USING INNOVATIVE ELECTRICAL AND ELECTRONIC DEVICES IN THE REDUCTION OF PANEL SIZE

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Abstract

Good substation panel design must take into account many requirements. One important factor is panel size. TNMP has over the last years employed new storage media, state of the art relays and a reduced number of test interfaces to reduce overall front panel size by 60%. The harmonization of all these devices calls for an advanced testing and maintenance approach. The close interaction of panel design with maintenance and asset management is improving TNMP's operating procedures. While we are continually challenged by the rugged environment of our installations (part of TNMP's service area includes one of the largest refinery complexes in the country), our substations are at the forefront of automation. This paper intends to look at panel design from a fresh perspective. Based on the real-world experience of TNMP, panel space and installation costs savings will be discussed and quantified.

Introduction

TNMP faces similar challenges as many other utility companies in the United States: aging workforce and infrastructure combined with the need to maintain and improve system reliability. Correct protective relaying systems operation is essential to maintaining the electric system reliability since they are designed to detect abnormal conditions and initiate corrective action by removing the faulted equipment from service so that the rest of the power system continues to operate in its normal state. Like any other type of substation equipment, protection and control system equipment needs to be tested and maintained. Aging electro-mechanical and static (solid state) relays (with their associated control circuitry) have to be tested at scheduled maintenance intervals. Also, the number of skilled technicians previously trained to test and maintain electromechanical relays is declining due to retirement. This workforce is being replaced by more computer-savvy technicians who are much more familiar with the computer-aided testing of microprocessor relays.

Utilities are now aware that maintenance procedures should be changed to utilize maintenance resources based on the condition of the equipment rather than only using time-based systems [1]. NERC, in its effort to help maintain and improve the reliability of North America's bulk power system, has facilitated a committee to develop a new standard for Protection System Maintenance and Testing (PRC-005-2). PRC-005-2 establishes parameters for condition-based maintenance in addition to simple time-based maintenance. Condition-based monitoring only applies to "protection system components in which every function required for correct operation of that component is continuously monitored and verified" [2]. Microprocessor-based relays can be programmed to continuously monitor many of its components and generate an alarm should any critical component fail. Operators can then be immediately notified and a technician can be sent to the substation to repair or replace the failed relay (component).

The availability of powerful multifunction intelligent electronic devices (IEDs) allows for the integration of protection, metering and control functions into a single device with built-in continuous self-testing features [3]. Pressures for cost reduction (particularly O&M costs) while concurrently improving system reliability have led TNMP to look for ways to optimize operations to provide the most efficient and cost-effective power delivery. A modern relay panel design to be employed with either retrofit panels (replacing aging electromechanical and static relay panels) or new panel construction is a first step towards improving protection system reliability, meeting maintenance and testing requirements and reducing installation and ongoing operating costs.

Relay Panel Design

TNMP believes the best way to get the most efficient and cost effective panel design is by using those features of substation IEDs that allow for the elimination of unnecessary devices that replicate functionality already available in protective relays. Functions that are now incorporated in the relay include: metering (phase voltages, currents, real and reactive power, etc), breaker controls, local/manual and remote controls (local/remote switch, transfer trip cutoff switches, etc), interlocking relays (breaker failure and transfer trip lockout relays), system monitoring (via front-panel HMIs on the relays) and equipment monitoring (DC battery system monitoring and circuit breaker monitoring functions).

It is important to note that even though the goal is to eliminate duplication of common functionality, sound protection system design demands redundancy for the two functions critical for correct protection system operation: fault detection (protective relays role) and fault current interruption (circuit breaker operation). The main characteristics of our transmission panel design are:

- **Dual redundant relay systems:** we employ two independent relays from two different vendors. These relays operate under two different operating principles, with a line current differential relay as primary protection and a distance and directional overcurrent relay and as dual primary. The differential relays use a microwave radio based communications system. The distance scheme is a communications-assisted POTT via fiber-optic cable (preferred) or power line carrier (no fiber available). This scheme design puts an emphasis on elimination of common mode failure.
- **Breaker failure protection scheme:** this functionality is accomplished in two possible ways. In the first option, applied in substations with a breaker and a half bus configuration, a separate relay is used for breaker control and breaker failure protection. The second option involves the integration of breaker failure protection and transmission line protection in one relay. The latter option helps reduce wiring and simplify the design. The design also uses the breaker failure re-trip function enabling operation of both trip coils. A second command to open a circuit breaker is issued after failing an initial attempt before adjacent breakers are tripped.
- **Redundant local/remote manual breaker control:** local breaker control (open/close command) is performed either via the station's HMI computer or using independent control pushbuttons on the relay (these pushbuttons will operate even when the relay is out of service). Remote breaker control is accomplished through remote supervisory control and data acquisition (SCADA) commands. Again, the intention is to eliminate single points of failure.
- **Elimination of auxiliary relays and cutoff switches:** all previously used external cutoff (ON/OFF) switches and auxiliary interlocking relays have been replaced by programmable logic inside the relay.
- **Use of a novel test interface:** conventional knife-blade type test switches have been replaced by a test interface consisting of a test block and respective test plug. The interface's modular design allows us to custom-order the precise combination and quantity of modules needed.

Use of a Novel Test Interface

Traditionally, knife-blade type test blocks have been used to provide technicians with individual switching control of the current, potential and trip circuits wired to the relay. These test blocks consist of red-handle switches used for trip circuits and black handle switches used for potential and trip circuits. Opening a current transformer configured knife-blade switch causes the engagement of a shorting jaw across the current transformer secondary, consequently isolating the current input associated to that switch from the relay (for testing purposes). Opening all test switches isolates the relay.

TNMP has decided to employ a different technology for our new installations. The interface test system consists of a test block that is installed in the panel, and a test plug that is used to simultaneously isolate the relay from the system and establish a test connection point. Upon insertion of the test plug, current transformer circuits are automatically short-circuited through shorting bars located inside the test plug. Voltage and signal contacts are opened. Figures 1 and 2 show the functional principle:

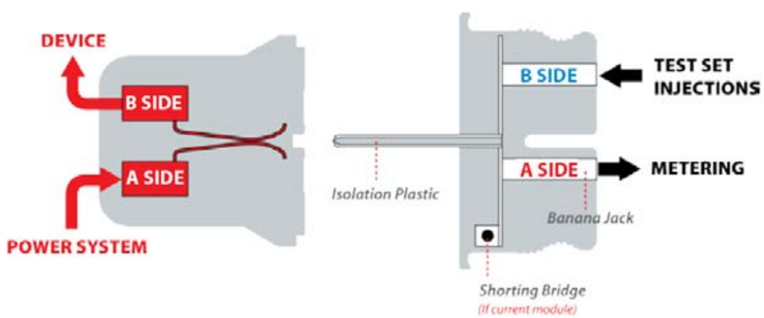

Figure 1. Test Block Flush-Mounted in Panel, in Normally-Closed Standard Position (Test Plug Not Inserted).

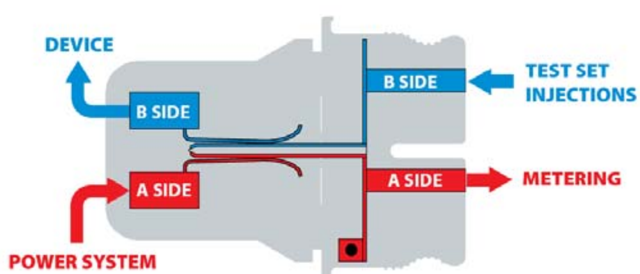

Figure 2. Test Plug Inserted into Test Block, Isolating Relay from the Power System and Providing Test Access to the Relay. CT Circuits are Short-Circuited via Shorting Bridges in the Test Plug.

The test plug is designed with an integrated contact opening sequence, so that signal contacts are automatically opened before voltage and current contacts. When removing the plug from the test block, all contacts are closed in reverse order and the relay goes back into service. TNMP's decision to use the novel test interface has been influenced by a number of advantages, among them the following:

- **Reliability benefits:** using knife-blade test switches, contacts are opened or closed one by one until the relay is fully isolated. In order to avoid false trips, signal contacts should always be opened before current and voltage contacts. The test interface on the other hand performs a pre-defined contact opening sequence upon test plug insertion. The correct opening sequence is guaranteed in every operation, increasing reliability.
- **Safety benefits:** safety benefits associated with the test block / plug system include the automated short-circuiting of current transformer circuits upon test plug insertion, and the finger-safe design of the test block front, which does not contain any contacts that are exposed to the user. In addition, contacts for the test block/plug system are normally-closed (pressure springs are keeping the contacts together). They are only opened when a test plug is inserted, while knife-blade switches can remain in any position after the test is concluded.
- **Panel space savings:** the test blocks utilized by TNMP are built modularly, not restricted to the 10-pole design as it is found in knife blade switches. This allows TNMP to custom-configure test blocks to our exact needs – placing all the current, voltage and signal contacts that are associated to one device in just one test block. When testing, only one test plug has to be inserted to open all relevant contacts for the relay. Figures 3-5 show some of TNMP's standard configurations that have been established after careful analysis of our testing requirements. The 20-pole and 14-pole test blocks shown below (Figures 3 and 4) are mounted next to each in one 19" rack, allowing for a total of 34 contact poles per rack. These two test blocks are associated with the two relays used per line terminal. A 60% reduction of panel space has been achieved compared to using knife-blade switches, in which 7 knife blade test switches were used per line terminal in the old panel design (7 10-position knife blade switches would be needed to isolate relay circuits and an additional 2 switches were used to isolate lockout relay trips).
- **Cost savings**: the reduction in the amount of test blocks used per line terminal led to cost savings, even though an individual test block costs more than an individual knife-blade switch. The reduction in the number of test switches (blocks) led to decreased wiring in the cabinet, saving money both in material costs and required installation time. Panel space savings also translate to substantial cost savings, since they allow for the same functionality in less substation space.

Figure 3. 20-Pole Test Block Used for a Line Distance (21B) Relay

Figure 4. 14-Pole Test Block Used for a Line Differential (87L) Relay

Figure 5. 17-Pole Test Block Used for a Breaker Failure/Breaker Control (86BF) Relay

- **Improved testing procedures:** the possibility to custom-configure length and contact types of the test blocks is a big advantage for TNMP, allowing the concentration of all contacts for one relay in just one test block. Testing procedures can change accordingly – facilitating easier and standardized test methods.

Based on the design characteristics of the new panel, it is possible to build panels that contain all relays and test interfaces for two transmission line terminals in one panel. Typical vintage relay panels for a breaker and a half configuration substation are shown in Figure 6 (left). These 7 old panels have been replaced by the 3 new panels plus a local HMI panel (not previously available) also shown in Figure 6 (right).

Figure 6. Retrofit of Relay Panels for a Breaker and a Half Configuration

Microprocessor based relays started replacing electromechanical and static relays in the mid 1980s and by the mid 1990s they were the most popular protective relay technology worldwide. However, in many cases, the multifunction attributes inherent to modern IEDs are not being fully capitalized. This panel designed shown in Figure 7 (built and installed for TNMP in 2002) is an example of this. In the panel on the left side of the picture, auxiliary lockout relays, cutoff switches, watt/var transducers and panel lights whose functionality is already available in the IEDs are used. Only one line terminal fits in this panel. The panel on the right side of the picture fits two line terminals by eliminating duplicated functionality.

Figure 7. Example of Non-Integration vs. Integration of Protection, Metering and Control Functions

Benefits to Using New Panel Design

Financial Benefits

By combining protection, control and metering functions into the available IEDs and using a novel interface test system, TNMP has reduced initial installation costs due to:

- Equipment cost savings: the efficient use of IED functionality instead of conventional designs reduces the number of panels required by as much as one-half. Also, the added costs of unnecessary auxiliary relays, cutoff switches and panel lights are eliminated.
- Using less panels translates into a reduction in control building size
- Installation and commissioning labor costs are also reduced

Table 1 provides estimated savings for an 8-panel installation using the new design:

Table 1. Estimated Cost Savings for an 8-Panel Installation

Savings Description	Typical Space Savings	Estimated Savings ($)
Use of programmable logic instead of external cutoff switches and lockout relays	9 RU	48,000
Use of novel test interface	6 RU	
Elimination of RTU panel (replaced by communications processor in HMI panel)	1 Panel	30,000
Reduction in control building size (approx. 2.5 feet length reduction per panel)	20% (length)	10,000
Installation and commissioning cost (Labor)	20%	20,000
	Total	108,000

Also, with an integrated panel design, ongoing maintenance and testing costs are reduced. Continuous self-checking features coupled with advanced monitoring features via the local HMI eliminate many periodic inspections in favor of condition-based maintenance.

Reliability Improvements

The reliability of the protection and control system has been improved in the following ways:

- By taking greater advantage of the IEDs continuous self-checking features we are able to immediately detect problems that could cause system outages if corrective action was not taken. Reliability improvements derived from the use of a station HMI combined with the extended use of self-checking and continuous monitoring is discussed over the next sections of this paper.
- Failure-prone devices such as control switches and auxiliary relays are not used in the design. These functions are now performed through programmable logic.
- Redundancy for critical protection and control functions has been achieved hence eliminating single points of failure.

Implementation of an Ethernet LAN and a Local HMI

Ethernet LAN

Until just a few years ago, only serial communication was available in TNMP's substations. TNMP has now chosen Ethernet technology as the backbone for its substation communication networks (substation LAN). Ethernet has been chosen because it provides interoperability, which is backed up by proven communication standards. It is also the framework of choice for future communication protocols such as IEC 61850. Today, every IED installed in a TNMP substation is IEC 61850 compliant. This is a natural requirement since our panels and protection philosophy is based on using multi-vendor IEDs. As a result, there is a need for devices from multiple vendors in our substations to communicate and exchange data over the substation LAN. IEC 61850 was created as an international standard communications protocol to allow for multiple devices (regardless of the manufacturer) to exchange data used for protection, metering and control.

The equipment needed for TNMP's substation LAN implementation is placed on the HMI panel. A front view of a substation HMI panel is shown in Figure 8. The following is a list of the devices on the panel:

- Satellite-synchronized clock
- Managed Ethernet switches: they manage data traffic. Using a managed switch makes data collision less likely which results in higher dependability.

Figure 8. Substation HMI Panel Front View

- 17” touch screen monitor.
- Local HMI computer: industrial-grade computer used for SCADA and local HMI data collection.
- Discrete and Analog I/O processors.
- Rack-mount keyboard with trackball

Local Human Machine Interface (HMI)

In TNMP’s integrated protection and control system design, local control can be achieved either by using the front-panel HMIs available on the IEDs or via the local HMI computer. HMI software in the computer supports the Graphical User Interface (GUI). A local HMI computer, while not a required element of a protection system, provides substation personnel with large displays through which they can have direct control of the equipment (opening/closing of circuit breakers/motor-operated switches, transformer tap changer local control, etc). The following are some of the functions programmed within the local HMI:

- **Overall substation monitoring:** via one-line view displaying breaker/switch status and metering data such as: bus voltages, current and power (watts and vars) flowing through each line, feeder and transformer.
- **Circuit breaker control and monitoring screen:** shows the current status of the circuit breaker along with metering data for the line or feeder the breaker is on, reclosing can be controlled (enable/disable) and open/close commands can be sent to the breaker via this screen.
- **Circuit breaker monitoring function in IEDs:** the circuit breaker monitoring function within the relay has been enabled and programmed to generate an alarm through the local HMI is any of the following conditions is detected: excess breaker contact wear, mechanical operating time, pole discrepancy and motor running time.
- **Transformer monitoring and tap changer control:** displays data essential to evaluate transformer condition such as: winding temperature, oil level (high/low), nitrogen pressure, etc. Also, tap changer control can be performed through this screen
- **DC battery system monitoring:** IEDs monitor the health of the station battery system by measuring their dc voltage input (alarms are set for low/high dc voltage), ac ripple (indication of battery charger health), and voltage the battery terminals and ground (used for indication of dc ground). Also, modern battery chargers have self-checking capabilities and their health is directly monitored via an Ethernet TCP/IP interface into the local HMI.

Figure 9. Portable Test Bed Used for Personnel Training

TNMP Field Personnel Reception

As we were designing the panels we brought in some of our substation technicians and ask them their opinion on the panel. Most of the concerns were with operating switches on the relay versus control handles. We then realized that labeling was important in these panels. We tried different ideas including printing different functions as different colors on the labels placed on the relay, different wording and the use of multi-color LED on the relays. At last, we developed a system in which we used the LED color to differentiate problems. For example, red color LED was used to annunciate alarms that needed to be answered, amber indicated a switch that the operator could turn on or off and green was an indication for items in their normal state (communication channel OK, IRIG lock, etc). We also had our technicians build prototypes of some of the panels and they helped develop the test procedures. We also made use or our portable test bed (see Figure 9) to help train the operations personnel on how to work with the new panels. As a result of taking into consideration our technician's ideas and incorporating many of them in our design, we were able to avoid some of the possible pitfalls with the operation of the panels.

Conclusion

At TNMP we have used the latest technology to minimize valuable floor space in the substation control room. We have developed line panels that now cover two line terminals in one panel. We also have installed Human Machine Interface's at our substations that serve not only as a data concentrator, but also replaces the Remote Terminal Unit. Again, this will save more space in the substation. In addition we have considered future protocols (IEC 61850) in the network topology and control structure of our protection systems. The system also has considerations for future Critical Infrastructure Protection and automation requirements. Condensing panel space not only saves money on individual panels, but it keeps us from having to do costly additions and renovations to substation control houses. TNMP has over the last years employed new storage media, state of the art relays and a reduced number of test interfaces to reduce overall front panel size by 60%.

References

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Biographies

Levi Portillo received his B.S. in Electrical Engineering (2000) from Zulia University, Venezuela and M.S. in Electrical Engineering (2006) from Texas A&M University, College Station. He worked for Dashiell Corp., Houston, TX, 2006-2008. He has worked for TNMP's engineering department since 2008. His research interests include power system monitoring, protective relaying and substation automation.

Sam Woolard received his BSEE from the University of Texas Arlington in 2000, and his MEEE from the University of Idaho in 2006. He has worked for TNMP since 2000 in the distribution, substation and metering departments. He is a registered professional engineer in Texas. He lives in Friendswood Texas with his wife and 3 children

Tobias Planert was born in the state of Lower Saxony, Germany, in 1977. He received his degree in International Business, Language and Cultural Studies from the University of Passau, Germany, in 2005. Tobias worked for a consulting firm in Duesseldorf, Germany, from 2005-2006. Since 2007, he has been with SecuControl, Inc. in Alexandria, VA. His professional interests include all questions related to advanced test interfaces for secondary injection testing.