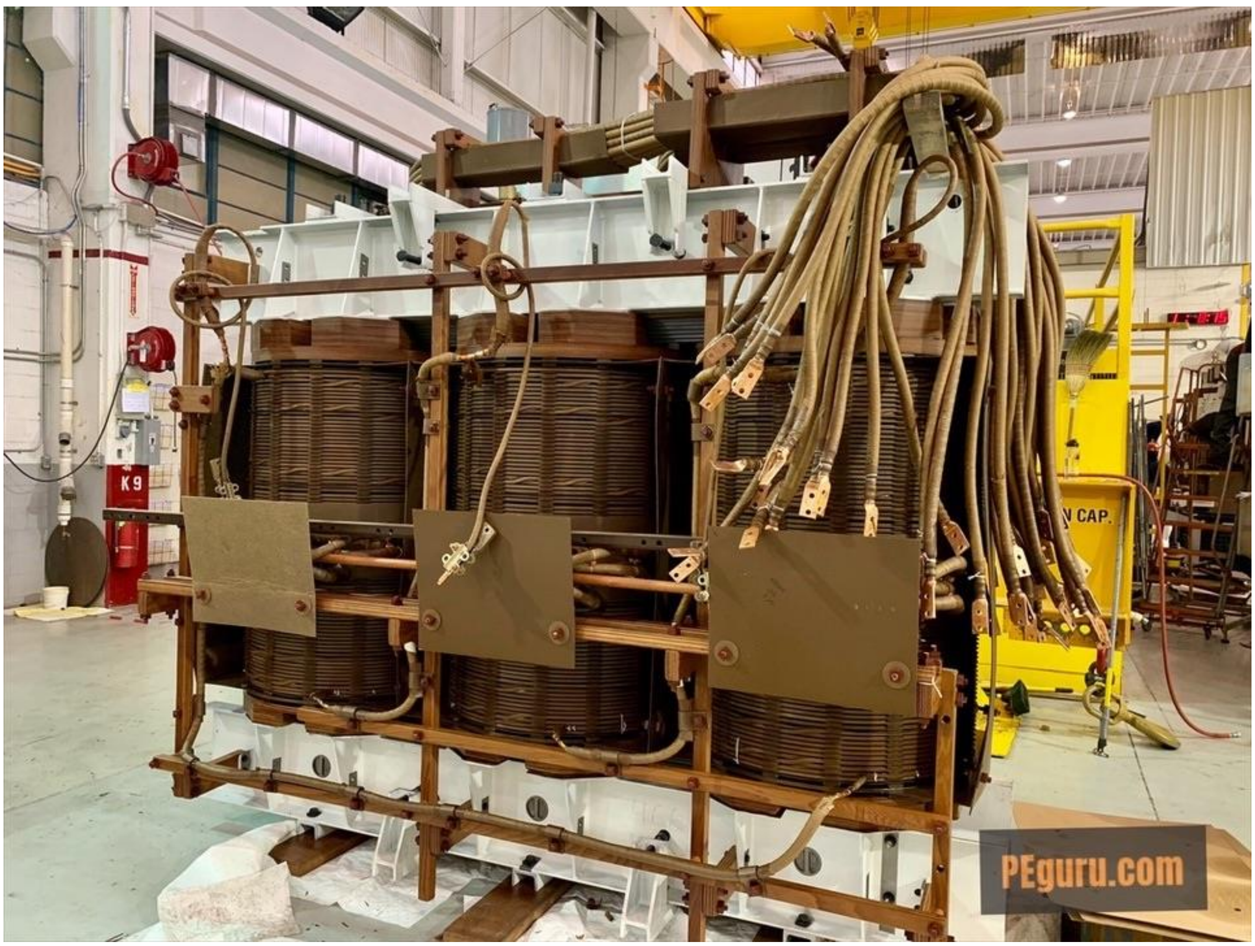
Power Transformers – Design and Application

Power transformers are widely used in a power system to transform voltage. The most common type, a two-winding transformer, has one winding connected to a high voltage – low current circuit while the other winding is connected to a low voltage – high current circuit.

Transformers rely on Faraday's induction principle and ampere-turns to induce voltage from primary winding to the secondary.



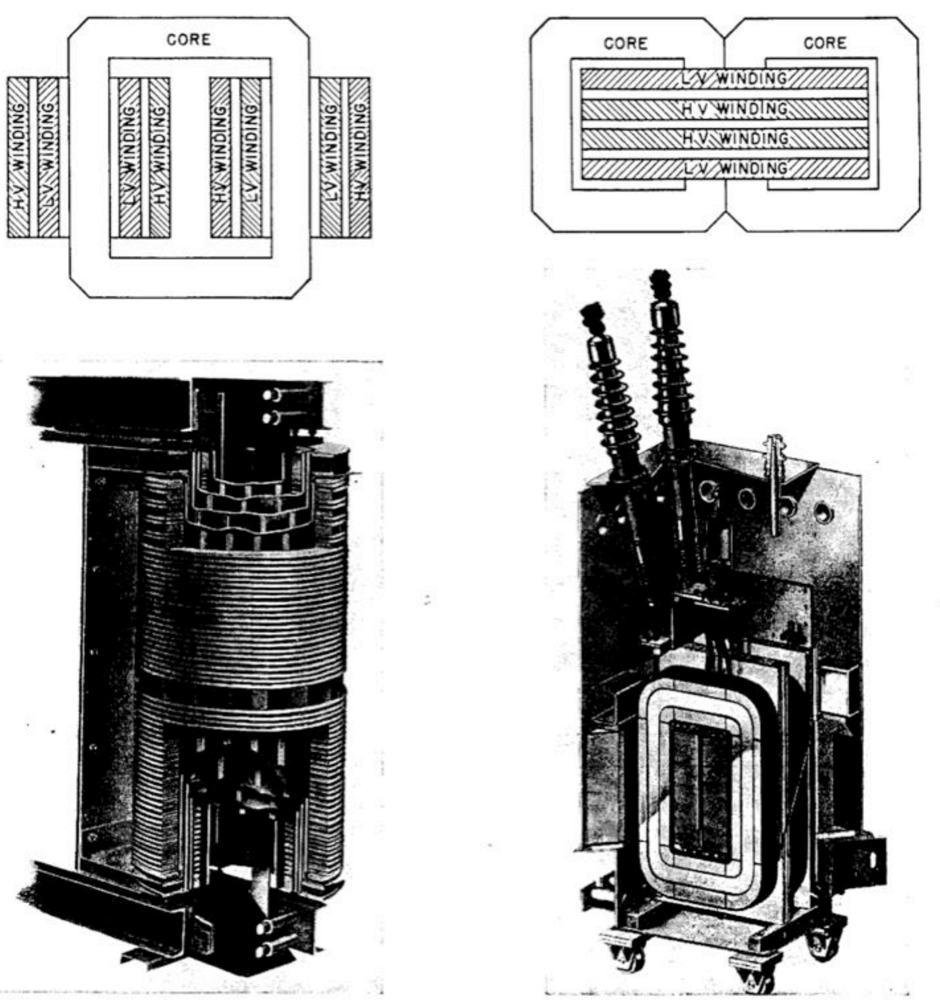
Fully assembled transformer, ready to go in the tank

Top clamps that holds the windings in place

Low voltage winding on laminated sheets of core metal

Transformer Design

The transformer's core is made of laminated sheets of metal. It is constructed either as a shell type or a core type. See figure 1. With the ubiquitous application of three phase power, these cores are then wound and connected using conductors to form three 1-phase or one 3-phase transformer. Three 1-phase transformers have each bank isolated from the other and thereby offer continuity of service when one bank fails. A single 3-phase transformer, whether core or shell type, will not operate even with one bank out of service. This 3-phase transformer however is cheaper to manufacture, has a smaller footprint, and operates relatively with higher efficiency.



Core-form construction.   Shell-form construction.

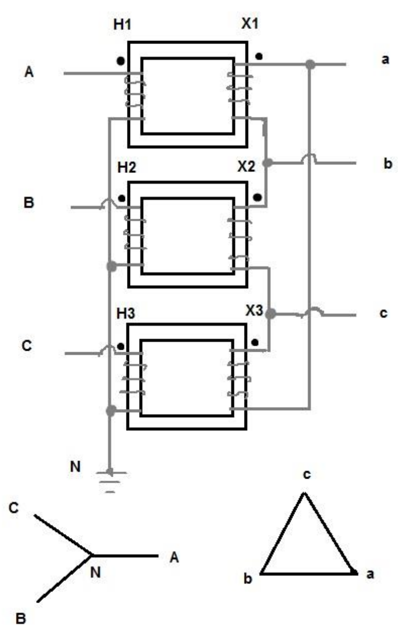
Figure 1: Forms of Construction. Image Courtesy – Electric T&D Reference Book by Westinghouse Engineers.

The transformer's core with its windings is immersed in a fire-retardant insulating oil inside a tank. The conservator on top of the tank allows for the expanding oil to spill into it. The load tap changer on the side of the tank changes the number of turns on the high voltage-low current winding for better voltage regulation. The bushings on top of the tank allow for conductors to safely enter and exit the tank without energizing the outer shell.

The transformers power capability is limited by thermal rating. This means the transformer can be operated beyond its MVA rating as long as the temperature of its top oil stays within the 65ºC temperature rise above ambient temperature (See IEEE C57.91-1995 standard). For instance, if the ambient temperature is 45ºC then the transformer can be pushed to a value less than 45ºC + 65ºC = 110ºC. Since temperature is usually the limitation, the radiators on the transformer are fitted with fans so they can force cool the oil flowing through the radiator fins. Prolonged overloading of the transformer is not recommended on account of saturating its core (higher losses), loss of life expectancy, and deterioration of winding insulation.

Transformer Winding Connection

In a three-phase core type transformer, for each phase, the primary winding and the secondary winding are wound on the same leg. The windings are ofcourse insulated from each other. The low voltage secondary winding is typically on the inside while the high voltage winding is on the outside. This is done to minimize the leakage flux during the whole induction process.



Star-Delta Transformer Connection

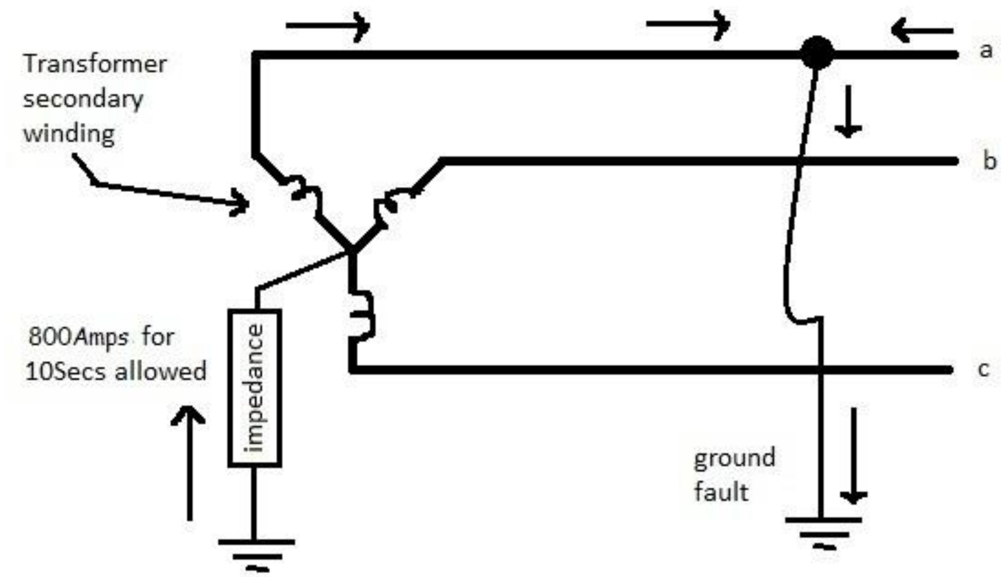
To enable the conduction of currents, the windings are wound and connected either as a delta or a star. These shapes form as a result of the way the three conductors inside the transformer get connected. See figure 2. The use of these connections delta-star, star-delta, star-star, or delta-delta make a huge impact on the design of power system. So, the choice of connection is critical.

How Transformer Grounding Affects Power System Design

Without going into a lot of detail, for cost savings and safety, the star connection is the preferred connection for high voltage transmission. In this scenario, the common point in the star, also called the neutral, is grounded or earthed. Doing this causes the phase to neutral voltage or phase to earth voltage to be reduced by a factor of $1/(\sqrt{3})$. You will not get this reduction with a delta or any ungrounded connection.

It only makes sense to use a delta-star transformer near the generating station where the delta is connected to the generator terminals and the star is connected to the high voltage transmission lines. With grounded star connection on the high voltage side, the transformer winding can be insulated for lower voltages. The transmission system too will have a lower insulation requirement. These provide for huge cost savings in the design and construction of a high voltage power system.

There is, however, a disadvantage in grounding the transformer. When one of the lines or all three lines on the star side gets short-circuited to the ground, the grounded neutral in the transformer serves as a return path for the current. These currents are pretty high in magnitude and if not cleared in fractions of a second, it can severely damage the transformer and all the equipment connected to it. These ground fault currents are also rich in third harmonic currents. Third harmonics disrupt telecommunication network which, by the way, is used to implement pilot relaying in a power system.



Ground Fault Current Path

But all is not lost with grounding the transformer. The delta connection on the primary winding helps here. It offers high impedance to third harmonics and traps the ground fault current in the delta thereby isolating the ground faults to the secondary system.

Now, you would think the delta-star configuration of the transformer is pretty awesome and that it is installed everywhere in the system. However, it is not. To retain the advantage of a star connected system, few bulk power stations have a star-star connected three winding transformers, the third winding being a delta tertiary. With this three-winding transformer, the primary star connection keeps the primary system solidly grounded while the grounded secondary star connection extends the cost savings into the secondary system.

Delta Tertiary and Its Application

A star-star connected transformer is rarely applied in the power system. It is susceptible to third harmonics and voltage transients when left ungrounded. However, to incorporate the design advantage of a star winding and those of delta winding, a third winding – a delta tertiary is built into the two-winding star-star transformer. The delta in a star-star-delta transformer not only traps ground fault currents and offers high impedance to third harmonics, it also allows for connecting a:

- Capacitor bank – for voltage or power factor correction
- Reactors – for limiting ground fault currents (resonant grounding)
- Resistors – for limiting ground fault currents
- Station service transformer – AC power for equipment inside the substation

On a final note, transformers should be specified with the following information among others for proper selection or analysis:

- Size of transformer in MVA (nominal and full load)
- Primary and secondary voltage. If supplied by load tap changer, then available voltage taps
- Primary and secondary winding connection
- Per unit impedance (%Z)

Summary

- Delta-star transformers: Useful at generation and load centers.
- Star-star-delta transformers: Useful at transmission substations (765kV, 500kV, 345kV).
- Grounding the neutral provides higher ground fault currents however the cost savings realized by lower insulation requirements makes grounding viable.

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