Improving Protection Applications for Modern Industrial Switchgear Systems

Benton Vandiver III, ABB ES.

Introduction

Medium voltage (MV) switchgear must meet many different requirements due to the range of its applications. While it is often used in traditional utility distribution substations, it is also widely used in industrial power systems, large commercial facilities, university power systems, as well as for the interconnection of large distributed energy resources. This means that the switchgear design should be flexible in configuration with variable bus ratings. PAC systems (protection, automation, and control) must therefore be accurate over a wide range of currents and voltages, while at the same time providing safe and reliable operation, with minimum maintenance requirements.

Something these various applications have in common is the current practice of using modern microprocessor protection and control technology in place of legacy P&C devices. However, advanced communications (IEC 61850, DNP 3, etc.) and system automation for EMS/DMS is requiring more from the PAC system. Both conventional and non-conventional instrument transformers are used in MV switchgear design; this elevates the MV switchgear into the era of Smart Grid/IoT/Big Data requirements.

This paper focuses on industrial power system applications of MV switchgear. Industrial facilities execute upgrade cycles more frequently to maintain their efficiency and competitive edge. Often, they adopt state of the art technologies much faster than the utility sector and in this age of data driven metrics and optimization, an efficient and reliable industrial power system is a must. Industrial MV switchgear also requires the best safety features integrated with comprehensive protection, automation, and control features for operator ease of use and plant safety while simplifying training. If we make a short list, a MV switchgear that is more efficient, safe, smart, reliable, environmentally friendly, and easy to engineer, install, operate and maintain would be an ideal solution.

The Challenge

It benefits the industrial facility to maximize standardization across their installed switchgear base if possible, even though most industrial systems were customized to each specific plant process. A traditional industrial power system is hierarchical in its grid architecture - stepping down the voltage in stages from the power source to the distributed process voltage level. Typically, source voltage is 69kV and above, and the process levels are 4kV and below. In many facilities traditional metal enclosed switchgears similar to Figure 1 are used. This illustrates a typical hierarchy with source and distribution level redundancy to the process loads. In many cases, the vendor switchgear blocks and P&C systems varied by voltage based on competitive bidding.

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Today's newest switchgear technology is GIS (gas insulated switchgear), with the benefit of a smaller footprint and less maintenance, it is often used in both brownfield and greenfield applications. There is an added operational and protection consideration with the addition of ground switches and gas monitoring, but the grid architecture is the same. Redundancy can be improved since double bus bars take no additional space.

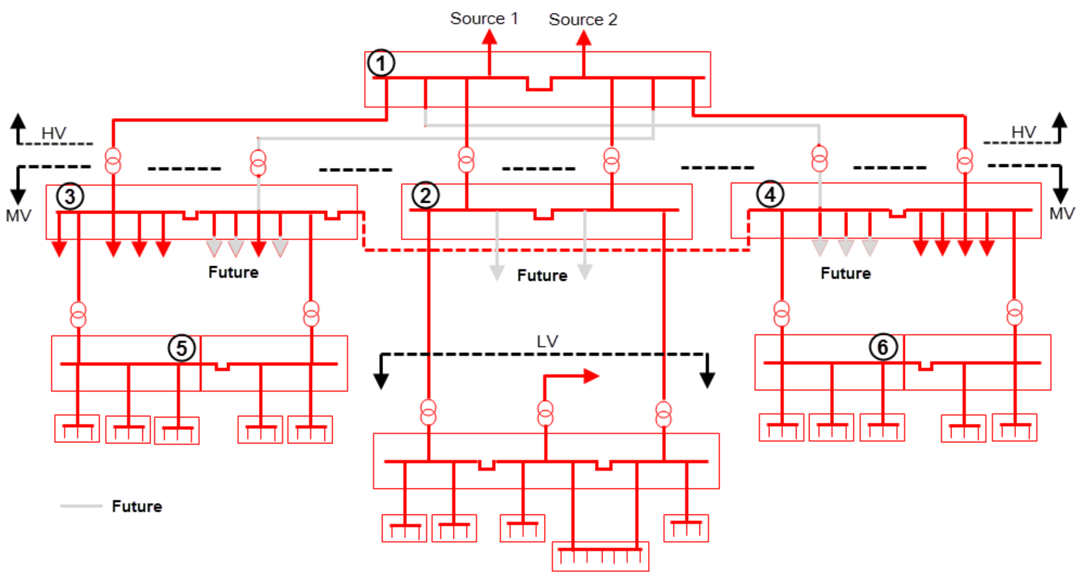

Figure 1: Typical Industrial One Line diagram with redundant switchgear

Design Goals

The design goal is to ensure an uninterrupted power supply to the whole industrial network with standardized power blocks. Modern MV switchgear is often applied as a unified power block bay component. (Figure 2) Bay blocks are combined to make the required power block for each distributed switchgear system.

Whether GIS or conventional switchgear, integration of non-conventional instrument transformer (NCIT) sensors for current and voltage measurement into the MV switchgear combined with modern

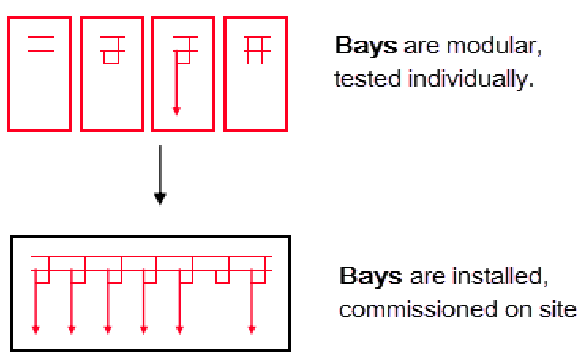

Figure 2: Conventional switchgear – bay to power block

protection relays utilizing IEC 61850 communications means a high degree of flexible standardization. The bays can be grouped to provide various combinations of incomers and feeders based on the source/load requirements.

The NCIT's are often Rogowski-based and highly compact and optimized for use in a MV switchgear. Each bay easily accommodates two sets of current sensors. The voltage sensors (resistive or capacitive) are very compact as well. They can be integrated as part of support insulators housed in the cable compartment or mounted additionally in the busbar compartment. (Figure 3)

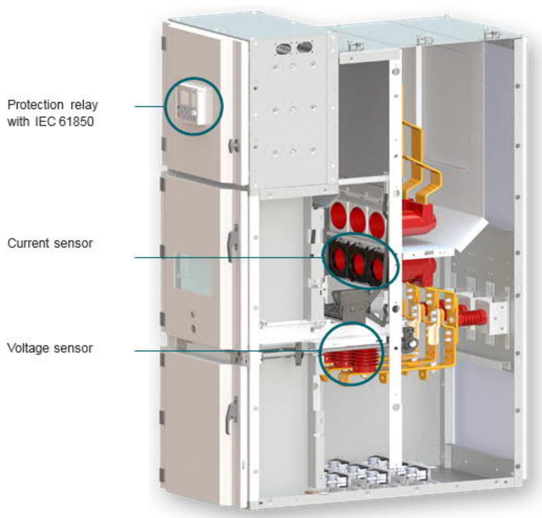

Figure 3: Bay Configuration with NCIT's; (breaker removed for clarity)

The NCIT's are generally high accuracy (class 0.5), however revenue metering might require even higher accuracy classes or the installation of additional instrument current and voltage transformers for separate metering purposes. (Often in coupler bays or dedicated metering bays.)

When protection functions are integrated with operational and safety requirements the interlocking and control logic should be portable extensions of the bay/switchgear configuration. Many different PAC philosophies can be applied, but when implementing new technology, a common motivation is to leverage the PAC system to reduce installed cost while improving the protection scheme. (Increasing zones of protection) But this can also mean added complication to what was a simple protection philosophy. So, what is best?

Part of the job of the system protection engineer is to leverage technology and apply cost effective solutions to achieve the PAC design and operation goals. This includes balancing capital costs, with operational and maintenance costs for the overall ROI. Considerations for the ease of construction, commissioning, maintenance, operations and effectively protecting the switchgear under all operating conditions is fundamental to a well-engineered PAC system.

For that, a comparison between some conventional approaches, communication-based adaptations, and a proposed integrated zone approach is presented. Operational improvements, and new capabilities gained from the integration is presented; i.e. expected enhancements to overall operations, reporting, compliance, disturbance recording, predictive maintenance, asset health analysis, and operational safety.

Conventional approach to P&C Zones

If we consider one of these MV switchgear (#2 in Figure 1) that would typically be used for 4-12kV distribution; the usual P&C scheme requires a minimum of 7 conventional relays; but could be more depending on the protection philosophy applied. (Figure 4)

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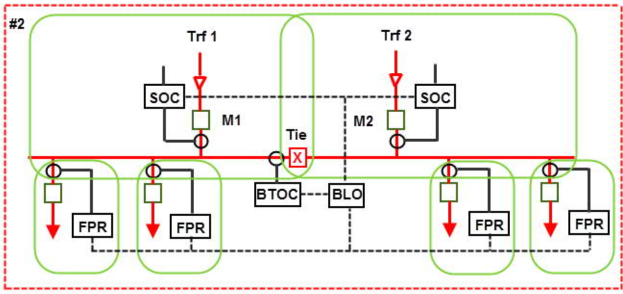

Figure 4: Typical Main-Tie-Main with conventional P&C zones

In this scheme, there are six zones (in green) – the four feeder zones and the two incomer virtual zones that share the Bus Tie. In normal operation the Tie is open, the SOC (source overcurrent function) is part of the incomer transformer protection zone set for the max/overload expected of its two feeders. Each feeder is set for its respective max load and overload conditions. Each feeder provides a zone interlock trip upstream and if an external fault persists, the Bus LO with additional logic trips. The entire switchgear would be tripped if the BT is closed when one incomer is open for maintenance. BTOC and SOC protection could be adapted with temporary settings for staged coordination. In some cases, separate breaker failure relays are used, and the logic is adjusted according to the Bus Tie state. All trip operations are expected within a typical 300mS target window.

This type of scheme has been utilized for many years with both electro-mechanical and microprocessor relays. However, there are several drawbacks due to inconsistent fault detection and relative slow tripping response based on changing loads and operating conditions. Arc-flash during maintenance is a danger and mis-operations due to wiring, mechanical interlocking, switching, and human error are predicted. Testing, commissioning, and trouble-shooting are manageable with 7-14 protection relays and other auxiliary relays in this scheme.

There are several working group and technical reports from the Power System Relaying Committee (PSRC) that relate to these P&C scheme issues. [1] [2] [3] In essence, the goal is to reduce human error, provide proper zone protection with redundant protection if possible, and limit apparatus damage while increasing safety and reliability. All topics are relevant to our switchgear P&C goals.

Communication-based P&C Zones

Data has been the primary driver in industry modernization, today it is referred to as "Industry 4.0" or the connection of everything – termed "IoT" (Internet of Things). For industrial complexes the process control networks have been around well before "IoT". But many of these networks used proprietary protocols for only the process part, the electrical system supply was not included and was slow following suite. PMS or DCS systems were add on's using RTU's or other data collection devices.

This has changed fundamentally with the maturing IEC 61850 standard. [4] IEC 61850 has a basic strength of a distributed architecture with flexible communications, meaning the system designed is not bound by a physical box. But, it can also support a compact centralized architecture which can provide benefits too. That list includes:

- Minimizing copper wiring -by using fiber and a substation network
- Optimize sensor data and share it everywhere it is logically needed.
- Potentially reduce the number of physical devices
- Maximize protection zone coverage and operational flexibility

- Improve safety for operations through interlock extensions
- Create a deployable engineering standard
- Provide a Hybrid solution, leverage the standard into Brownfield facilities

When we apply this technology there are still many aspects of the protection scheme that should fundamentally remain the same. Leveraging standardization yields core benefits in cost reduction but there are risks too.

Feeder protection for example should be a straight forward application of the operational philosophy and may have several options depending on the point of application in the distribution grid but should not be re-engineered for each project. It should be one scheme with optional settings to dynamically adapt it. Same goes for transformer protection.

Going back to the MV switchgear of Figure 4 and now applying these principles we get the protection scheme of Figure 5. If using the core of IEC-61850 which is MMS messaging and GOOSE (Generic Object Oriented Substation Event) at the required performance level, the scheme can improve upon the performance of the scheme in Figure 4. However, it adds the complexity of the network switch and communication interfaces including GOOSE engineering; as these replace the hard-wired interlocks of Figure 4. The benefit is all devices can know and use the information of others in the network as the sensor and status data are digitalized once and multicast network wide.

This provides the protection engineer an order of magnitude in flexibility to create a more complete scheme, but it also adds complex protection and control logic. The communication engineering is critical to understand, apply, and document the GOOSE mappings to implement it successfully. This may make the protection zones operate more securely and maybe faster, but other aspects are often overlooked; engineering time, proper documentation, testing, commissioning, operations training, and trouble-shooting may all take longer (much longer) and ultimately negate the initial perceived cost advantage.

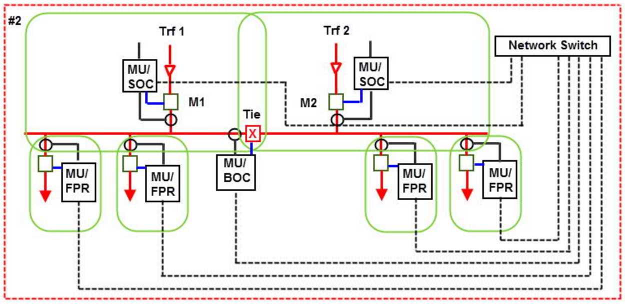

Figure 5: Main-Tie-Main with IEC 61850 P&C system (no redundancy)

It's to be noted that the zone protection wasn't changed between Figure 4 and Figure 5. This remained the same, the performance improvement is mainly owed to the GOOSE mechanism. Any operations improvement is due to the additional control logic carried by the GOOSE messages and used in the shared system. This implementation can be standardized, but it also can be changed at many points in the project implementation process, unless strict rules dictate engineering compliance to a standard implementation. There are numerous ways to achieve the same end logic and only one relay being changed can disrupt the carefully engineered communication-based solution.

One additional capability of IEC-61850 could be utilized, that is Sampled Measured Values. (SMV, Part 9-2 of the standard) Each relay noted in Figure 5 could also be a merging unit, (noted as MU) where the measured analog current/voltage is digitalized and sent as a message to the network. (Note: the network performance and configuration become critical.) Any distributed function which might need that nodal information simply subscribes to it. It would be possible then to add a zone of protection and use all of the SMV streams to make a bus differential zone of the entire switchgear replacing the virtual bus zone. This function just needs a home in the network with the ability to process that function and act by issuing a trip for an internal fault via a GOOSE trip message. Likely this would need to be another physical box which is not making the scheme simpler; but it should again increase reliability and speed the fault clearing time adding to safety. IEEE Recommended Practice P2030.100 [7] is a good source for evaluating these IEC-61850 systems.

It is critical to have the right communication engineering and documentation control tools to make these communication-based solutions truly work. This also means secure settings, data management, and user roles across the products, network, and operations to keep these systems cyber secure.

Integrated multi-object P&C device with integrated Zones

Being this exercise is based on a typical MV switchgear application it might be interesting to take a blank sheet approach with a target budget and shop for a solution. If we use the Figure 5 example and use one IEC-61850 MU capable Feeder Protection relay as a one per unit cost; then the HW cost (excluding the switch, cabling, and engineering) would be about a seven (7) per unit cost for this switchgear. This sets the baseline cost and can be vendor agnostic. And, we don't have to confine our search to just "Distribution" class protection devices, but any protection solution that checks the most boxes identified when reviewing all the requirements noted, plus fit the budget.

Thanks to IEC 61850 yesterday's HV multi-functional microprocessor-based relays have evolved into digital multi-object-oriented communication based programmable protection systems. That's a mouthful, and since IED is shunned as an acronym today, I'm just going to use "Switchgear Protection Relay" (SGPR) so it can't be confused with feeder protection relay.

Since the one protection function missing from the above examples is true bus differential protection, we should give it a first look. The reason bus differential protection was not considered in the past was due to the cost of implementing either high impedance or low impedance schemes on switchgear of this voltage level. But, since the switchgear designs are more efficient, can easily accommodate cost effective NCIT's, and since communications are required today; plus, multiple box P&C scheme costs have risen to where they are today, and due to the critical operational status of most industrial applications, maybe the magical line in the sand has been crossed.

Applying current IEC 61850 technology in a high-performance low impedance Bus Differential relay yields interesting possibilities when looking at our switchgear application. To create a proper bus diff zone, we should locate the CT's or NCIT's to include the CB's in zone. (Figure 6) The bus diff can accommodate up to 24 analog channels, so this works out as we have 21 in the Figure 5 example. With this zone there is 100% switchgear coverage with high speed clearing of less than 1 cycle. This is a huge improvement over the best virtual zone performance of 140ms and reduces the arc flash hazard by a factor of 10!

Leveraging the multi-object capability, full feeder protection can be easily provided as multiple current protection functions are available for each branch. So, the previous feeder protection standard can be easily implemented too. Even the incomer branches can have the same functional OC protection philosophy.

Logic and control of the CB's are easier to implement since it's all internal control logic to the one physical device. Any operational configuration is supported automatically as the bus diff zone automatically adapts to the switchgear's configuration. Safety interlocks for operations are simplified with one point of interface and safety is improved with all checks being internally centralized in one device. Safety protocols are easily implemented and easily tested.

There are now numerous benefits of having all P&C centralized in one box. They are listed below. But what about the relative costs? It turns out that of the 7 per unit cost of Figure 5, the per unit cost of Figure 6 is only five (5). But to balance that advantage, we should fairly add in the costs of the additional CT's or NCIT's for the overlapping transformer protection zone. With a relative cost of 2.5 per unit for each position, the cost over Figure 5 is a +3 per unit. But the benefits far exceed this incremental cost increase and are easily accommodated in today's modern switchgear without size penalty.

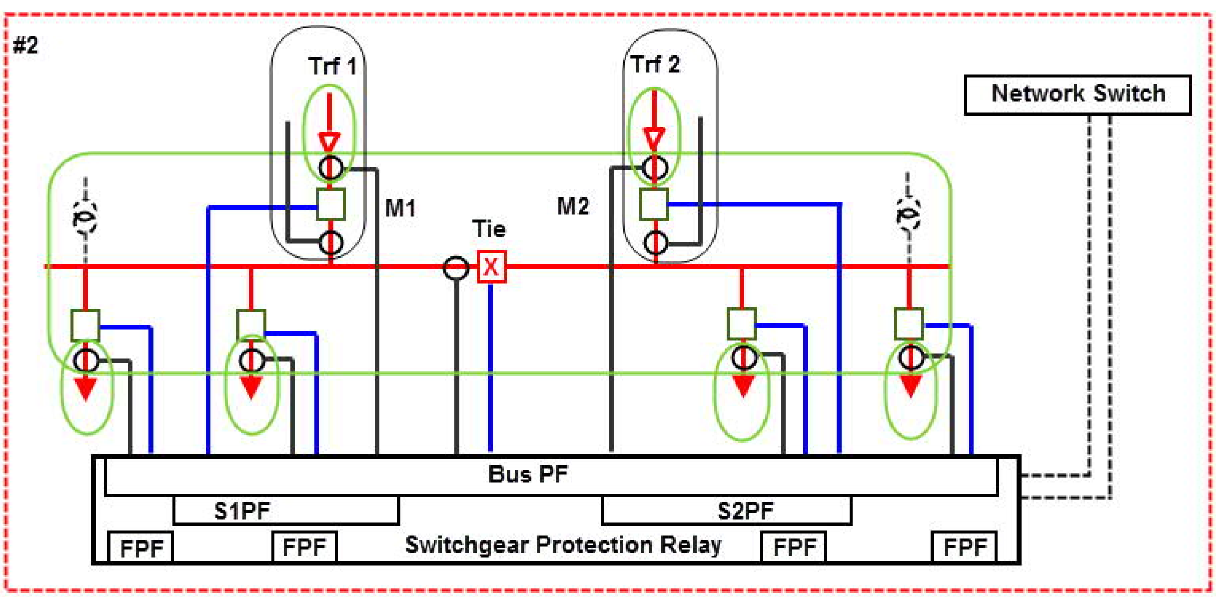

Figure 6: Main-Tie-Main with Multi-Object P&C system (with redundant comms)

Many additional protection improvements are possible, VT's are shown optional because the source transformer often has low side VT's already. Leveraging a VT merging unit, the SMV stream can provide those measurements to the Bus Diff relay via the Network Switch. (which I've re-labeled in Figure 6 as the Switchgear Protection Relay (SGPR) with Feeder Protection Function (FPF), Source X Protection Function (SxPF) and Bus Diff Protection Function (BusPF)) The OC protection may be upgraded to directional OC protection adding additional application flexibility.

Having flexible and multiple networking capability this HV Bus Diff relay can also provide full GOOSE /MMS messaging or DNP 3 data to the network for consolidated datasets to a SCADA or DCS/PMS system, especially for a local or remote HMI/ Control Center not to mention all metering and Fault/Event records. This greatly simplifies the communication engineering and network management.

Integrated Multi-Object Optimized Scheme and Benefits

Key benefits from this centralized switchgear application approach in just one device are:

- Reduced protection devices a minimum of 7 to 1 (reduce installation time, maintenance, testing, and cost with better protection)
- Eliminate the complex zone interlocking scheme and its coordination.
- Simplify entire fault study requirements with improved coordination/operation.
- Standardized integrated scheme eliminates wiring and settings errors, one device configuration, one firmware to manage if needed, one consolidated alarm picture
- Enhanced security for operators and field personnel with proper interlocks and automatic fast OC protection during switching and maintenance.
- Vastly improved arc-flash protection (10x less) for apparatus and personnel safety
- Station expansions are covered for the given switchgear configuration (enable feeder, enable protection block/settings, test, commission)
- Each switchgear event/disturbance reports are automatically time aligned/stamped. (Simplifies analysis/trouble-shooting from one DR/SER report, remote access simplified, upstream consolidation to system events reduced [7 to 1])
- Station logic is consolidated, no auxiliary relays required unless desired.
- Simplified communications within switchgear, fewer datasets to manage, single interface for data in up/down stream systems.
- Easier SCADA/DCS interfaces, easier to test and trouble shoot.
- Performance monitoring of all CBs, asset health monitoring, predictive maintenance (includes alarms, sensors, trending, and operations)
- Consolidated compliance reporting based on operations/outage monitoring/events/measurements
- Cross checking CT/NCIT data extends testing, eases compliance.
- Simplified Network Architecture and easier redundancy.

Conclusions

Due to the flexibility of IEC 61850 architecture there are many possible solutions to such applications and implementation philosophies. As the industry continues to evolve and leverage the capabilities provided by this technology. Some will counter that this “all your eggs in one basket” approach is not feasible, but I would counter that if simplification and safety are of value, then the existing schemes are the real risk. Redundancy can be added, even trading

7 for 2 is a bonus and easily achievable. Today's digital devices should be expected to perform at a high level, and our system protection designs should too.

References

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[3] IEEE / PSRC / C-16 Working Group report, "Relay Scheme Design Using Microprocessor Relays", 2014

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Biography

Benton Vandiver III received a BSEE from the University of Houston in 1979.

He is currently the Technical Sales Engineer for ABB in the Central US Regions located in Houston, TX. A registered Professional Engineer in TX, he is also an IEEE senior member, PSRCC member, PSCCC member/Chair of the P0-Protocols and Communication Architecture Subcommittee, and IEEE-SA member. He has been in the power industry for 40 years and worked previously with Houston Lighting & Power, Multilin Corp., and OMICRON electronics. He has authored, co-authored, and presented over 100 technical papers and published numerous industry articles.