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Increased Reliability of EHV Systems through Station Switchable Spare Transformer and Shunt Reactor Design and Operation

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SUMMARY

An innovative new concept for the design and operation of EHV single-phase transformer and shunt reactor banks was developed and implemented within AEP substations. Recognizing the consequence of prolonged outages, Regional Transmission Organizations (RTO) have begun to require system upgrades such as EHV transformer and reactor banks. By incorporating a switchable spare transformer or shunt reactor into the design and operation of 765kV substations, the spare can be placed into service within a few hours following the removal of one of its sister units from service. Prior designs took days, weeks, or months to restore the transmission system depending on location and availability of the spare unit. In addition to faster restoration times, the new design reduces the exposure of field personnel to construction hazards, improves system reliability, and saves money. Other key components of this design include having the reconfiguration control schemes incorporated into the original construction and fire mitigation to reduce collateral damage.

KEYWORDS
Reliability, Resiliency, Restoration, Transformer, Shunt Reactor, Extra High Voltage (EHV), Oil Containment, Firewall, MEGA Switch, Relays, Protection

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Introduction
An innovative new concept for the design and operation of EHV transformers and shunt reactor banks was developed and implemented within AEP's 765kV substations. This improvement provides our utility the ability to restore 765kV bus and circuits in the event of a failure of a transformer or shunt reactor in a fraction of the time previously spent.

Historically, AEP relied upon having a very solid sparing strategy for critical transmission assets. This assured availability of equipment across the system in the event of extended maintenance or failure. Two of the most expensive and logistically challenging pieces of substation equipment are 765kV transformers and shunt reactors.

While this sparing strategy assured that equipment was available when needed, there was still considerable time and effort required to restore service following the failure of a 765kV transformer or shunt reactor. Coordination across multiple departments (Transmission Field Services, Transmission Station Engineering, Transmission Planning, and Transmission Operations) was required. Restoration time ranges from multiple days if the station design included a spare (requiring modification to the existing bus), to months if the replacement must be shipped from another substation. The latter circumstance left the 765kV system vulnerable and requiring additional measures by Transmission Operations to ensure system reliability and stability are maintained.

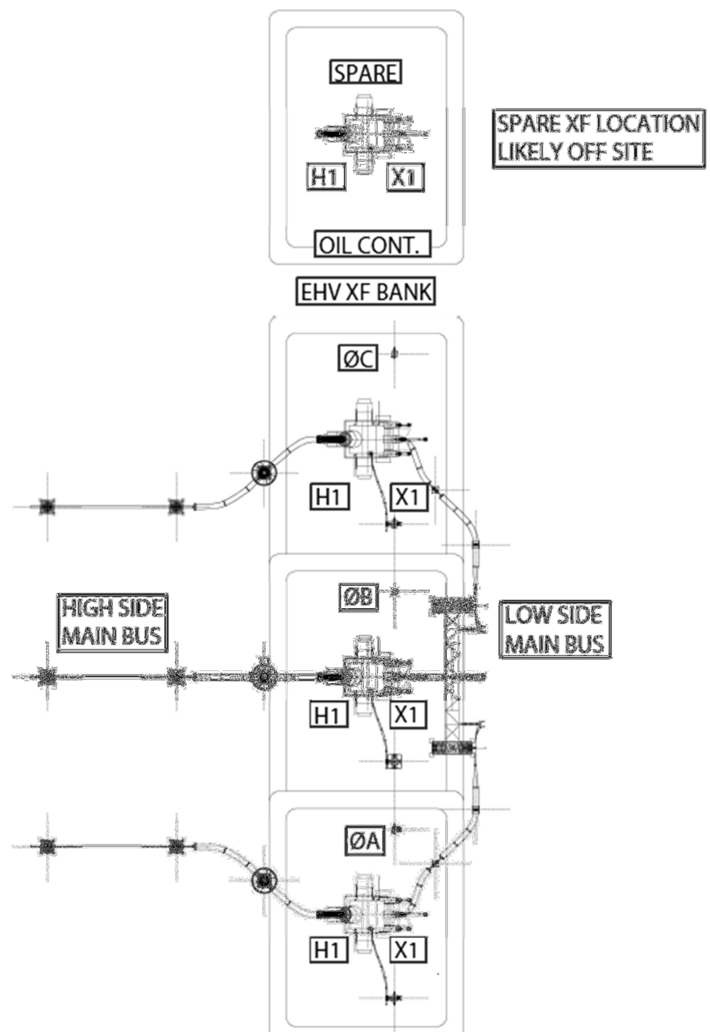

Figure 1: Plan View of Historical 765kV Layout

New Standard Physical Layout

Seeking a quicker way to switch a transformer online, AEP found a more efficient layout to reduce outage time. The new layout involved the spare unit being installed directly next to the other units and be permanently connected through switchable systems that enable only a short outage to perform the switching operations. This new layout also included necessary electrical and overhead clearances of the structures and bus work so that maintenance, repair, and removal of the de-energized unit can be done while the three remaining units of the bank remain energized. This system also allows for two electrically identical side-by-side banks to share one spare.

The switchable spare design required the development of new electrical equipment and structures, most notably the phase-to-phase air gap MEGA switches and the take-off structures. The MEGA switches were developed specifically for AEP's layout and are the first-of-their-kind in the world.

Although the switchable spare layout requires the upfront cost of the spare equipment, it is estimated that the cost to tear down, move, transport, reassemble and test a new unit during an outage can total up to $1 million. Additionally, a shorter outage benefits operations and grid reliability immeasurably.

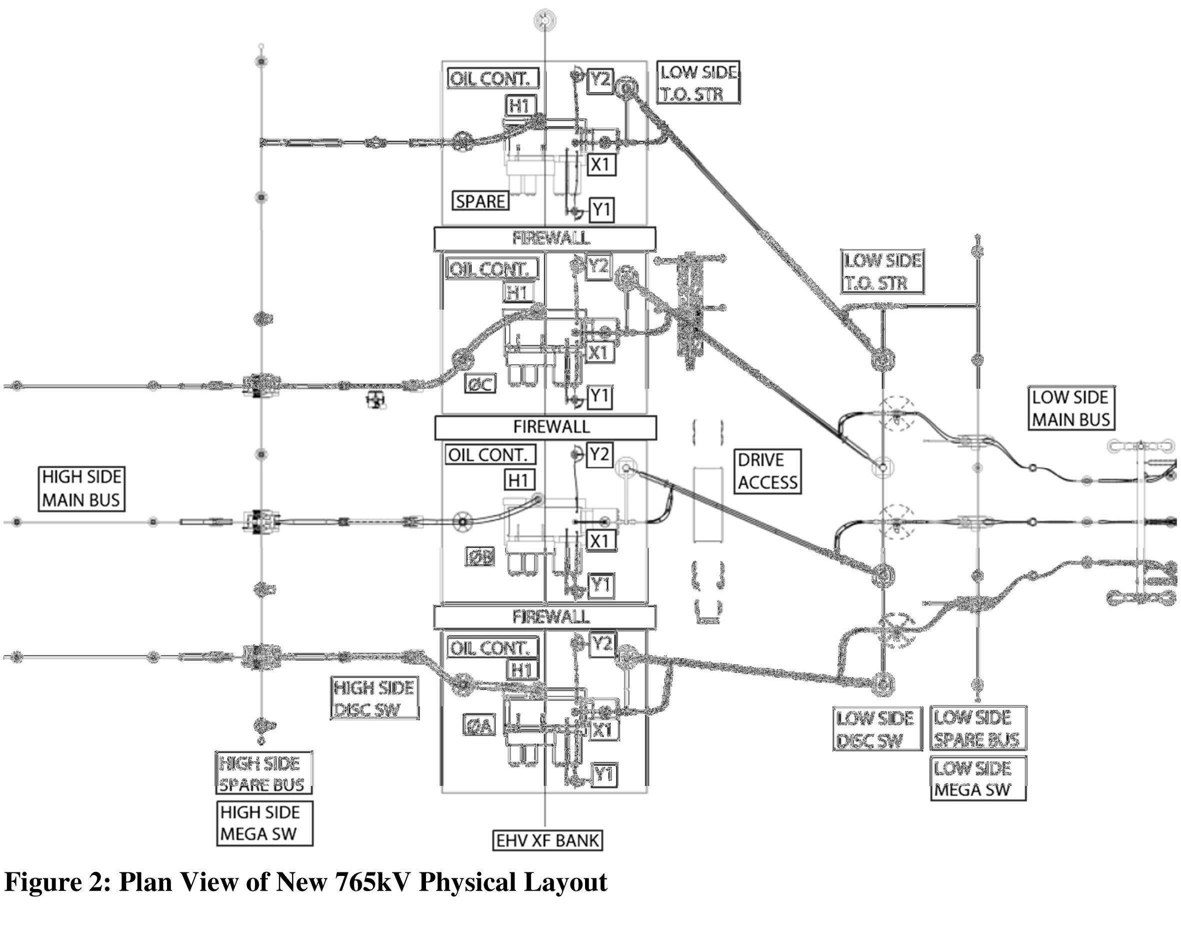

Figure 2: Plan View of New 765kV Physical Layout

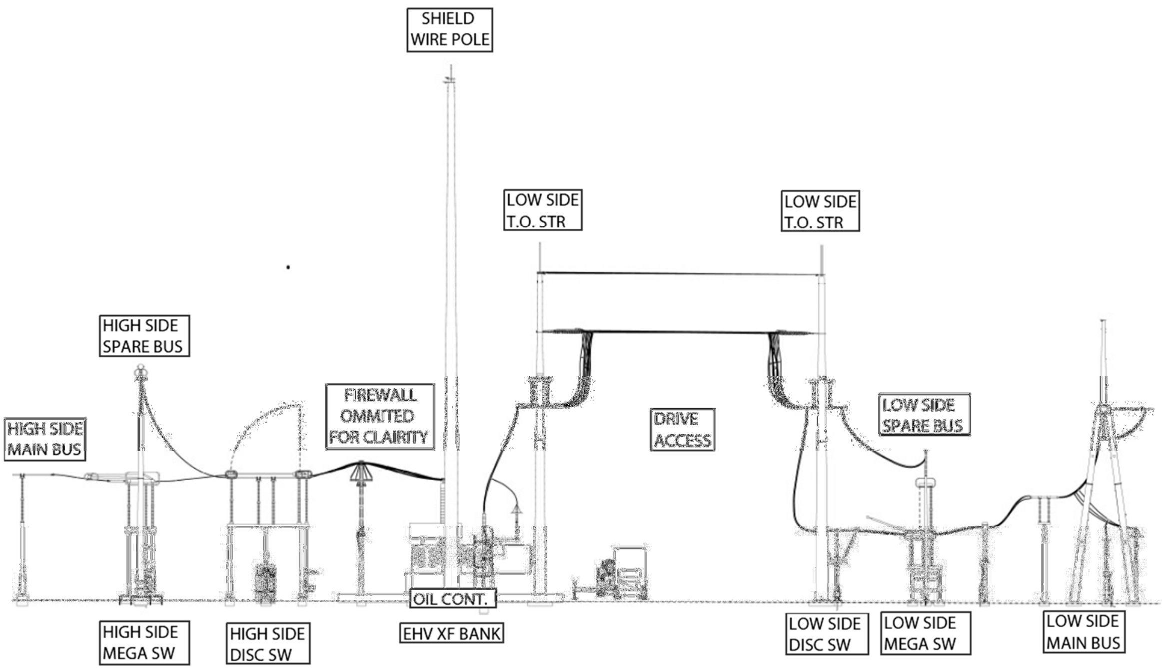

Figure 3: Elevation View of New 765kV Physical Layout

Protection and Control Scheme

A new protection and control scheme was devised, where fast reconfiguration of the protection scheme is incorporated. This results in no field wiring during restoration, saving valuable time.

In past protection designs for this application, when the spare transformer or shunt reactor needed to be placed in service, the CT circuits, tripping circuits, control circuits and alarm circuits would need to be modified to place the spare transformer into the correct phase position of the protection scheme. This would require modification of wiring and retesting of the protection scheme. This process could take up to two days to complete.

With the application of modern microprocessor relays, a new protection scheme was developed to cut the time of protection system reconfiguration to a matter of seconds. This was accomplished by taking advantage of modern differential relays being able to reconfigure the differential protection using programmable logic.

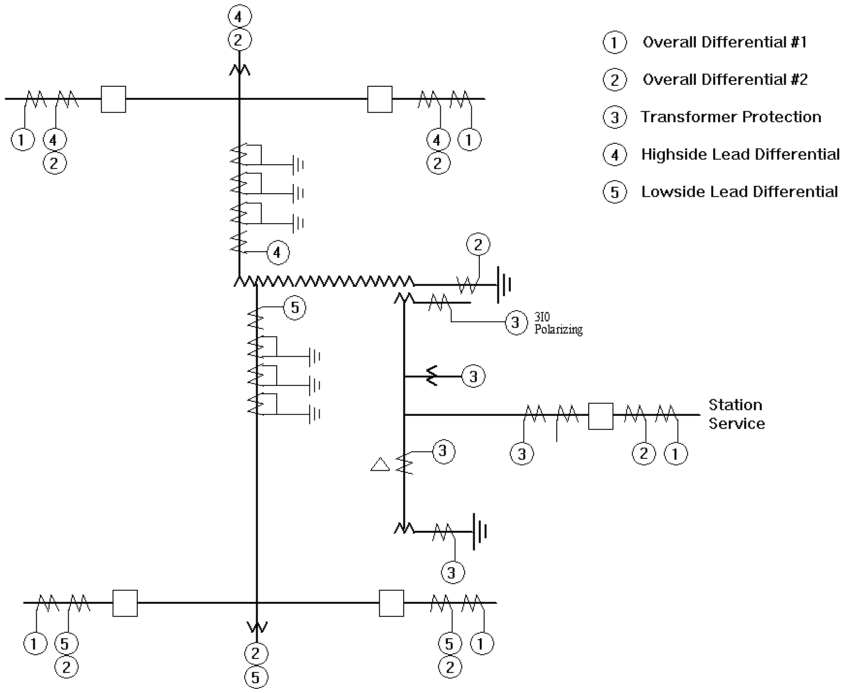

Figure 4: Protection Scheme

The protection scheme incorporates two overall differential protection relays. These relays do not need to be reconfigured when the spare transformer is placed into service in any phase. The Overall Differential #2 relay includes Restricted Earth Fault protection. Since the transformers are single phase units, the neutral CT from each phase transformer and spare are connected in parallel.

The scheme includes high-side and low-side lead differential relays. These two relays provide the ability to determine fault location, that is, whether the fault is inside the transformer or outside the transformer. The high-side and low-side differential relays must contain the feature of reconfiguring the differential protection, that is, the CT circuits feeding into the differential protection, using programmable logic. The only CT circuits that need to be manipulated in the high-side and low-side lead differential relays are the associated transformer CT's. The low-side lead differential relay also provides additional protection functions that need to be reconfigured. Those protections include sudden pressure tripping and lowide phase time overcurrents. In addition, both the high-side and low-side lead differential relays provide the transformer metering for SCADA and must be reconfigured as well.

The final protection relay in the scheme focuses tertiary protection and does not need to be reconfigured.

Reconfiguration of the protection scheme is accomplished by pressing pushbuttons on the front of the high-side and low-side lead differential relays. There are four protection modes: Mode N (Phase A, B and C in service); Mode A (spare-switched into Phase A); Mode B (spare-switched into Phase B); and Mode C (spare-switched into Phase C). During the reconfiguration process, the high-side and low-side lead differential relays monitor each other's protection mode. This is accomplished using IEC61850 GOOSE messaging. In addition, the protection mode of each relay is compared to the status of all the transformer switches used to reconfigure the bank. An alarm is generated when the relay protection modes or transformer switch statuses do not agree on the location of the spare transformer. Once all are in agreement, the alarm will clear.

All circuit wiring for this protection scheme is performed when the system is commissioned, eliminating the need for rewiring and relay testing when the spare transformer is placed in service. All testing is completed during commissioning. This allows for simple protection reconfiguration using pushbuttons located on the highside and lowside lead differential relays.

Fire Mitigation
Fire mitigation is a key component of reducing outage time. AEP's choice for fire mitigation includes a combination of fire walls and an oil containment that allows oil to be drained to a remote location. The firewalls protect adjacent high-risk equipment, while the stone-lined containment and drainage is designed to suppress a high radiation energy pool fire.

The firewalls are installed between each phase. Consideration also is given to other nearby sensitive equipment. Large structures, such as deadend or take-off structures, that are located within the oil containment have a fire-resistant coating applied in order to avoid failure of the structures and cascading damage to nearby equipment. In addition, these large structures tend to have a longer procurement lead time, and would require outages of additional equipment if replacement was required; therefore their preservation reduces the risk of a longer restoration and outage.

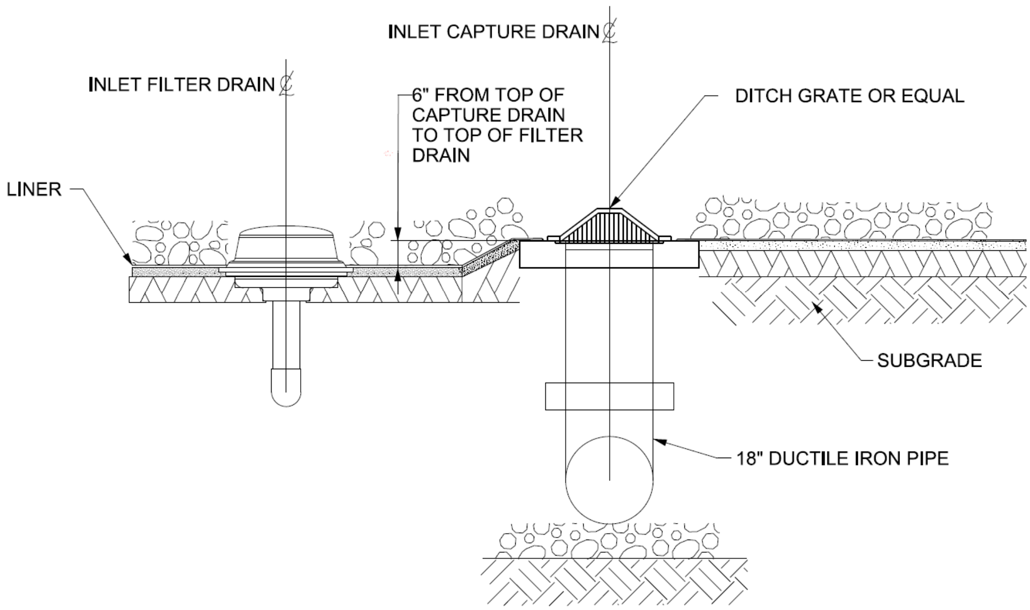

Figure 5: Oil Containment Dual Drain Section View

The oil containment design has been an iterative process. As newer technologies have been made available, we have sought to minimize installation costs and maintenance needs. The current design is in the pilot phase. It is comprised of a structural containment and a dual drain system with filters and oil capture. The above grade structural oil containment is sized for the full oil capacity of the largest version of the contained equipment, thereby eliminating changes to the containment in the event that a replacement unit is purchased from a different vendor. The dual drain includes a lower-elevated drain intended for the majority of rain water to flow to daylight through an oleophillic polymer filter. The upper drain leads to oil capture containment via ductile iron pipe. The oil capture containment then leads to another oleophillic polymer filter or an oil detecting pump (depending on site drainage conditions), allowing continuous drainage of water and the ability to retain oil in the event of a catastrophic event. The only maintenance anticipated will be the occasional cleaning and replacement of filters.

Application
The first pilot application was installed in 2012 for a 765kV transformer bank. After a successful installation, the design was applied to other voltage combinations and equipment such as shunt reactors. The switchable spare design has been successfully implemented for the 765kV shunt reactor

banks at four stations and 765kV transformer banks at three stations. It is also either completed or under construction for 11 additional 765kV transformer or shunt reactor banks.

The system is tested after each installation during commissioning. AEP has since experienced two failures that successfully utilized this system and the outages were minimized, confirming the benefits of the new design.

Conclusion

The time to restore 765kV service to as little as three hours, down from a range of three days to three months was achieved through a layout that involved a new switch design, a supporting protection scheme, and fire mitigation. Once the spare is energized, the removal and replacement of the failed unit can occur while the restored transformer bank remains energized.

The following points summarize the value of the switchable spare design to AEP and why this layout is now the standard application to be utilized across its system.

- Safety – Eliminates the exposure of field personnel to the potential hazards that may be encountered during the removal and installation of EHV equipment and bus reconfiguration.
- Maintenance - Provides for in-service spare rotation, keeping the transformers at their highest performance level since the spare arrangement can be energized routinely.
- Grid Resiliency – Reduced outage time removes burdens on the grid.
- Cost Savings – Cost to remove, transport, install, and commission a remotely located spare unit is estimated at up to $1 million per event, in the event of a failure.

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