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# Design Principles for AC Station Service Connections in EHV Substations

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## SUMMARY

Design of AC station service connections to supply 120V/240V for EHV substations presents several challenges unique to stations at EHV such as: excessive fault current magnitudes, requirement for source and equipment redundancy owing to reliability considerations, vector diagrams for transformer connections, necessity for a ground reference on ungrounded bus for fault selectivity and increased voltage drops in LV cables due to large size of the station yards. This paper presents the design principles and necessary calculations to overcome above-mentioned challenges, and addresses several key components for station service design in general. Based on lessons learned in AEP's footprint, a description of some utility best practices that can be incorporated as standard design procedures is presented at the end.

## KEYWORDS

Station Service, Transformer Vector Diagrams, Grounding Transformer, Current Limiting Reactor, Voltage Drop

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## SOURCES OF STATION SERVICE POWER

There are three common primary sources of three-phase station service power for an EHV substation:

1. Autotransformer Tertiary
2. Transmission Bus
3. Distribution Line

This paper focuses on the design principles for station service from the tertiary of the autotransformer bank in a 765 kV station.

### Autotransformer Tertiary

All of the 765 kV transformers used in AEP's footprint are single-phase 765 kV/ 345 kV units that contain a tertiary winding, either at 34.5 kV or 13.8 kV. These tertiary windings are isolated from the ground and hence do not have a ground reference. Three such windings from a bank of three autotransformers are connected in Delta configuration to form a three-phase ungrounded source for station service power. A switchable spare is often included, with bus work designed to connect to any of the available three phases, essentially giving the ability to replace any of the three units [1].

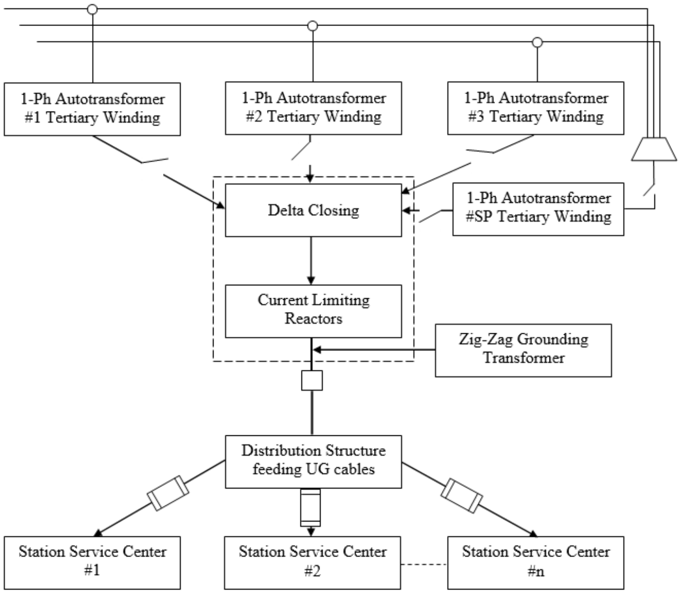


Fig. 1. Station Service Block Diagram with Autotransformer Tertiary + Grounding Transformer

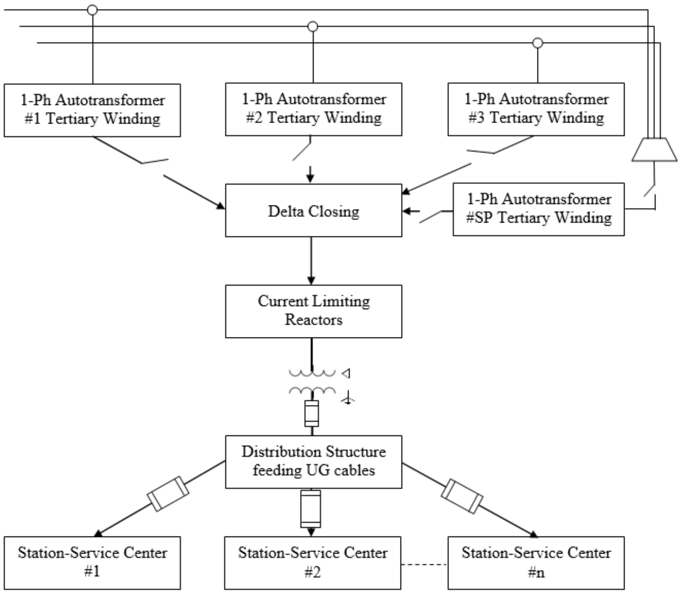


Fig. 2. Station Service Block Diagram with Autotransformer Tertiary + 2-winding D-Y Transformer

## ZIG-ZAG GROUNDING (or) D-Y TRANSFORMER

The station service load in a 765 kV station with autotransformers is large enough to warrant the use of multiple station service transformer banks with close proximity to auxiliary loads to mitigate voltage drop concerns [Fig. 6.]. As can be seen from Fig. 1 or Fig. 2, after closing the delta with tertiary windings of the three autotransformers, underground cables are utilized to connect to respective station service transformer banks where the tertiary voltage (34.5kV or 13.8 kV) is stepped down to utilization level (120V/240V).

Since the source is ungrounded, a ground reference must be provided on the bus to selectively isolate faulted circuits/ cables. This is achieved through a Grounding or Delta-Y (D-Y) transformer.

**Zig-Zag Grounding Transformer [Fig. 1.]:**
There are two scenarios for faults: Fault downstream of the circuit breaker and fault upstream of the circuit breaker.

For a fault (say single L-G) downstream of circuit breaker in one of the UG cables, presence of a zig-zag grounding transformer helps reduce the zero sequence impedance to a low value, driving fault current through the corresponding cable. The fuses in each branch circuit are sized to coordinate with the breaker and operate to isolate the faulted circuit, leaving other circuits in service. In essence, presence of a grounding transformer helps achieve fault selectivity. For a fault on the distribution structure bus work, the same principle applies. This time, the circuit breaker operates to isolate the faulted distribution bus from the delta source. Thus, the EHV bank need not be taken out of service for a fault on the distribution bus.

For a fault on the delta closing structure, the grounding transformer drives fault current through the transformer windings, where it is picked up by transformer protection scheme, taking the EHV bank out of service.

**D-Y Transformer [Fig. 2.]:**
The D-Y transformer essentially converts an ungrounded system on the high side to a solidly grounded system on the low side (34.5 kV/12.47 kV or 13.8 kV/12.47 kV). There are two scenarios for faults: Fault downstream of the D-Y Transformer and fault upstream of the D-Y Transformer.

For a fault (say single L-G) downstream of D-Y transformer in one of the UG cables, fuses in each branch circuit are sized to coordinate with the main fuse (or circuit breaker) upstream and help isolate the faulted circuit, leaving other circuits in service. As in the case of the grounding transformer, presence of a D-Y transformer helps achieve fault selectivity. For a fault on the distribution structure bus work, the same principle applies. This time, the main fuse (or circuit breaker) operates to isolate the faulted distribution bus from the delta source. Thus, EHV bank need not be tripped for a fault on distribution bus.

For an accidental ground on the delta closing structure (single L-G), there is no fault current unless there is a second accidental ground, since the source is ungrounded. In this case, the protection system may be designed to send an alarm based on 3E0 scheme and ultimately trip out the EHV bank after specified time or trip the EHV bank within a few seconds.

**Grounding Transformer Sizing:**
The selected zero sequence impedance of the grounding transformer shall bring line-to-ground fault current at the location of the transformer to a desired value. On one hand, sufficient line-to-ground fault current would be required for proper relay coordination. On the other hand, line-to-ground fault current should not exceed equipment withstand capability. The short time neutral current rating shall be equal to the line-to-ground fault current at that location. To account for failure of primary relay protection scheme, duration of fault current for short time neutral current rating shall be 4 seconds. Nominal voltage of grounding transformer shall be equal to system nominal voltage at that location.

## CURRENT LIMITING REACTORS

Due to high magnitude of fault current on the tertiary of the autotransformer, it is recommended to use current limiting reactors to reduce fault current level to less than 10 kA to enable use of commonly used distribution structure and bus work, fuse cut-outs and UG cables. The reactance of current limiting reactors and zero sequence impedance of the grounding transformer shall be selected such that there is at least an order of magnitude difference between load current and fault current magnitudes in all possible cases.

**Required Data for Calculating Reactance:**
Three-phase symmetrical fault current magnitude on tertiary bus (without reactors) ($I_{f1}$): From network modelling software (Eg: ASPEN)
Maximum allowable three-phase symmetrical fault current magnitude (with reactors) ($I_{f2}$)
Pre-fault L-N voltage level of the tertiary bus (V)

Let $X_1$ be the positive sequence impedance at the fault location in the absence of reactors.
Then, fault current is $I_{f1} = V/jX_1$

Let $X_2$ be the positive sequence impedance at the fault location in the presence of reactors.
Then, fault current is $I_{f2} = V/jX_2$

$I_{f1} / I_{f2} = X_2 / X_1 \Rightarrow X_2 = X_1 * (I_{f1} / I_{f2})$

But, $X_2 = X_1 + X_r$

$X_r = X_1 * (I_{f1} / I_{f2}) - X_1$
$X_r = X_1 * [(I_{f1} / I_{f2}) - 1]$

$X_1 = V / I_{f1}$
$\Rightarrow \mathbf{X_r = V * [(1/I_{f2}) - (1/I_{f1})]}$

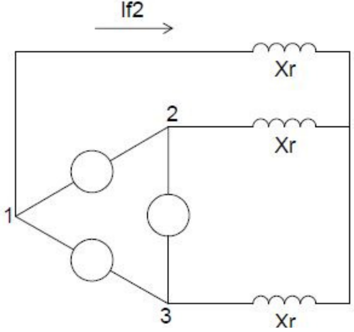


Fig. 3a. Three phase symmetrical fault on the tertiary
(Reactors outside Delta)

Another possible configuration is to have the reactors inside the delta [Fig. 3b.]. Calculation for reactance to limit the fault current to the same magnitude $I_{f2}$ is given below.

$Iph_{12} = (V_{LL}/jX_3) \angle 0°$
$Iph_{23} = (V_{LL}/jX_3) \angle -120°$

$I_{f3} = [(V_{LL}/jX_3) \angle 0°] - [(V_{LL}/jX_3) \angle -120°]$
$\Rightarrow I_{f3} = \sqrt{3} * (V_{LL}/jX_3) \angle 30°$

For the same magnitude of fault current,
$|I_{f3}| = |I_{f2}|$

$V_{LL} / (\sqrt{3} * X_2) = \sqrt{3} * (V_{LL}/X_3)$
$\Rightarrow \mathbf{X_3 = X_2 * 3}$

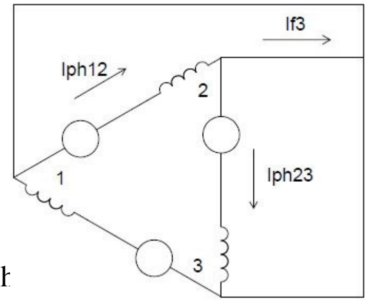


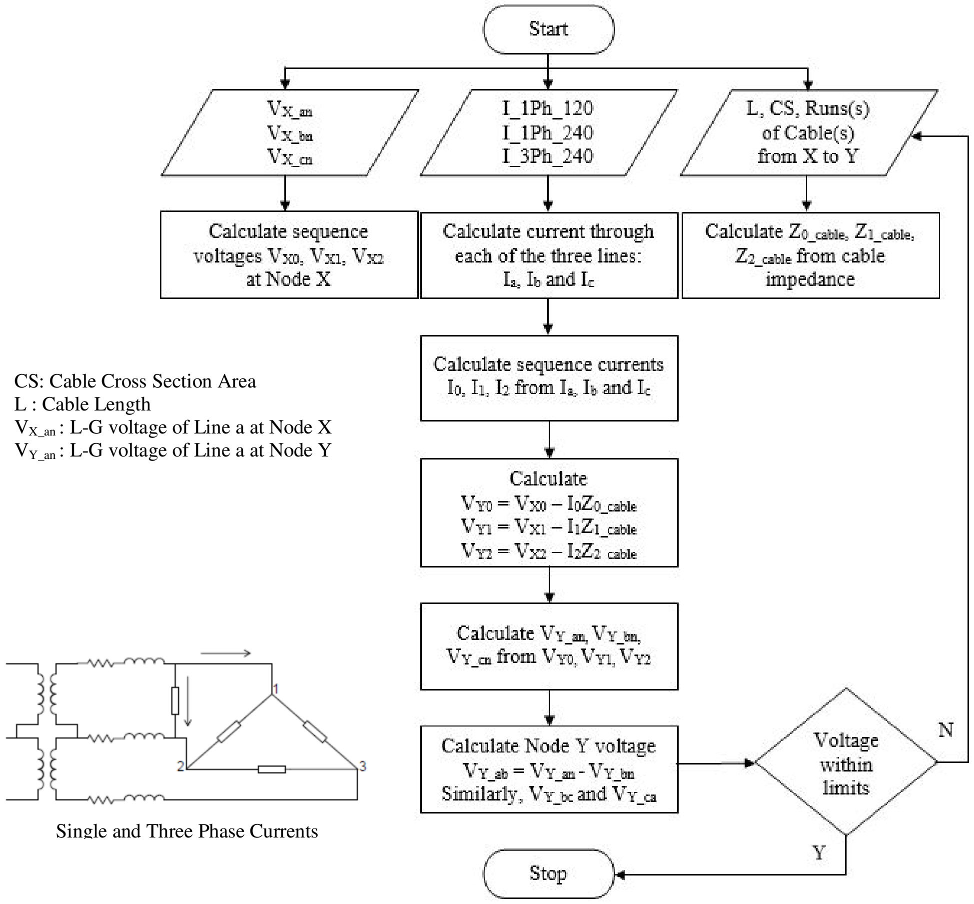
Fig. 3b. Th n the tertiary
(Reactors inside Delta)

Hence, the magnitude of reactance shall be tripled when connecting the reactors inside the delta. One possible advantage of this configuration is that for a L-L fault on the tertiary structure, the reactors would help reduce fault current magnitude, which would not be the case if reactors were outside the delta.

## VOLTAGE DROP

Since voltage drop is a major concern for 120 V / 240 V cables in a large 765 kV yard, approximate methods of calculation might lead to conservative sizing of cables and increased cost of installation. An accurate calculation would take the 120 V and 240 V single-phase and three-phase load currents as inputs and generate voltage magnitudes at each node of the station service one-line.

AEP has developed a spreadsheet tool that can be used to develop the station service one-line – from transformer secondary to the load, including intermediate nodes at safety switch, transfer switch and panelboard breakers [Fig. 5]. The tool would generate voltage magnitudes at each node based on symmetrical components (since the system is unbalanced), with no assumptions or relaxations on calculations. Given below [Fig. 4] is a flowchart for calculation.



CS: Cable Cross Section Area
L : Cable Length
$V_{X\_an}$ : L-G voltage of Line a at Node X
$V_{Y\_an}$ : L-G voltage of Line a at Node Y

Fig. 4. Flowchart for Voltage Drop Calculation

## VOLTAGE RATING OF EQUIPMENT

If the protection system is designed to only generate an alarm on an accidental ground on the tertiary for system shown in Fig. 2., all the equipment shall be rated for continuous operation on L-L voltage of tertiary, including insulators, surge arresters, instrument transformers and UG cables. This is because the L-G voltage on unfaulted lines would rise to L-L voltage for an accidental ground on a delta system. The transformer bank would stay in service unless there is a second fault (usually due to an equipment flashover such as an insulator), when it is taken out of service since fault current flows through the transformer windings and is picked up by the transformer protection scheme.

## BEST PRACTICES FOR STATION SERVICE DESIGN

**Arc Flash Analysis:**
Arc flash from electrical faults on the low-side of distribution (< 15 kV) or station AC service circuits (≤ 480 V) are possible safety hazards that drive safe work practices, personal protective equipment requirements for substation workers, and relay and other overcurrent protection settings and practices. IEEE-1584 method, which is built inside ASPEN software, is used by AEP to calculate risk location incident energy values for systems below 15 kV [2], the results of which are then passed on to the field personnel to ensure that the proper rating of FR clothing is used during work on or near energized equipment.

**Requirement for Second Backup Source:**
EHV Substations (especially 500 kV and 765 kV) are one of the most critical nodes on the grid. As a result, it is a good practice for these stations to have a backup source for station service, even when one of the two sources is taken out of service for extended periods due to maintenance or construction activities. For example, if a station has two sources from two autotransformer banks and one of the banks is taken out of service, the station shall have the provision to bring in a third source quickly so that it has two sources. This third source shall be taken into consideration during the design and engineering phase of the substation and can either be a local distribution line or generator.

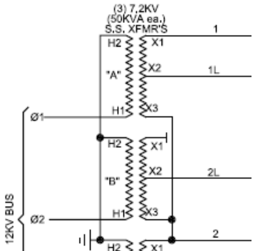
If not considered during the design and engineering of the station, there is no specific location in the yard layout for the generator and no specific cabling to tie into the bus work. This might lead to installation times greater than what the battery systems can support (designed for 8 hours), leaving the protection systems vulnerable to loss of DC power in case of an unforeseen contingency in station service source or equipment.

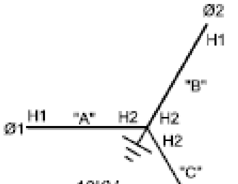
Thus, it is a good practice to either design and engineer the EHV station with provision for a third source, complete with termination cabling, specified location in the yard layout and/ or switching mechanism between backup and second backup sources, or to have a field plan in place to incorporate a reliable third source in minimum time in case of a contingency.

**Single vs Three Phase Station Service when using SSVTs:**
Station service design varies significantly when the loads are three-phase compared to when the loads are all single-phase. Three-phase systems require additional care with respect to phasing and connection of the transformers and equipment downstream. In general, installing a three-phase station service is costlier than a single-phase station service. This is especially true in case of SSVTs. SSVTs are costlier than their distribution counterparts, with costs increasing with voltage level. A three-phase station service would require at least one more SSVT compared to an equivalent single-phase station service. Although single-phase loads account for most of the loading in substations, a small fraction of loads in three-phase would require another SSVT to be installed.

Thus, if all loads inside the yard can be standardized to be single-phase, it may help in driving down the costs. This practice may be taken up by voltage level. Although it may not be possible to standardize on single-phase loads for equipment of all voltage classes, it is a good practice to change three-phase auxiliary power requirements to single-phase by working with the equipment vendors in greenfield stations where SSVTs are used and only a minute amount of loading is in three-phase.

**Vector Diagrams for Station Service:**
Vector diagrams are a useful tool to determine phase differences between station service voltage sources. When designing station service with legacy connections, vector diagrams help in correctly specifying the station service transformer connections and equipment downstream, such as the transfer switch. An example of a legacy connection in the AEP system is shown below.





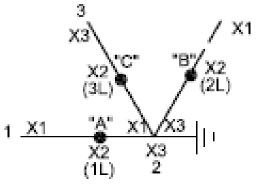


Fig. 5. Chicken Foot Vector

As can be seen from the above connection diagram and the one-line below [Fig. 6.], the chicken foot vector diagram is different from the center-tapped closed-delta that is used as a standard connection. When converting a connection such as this to center-tapped connection, attention must be given to vector diagrams. If chicken-foot and standard connections are to be used as primary and backup, off-the-shelf auto transfer switches cannot be used since line-line voltages in chicken foot are not all equal (120V, 120V, 120*1.732V) and the ATS concludes the source to be heavily unbalanced. One may have to proceed with a manual transfer or custom auto transfer switch.

The above scenario is just one example showing the significance of vector diagrams. In general, it is a good practice to specify accurate vector diagrams at each voltage transformation on the one-line drawing [Fig. 6].

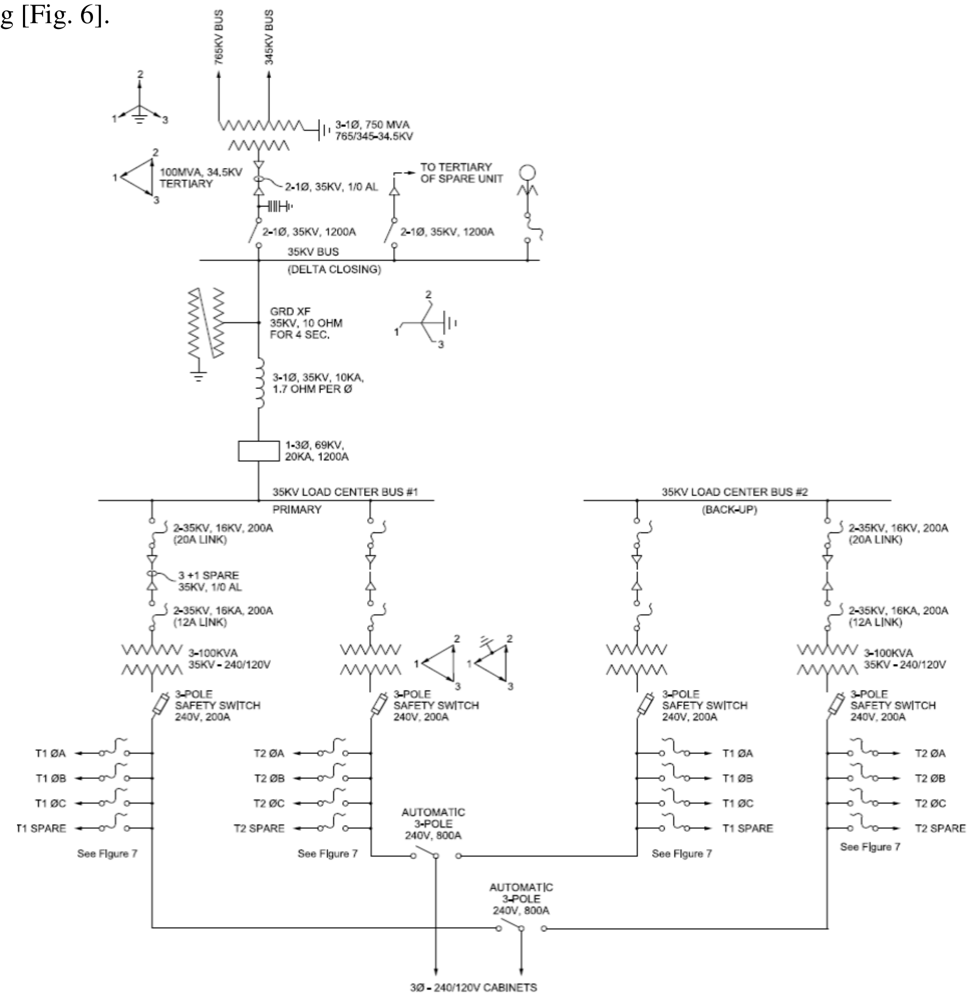


Fig. 6. Typical Station Service One-line for a 765 kV Substation

**INDUSTRY PRACTICES: AC STATION SERVICE DESIGN AT EHV STATIONS**

Given below is a table showing station service design practices at some of the other utilities in the industry. The list includes 6 utilities from USA.

| S. No. | Name of Utility | Primary Source for Station Service | Backup Source for Station Service | Second Backup for Station Service |
|---|---|---|---|---|
| 1 | Utility 1 | Autotransformer Tertiary | Autotransformer Tertiary<br>SSVT vs Local Distribution (cost based) | NA |
| 2 | Utility 2 | Autotransformer Tertiary | Local Distribution | Generator |
| 3 | Utility 3 | Autotransformer Tertiary | Local Distribution (SSVT if no availability of Local Distribution) | NA |
| 4 | Utility 4 | Local Distribution | Autotransformer Tertiary | NA |
| 5 | Utility 5 | Distribution Bus in Station | Distribution Line | Generator |
| 6 | Utility 6 | Autotransformer Tertiary | Autotransformer Tertiary<br>Local Distribution | NA |

## CONCLUSION

This paper describes the design principles for overcoming some of the unique challenges in station service design for EHV stations. As evident from the last section, there is no single best practice for designing station service, which in part is what makes it more challenging to standardize. Each station requires careful study of the available options, followed by a cost-benefit analysis among the options, with due consideration given to factors that may not have a direct monetary value such as safety and reliability.

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