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OPEN AUTOMATION FRAMEWORK

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ABSTRACT

Multifunction Numerical Protection Relays are boxed silos. Incredible opportunities for synergy are lost because of the inability of numerical relays to interact at the microchip or circuit board level, even when they might be housed in the same panel and/or are monitoring the same primary equipment.

We propose the **Open Automation Framework** as an open standard for substation design and architecture that transparently integrates various protection and automation functionality within a control panel. It will facilitate reliable and secure communications between protection and automation functions with the aim of increasing redundancy, improving reliability and maximizing reuse of components within the substation automation system. Such an arrangement will also minimize the need to employ inter-device communication protocols such as IEC 61850 leading to a reduction in capital investment as well as simplification of the substation design. At the same time, the reduction in downtime for repair and maintenance will simultaneously increase the availability and bring down the lifecycle costs of the substation automation infrastructure.

KEYWORDS

Open Automation Framework, Power System Protection, Protective Relaying, Substation Automation, Transfunctional Control Panel, Protective Relay, Numerical Relay.

1 Introduction

Tremendous advances have been made in the field of electrical protection over the past half century, both in the domain of techniques and technology. The progress from single function relays to Intelligent Electronic Devices has brought about significant changes in the conception as well as operation of power systems [1]. These changes have led to a decrease in the time of construction, commissioning and maintenance of control panels as well as an increase in control reliability and flexibility [2]. The technological progress in automation has not only been responsible for the development and deployment of new techniques and algorithms, it has also been the key driver behind upstream innovations such as packaged substations [3] and smart-grid [4].

The rapid technological progress in protective relaying, however, has not translated in the correspondent advancements in relay architecture and design, which remains squarely rooted in its historical antecedents. Multifunction relays continue to be built as if they are aggregations of single function devices, due to which the new possibilities that arise with digital technology remain unrealized. The design of a control panels has largely remained unchanged, save the reduction in space and wiring due to the replacement of many single function electro-mechanical/static relays with a fewer number of Integrated Electronic Devices.

The aim of this paper is to motivate an Open Automation System that addresses these shortcomings in multifunction numerical relays through an open standard for control panel architecture and design. The resulting Transfunctional Control Panels will allow information generated from numerical computations at multiple levels of granularity to be shared, thereby uncovering new opportunities for operational synergies. We shall further demonstrate that by unlocking the full potential of numerical technology, the Open Automation Framework leads to the realization of greater operational reliability, simplified substation design, improved operator experience and ease of maintenance. The adoption of the Open Automation Framework will allow utilities to provide improved quality of service while bringing down their operating costs.

2 Overview

2.1 Literature Review

The research literature on hardware design of numerical relays is exclusively focused on the development of microarchitecture[1], in particular, the implementation of relays and/or algorithms using specific devices or technologies [6, 7, 8, 9]. We were unable to find any research that deals with system architecture of numerical relays.

Proposals for modular construction of numerical relays found in literature include Pozzuoli's conception of a 'Universal Relay' [10], which is inspired by the design of Personal Computers [11]. This concept

[1][5] *Architecture* defines an interface specification that describes the functionality of an implementation, while being independent of the actual implementation. *Microarchitecture*, on the other hand, defines how this functionality is actually realized as a composition of modules and components, along with their associated software.

forms the basis for the UR and UR-plus family of relays manufactured by General Electric. A similar concept has also been espoused by Gurevich as a foundation to develop an (inter-)national standard for relay architecture [12]. These concepts, however, do not consider the design of a numerical relay in the context of other secondary equipment housed in the control panel or the substation. Their conception of modularization is limited to the purpose of simplification of the construction of a multifunction relay. These proposals also fail to account for the specialized architectural requirements of numerical relays due to the lack of distinction between general purpose computers and embedded systems.

We address these gaps in research by identifying the architectural principles for the design of numerical relays based on the extensive body of research in embedded systems [13, 5, 14, 15]. Taking account of these consideration lead us to the development of the Open Architecture Framework.

2.2 Protective Relaying

Before we introduce the Open Automation Framework, it is instructive to very briefly examine the operation of a relay. A protective relay is an embedded system that continuously monitors the power system to which it has been attached and upon sensing an abnormal condition such as a disturbance or a fault, performs the appropriate corrective action like raising an alarm and/or tripping a circuit breaker.

In electromechanical relays, this task of power system protection is accomplished by a single mechanism which converts the electrical quantity into a mechanical operation. An electromechanical relay is essentially a mechanical embedded computer system attached to the power system. Likewise, a static relay is an analog embedded system, that performs the same task in two steps: converting power system events into electronic signals which are then used to drive auxiliary switching devices.

Contrast these with a numerical relay, which performs a number of transformation steps in the process of determining an electrical fault and initiating corrective action. Incoming currents and voltage measurements from instrument transformers are continuously sampled and converted to numerical values by Analog-to-Digital (A/D) Convertors. The state of the power system is determined by processing these samples through numerical algorithms, which are typically implemented inside a microprocessor or a Digital Signal Processor. Finally, the results from various numerical algorithms are aggregated by a logic program or circuit in order to determine the signalling and tripping operations that the relay must perform. Apart from this, the relay also performs a number of auxiliary operations, such as communications with other substation equipment and/or the substation operator. Each of these operations also require that the raw data at each previously identified stage is converted to the requisite formats needed to perform the auxiliary function. The same applies for any recording and metering functions as well. Unlike electromechanical or static relays, data processing in numerical relays occurs over a number of intermediate steps. More importantly, the result at the end of each intermediate step is observable, which can be recorded as well as transmitted. This characteristic of numerical relays acts as the keystone upon which the Open Automation Framework is built.

2.3 Benefits of Numerical Relays

Numerical relays offer a number of benefits such as the implementation of multiple functions on a single device, custom logic schemes, reduced panel space, lower burden on instrument transformers etc., all of which lead to the simplification of secondary infrastructure and reduction in associated costs [16]. Self-monitoring and self-testing lead to greater reliability as these relays are capable of promptly alerting operators in case of failure, allowing the utility to initiate remedial action and minimize any disruption [3]. Data Recording and Oscillography provide valuable data for both fault diagnosis and asset management [17]. Microprocessor technology allow various protection and automation equipment to continuously communicate with each-other; this has been the driving force behind the development of universal communication standards such as the IEC 61850.

The emergence of numerical technology has also driven convergence of secondary substation equipment that perform protection, control, metering, data acquisition and programmable logic within a single unit referred to as Intelligent Electronic Device or P&C Substation Node [3].

The ability of numerical technology to implement functionality in software has also encouraged the development of novel protection and automation algorithms. Not only does software implementation bring down the cost of hardware development, it allows these algorithms to be added or updated in field as and when they become available.

Through the optimization of architecture and design, the Open Automation Framework aims to maximize these benefits offered by numerical technology.

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2.4 Shortcomings of Numerical Relays

We had observed earlier that despite the technological advances, multifunction relays continue to be built in the paradigm of single function devices from previous generations. Due to this, the potential of numerical technology remains unrealized with the following shortcomings:

- When a numerical relay is completely implemented in software (as is the case with almost all multifunctional relays in the market today), the entire functionality including all mission-critical operations, such as the protection and control functions as well as the non-critical operations such as user interfacing, data recording, communications etc. is executed by the same microprocessor. This requirement has been known to impede the performance of a numerical relay, given that the behaviour of the modern microprocessor is known to be chaotic [18]. This becomes especially likely when multiple functions are triggered simultaneously. Priority algorithms [16, 19] and faster processors help ameliorate this problem but do not entirely eliminate it.

- The use of microprocessors and Digital Signal Processors for the implementation of mission critical protection function is not secure due their inherent ability to run an arbitrary program. This exposes them to the risk of cyber-attacks and malware such as the BlackEnergy Trojan [20].

- Typically, the failure of a numerical relay is a consequence of a failure of individual components and/or circuit board. However, the entire relay needs to be taken out of operation for repair or replacement with the consequent need for a shutdown, even when such a failure is in a non-critical component.
- Preventive replacement of limited life equipment also requires for the relay to be taken out of service, though, at least the utility has an opportunity to plan a shutdown in advance.
- In cases of obsolescence, a numerical relay has to replaced entirely even when there has been an isolated failure and even when such a failure is in a non-mission critical component.
- Man-machine interface of numerical relays is rather limited in nature. The small LCD displays are capable of providing only limited information and few buttons make interaction with the device difficult. This not only makes the task of the operator difficult but also increases the risk of human error.
- Every multifunction numerical relay has a different interface, each requiring specialized training increasing personnel costs as well as bringing with it an increased risk of human-error.
- Numerical relays, even within the same panel, require external means of communication, with the associated need to convert data to and from a high level format such as the IEC 61850 protocol. This places additional processing burden on a relay even though the raw information might be available in the adjoining device.
- Failure of individual component or board puts a relay out of commission, even though the requisite functionality might be available in another relay within the same panel. That is, we are currently unable to employ components in the same control panel that perform similar or identical function to create redundancy because they are housed in separate relays.

In the following, we present the Open Automation Framework and demonstrate that it addresses the above-mentioned issues.

3 Open Automation Framework

The Open Automation Framework is a holistic approach to the design of control panels. It provides an open standard that will transparently bring together components implementing protection and automation functions and facilitate reliable and secure communication between them. This will simplify the substation architecture whilst allowing the utility to realize new efficiencies.

3.1 Architecture

At the electronic system level, the Open Automation Framework introduces a heterogeneous multiprocessing architecture aimed at the orthogonalization of functional concerns [5]. Heterogeneous multiprocessing [21] is an established paradigm in the design of embedded systems which exploits the fact

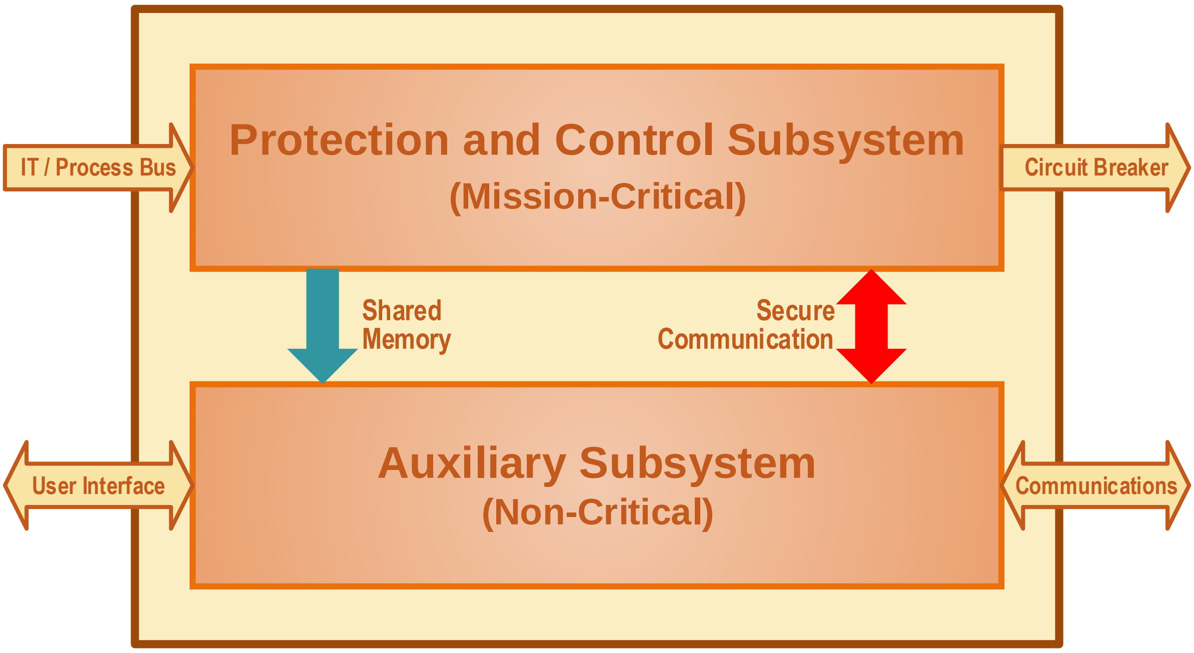

Figure 1: System Level Architecture

these computers are not general purpose but target a set of domain-specific applications which can be implemented independently of each-other. Such architecture considerations greatly simplify the design at higher levels of abstraction, in particular, the construction of PCB modules that connect together to form the protective relay. We shall orthogonalize the functional concerns of a protective relay across three dimensions:

The first dimension for separation of concerns in numerical relaying is criticality of operations. Whilst protective relays implement multiple functions that make it an integral component of a substation's automation scheme, its functional priority squarely remains the reliability of protection and control operations. This suggests a partitioning scheme where-in relay functions may be bifurcated into two sets[2] , mapped onto separate processing subsystems as shown in figure 1, viz.

- **Mission-Critical**: Protection and Control functions and
- **Auxiliary**: Data Recording, Metering, Interfacing and Communication functions

The second dimension for the separation of concerns is along transformation stages. In section 2.2, we had seen how a numerical relay performs its operations as a series of tasks, each of which involve an independent transformation of data. This suggests an orthogonal partitioning scheme in which such tasks are mapped onto separate processing units. Illustration A of figure 2 exhibits task based partitioning for the Protection and Control Subsystem.

The third dimension for separation of concerns involves the identification of independent relay functions. At any given criticality (first dimension) and/or transformation stage (second dimension), a relay performs

[2] In principle, it is possible to define an arbitrary number of partitions. Two partitions, though, are sufficient for the purpose of this illustration

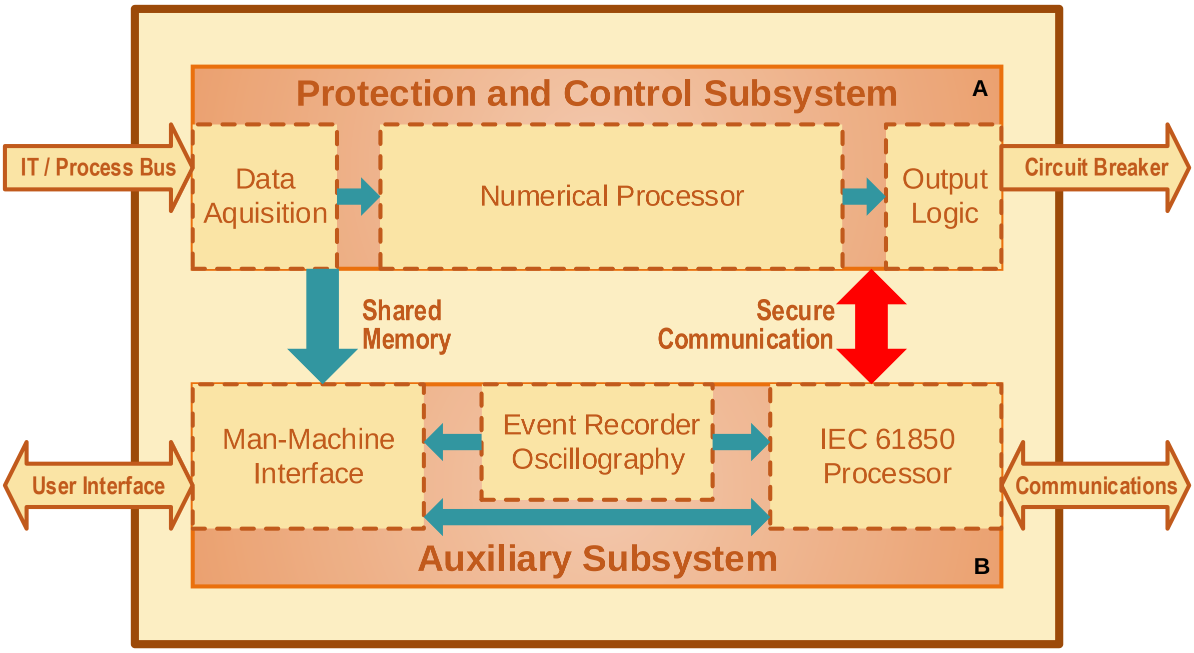

Figure 2: Detailed Architecture

a number of independent functions which may, again, be implemented in independent hardware and/or software. This is the case for the functional units implemented within the Auxiliary Subsystem as shown in illustration B of figure 2.

3.1.1 Protection and Control Subsystem

Due to their mission-critical nature, the protection and control functions are implemented in a dedicated set of processors independent of other subsystems. The partitioning allows the manufacturer to focus maximal design effort and resources on the development of this subsystem. Dedicated processing allows for the independent execution of these functions, ensuring that other relay functionality is in no way able to interfere with these mission-critical functions. This translates into higher reliability where most necessary. The micro-architecture implementation might be performed using a combination of custom processor, reconfigurable hardware and software.

The Protection and Control Subsystem may be further partitioned along the operational axis into the following stages as shown in figure 2:

1. *Data Acquisition*: is responsible for acquisition of analog data and conversion to a suitable numerical form,

2. *Numerical Processing*: performs the numerical computations required to identify disturbances and determine faults,

3. *Output Logic*: that aggregates the result of numerical algorithms to initiate corrective actions, such as, signalling or tripping.

Finally, it is also possible to partition the subsystem into groups of independent protection and control functions that implemented by the subsystem or any transformation stage. The former is in many ways analogous to the installation of multiple numerical relays within the same panel. These independent groups might be segregated in software and/or hardware. A possible approach that takes advantage of this inherent parallelism, is to implement the protection and control functions in hardware using a concurrent Dataflow architecture controlled by a Finite State Machine. Details of such a design, however, is beyond the scope of this paper.

The Protection and Control Subsystem serves as the interface between the primary equipment and the relay. Consequently, the communication interface defined by the Open Automation Framework imposes restrictions on its interaction with rest of the relay. This not only ensures operational integrity, but also to creates an additional layer of security. While the Protection and Control Subsystem is allowed to communicate the computational results that it generates as well as raises interrupts, write access to it is limited to change of settings, device calibration, functional testing and software updates. This communication might be implemented through a combination of shared memory and serial bus. Access to Protection and Control Subsystem will be allowed only through a multi-layer security protocol or directly on the physical hardware via an independent test-port.

3.1.2 Auxiliary Subsystem

Auxiliary Subsystem implements the non-critical functionality of a numerical relay such as communications, the man-machine interface, measurements, data recording etc. The partitioning provides an opportunity to the manufacturer to develop this subsystem with greater economy as well as the potential for reuse of individual processing units within the Auxiliary Subsystem across the entire protection and automation functionality implemented in the control panel .

These considerations suggest that the micro-architecture implementation is more likely (though not necessarily) to be exclusively in software. As many of these functions are independent, again it is also possible to implement them using one or more processors depending on the design requirements.

By virtue of its functions, the Auxiliary Subsystem serves as the interface between the relay and other secondary equipment as well as the operators within the substation. Since functions implemented within the Auxiliary Subsystem cannot directly interact with the power system itself, a less stringent security protocol will usually suffice.

3.2 Design

Open Architecture Framework is realized as a Transfunctional Control Panel built from functionally independent printed circuit boards that interconnect through a midplane. The functionality implemented by individual modules and the communication between them is informed by the system level architecture of the Open Automation Framework discussed in section 3.1.

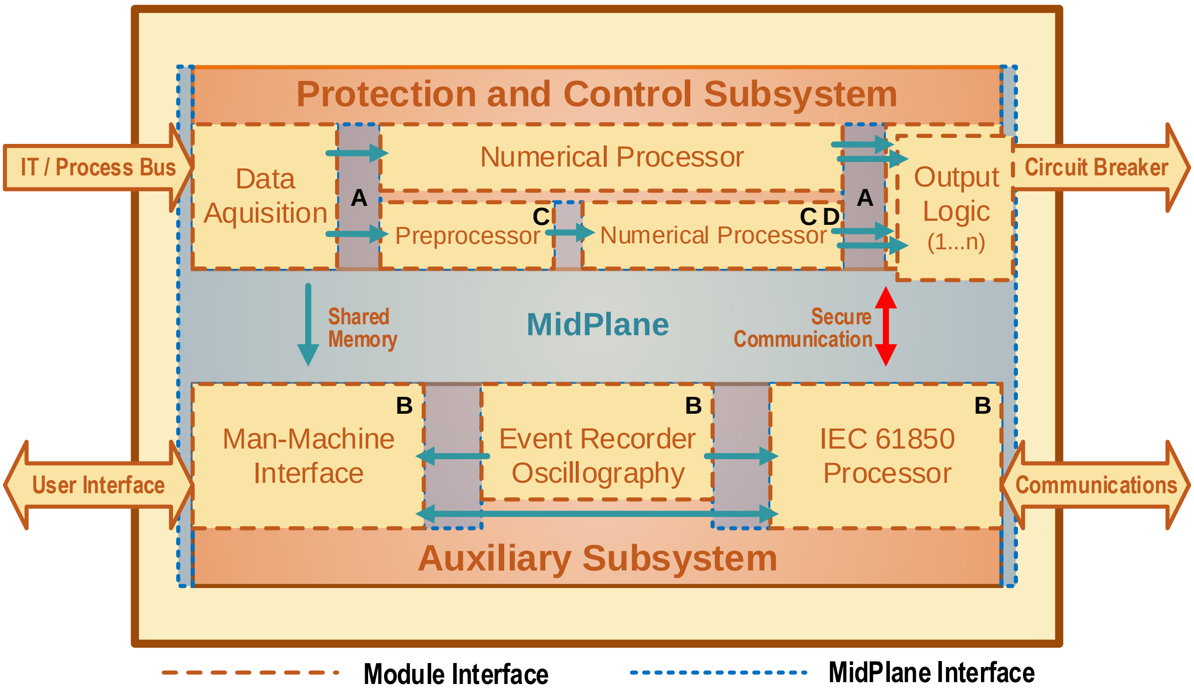

Figure 3: Transfunctional Control Panel Design

3.2.1 Midplane

The midplane serves as the backbone of the Transfunctional Control Panel. On one side, the midplane provides terminals to connect to power system equipment such as instrument transformers and/or the process bus as well as ports needed to establish communications to other secondary equipment in substation. On the other side, the midplane provides the high speed inter-connection fabric that facilitate communication between the functional modules. It also provides the power rails needed to carry electrical energy from the power supply module to all the other functional modules.

With the intra-node communication explicitly beyond the scope of IEC 61850 [22], the Open Automation Framework can be freely designed upon one from a number of interconnect standards that already exist in the market such as Peripheral Component Interconnect Express (PCIe), RapidIO and Backplane Ethernet(803.2ap). These standards allow for a number of different connectors and form factors such as AdvancedTCA, XMC, OpenVPX, VXS, CompactPCI etc. to name a very few.

3.2.2 Modules

Every functional partition along the three dimensions identified in section 3.1 might, in principle, be realized as its own module. However, design and commercial constraints will dictate that some of this functionality is aggregated together.

A Transfunctional Control Panel shall comprise of an assembly of vertically mounted modules of uniform height that plug into the switching fabric through a standard connector, akin to a blade server. The modules shall be user-replaceable and support hot-swapping to simplify assembly and minimize disruption. By virtue of all the modules in a control panel being connected to the same switching fabric, the protection and automation functions that reside in the panel are able to freely exchange information with each other.

3.3 Benefits

Together, the architecture and design of the Open Automation Framework lead to the realization of a number of benefits as we shall now see:

3.3.1 Reuse

One can immediately see that such a flexible setup encourages the reuse of information generated by modules, and by corollary, the reuse of modules themselves. The developers of such Transfunctional Control Panels benefit from a simplified design and reduction in development costs. Utilities benefit from such reuse with the availability of improved functionality at a lower price.

At one end of the spectrum, Open Automation Framework allows multiple modules to reuse the results generated by a common module. For example, various numerical processors in the Protection and Control Subsystem can derive their input data from a common Data Acquisition Module as shown in illustration A of figure 3. Contrast this with an installation of multiple Intelligent Electronic Devices in a panel, wherein each device has their own Data Acquisition System, with some employing inferior technologies than others. Not only is there wasteful redundancy of components, each device also needs its own separate wiring to the primary equipment – each coming with its associated costs.

On the other end of the spectrum, the Open Automation Framework will allow a single module to aggregate the result from multiple modules. For example, a single man-machine interface could be setup to interact with all processors in the Protection and Control Subsystem that reside within a panel. By virtue of not having to implement a user interface for every device or module, manufacturers could provide a more functional user experience similar to that of a personal computer while realizing significant savings. See illustration B in figure 3.

Yet another possibility arising from such an architecture is the implementation of a function across multiple modules as shown in illustration C of figure 3. This is especially useful if the results from a particular step might be reused in others, such as, a Fourier transform module whose results might be shared by various protection and automation algorithms implemented in separate modules.

3.3.2 Improved Performance

The support for Heterogeneous Multiprocessing will reduce the computational load on individual processors when multiple functions are triggered simultaneously. The reduction in response time will lead to improved performance, especially in case of complex substation events such as multiple faults occurring together. The improved performace will also significantly reduce the test burden for developers. See illustration D in figure 3.

3.3.3 Simplified Development

Manufacturers will find it easier to develop new products as they are only required to build individual modules at any given time and not a complete multifunctional device. This will simplify the development cycle and considerably bring down time to market for new products. With shorter development cycles, technological innovations can be incorporated into new products at a faster rate. Based on the market opportunities and available expertise, manufacturers also have the flexibility to specialize in the development of select modules.

3.3.4 Planned Redundancy

Open Automation Framework will allow engineers to build redundancy at various stages to improve the reliability of the protection system. One example of such redundancy is the use of multiple power supply modules within a control panel, such that the failure of one or more modules has no effect on the operation of the panel.

3.3.5 Flexibility and Scalability

The Open Automation Framework not only provides greater flexibility to the utility in setting up secondary infrastructure, the deployment of modules can scale with the requirements of the substation. Utilities will have the possibility to deploy modules with only the functionality that they actually require. This results in a significant reduction in complexity as well as costs when compared to the deployment of multifunctional devices, wherein much of the functionality might have gone unused.

3.3.6 Upgradability

The needs of a substation evolve over time, which require corresponding changes to the secondary infrastructure. The modular nature of the Transfunctional Control Panels shall allow the utility to add and/or replace specific modules to augment the functionality that resides in a panel. Without the need to resort to the replacement of multiple numerical relays, upgrades becomes easier to plan and more cost effective. It also shortens the upgrade cycle which will benefit manufacturers as well.

3.3.7 No Data Fragmentation

Presently, when a complex fault occurs, data for each numerical relay in a control panel has to be downloaded separately and then put together. With the Open Automation Framework, engineers will have the opportunity to examine fault and disturbance records for a control panel holistically using a single software interface. This will make it easier for the engineer to diagnose anomolies in the power system.

3.3.8 Simplified Configuration

With the Open Automation Framework, the control panel is set up as a whole. This eliminates the need to configure multiple devices, each of which (especially when built by different manufacturers) come with their own configuration system. The burden of maintaining multiple records is also significantly reduced.

3.3.9 Improved User Experience

With the Open Automation Framework, manufacturers will have the opportunity to offer an improved user interface that is shared across the Transfunctional Control Panel as discussed in section 3.3.1. Operators will no longer be constrained to minute LCD screens or have to fiddle with tiny buttons. Not only does this make the task of the operators easier, it also bring down the possibility of human error.

3.3.10 Elimination of Redundant Wiring

With multiple devices being swapped out for a unified setup, fewer wires are needed to connect the primary equipment to the panel. Further, there is no need to setup communications between multiple devices in the same control panel. This leads to a simplified substation setup with the attendant reduction in costs.

3.3.11 Simplified Commissioning

With the Open Automation Framework, extra effort is involved in the initial set up of the control panel and installation of modules. However, this will be offset by the reduced complexity of setup, simplified configuration and the reduction in wiring.

3.3.12 Personnel Training

A unified system means that there is far less operational variation, not just within a control panel but across the substation. Substation operators and commissioning engineers need not be trained in installation and operation of multiple devices, each with its own differing setup, significantly bringing down the cost and complexity of personnel training.

3.3.13 Ease of Maintenance

Since the modules might be hot-swapped, they can be easily replaced in case of a malfunction. Unless there is a more pervasive malfunction or damage to the switching fabric, such replacements might be performed without the need for a shutdown. Hot-swapping is also ideal for preventive replacement which, again, leads to improved reliability.

4 Conclusion

The revenues that a utility is able to generate is intrinsically linked to the quality of service it provides – the continuity of supply and the quality of power. A major driver towards substation automation has been the need for prompt and accurate decision required to deliver quality service despite the high cost and scarcity of skilled labour. At the same time, utilities need to manage substation infrastructure comprising of different power system equipments, each with their own unique lifecycle. One of the big impediments faced in management of a substation is the complex interdependence of various equipment that make both maintenance and upgradation difficult. This not only increases the capital expenditure but also lead to commissioning delays as well as service outages. Such complexity further adds to operation and maintenance costs of the substation.

The proposed Open Automation Framework will simplify the substation architecture and design, which will not only improve the reliability of the protection system but also make it easier to manage and operate, bringing down operational and lifecycle costs. The deployment of Transfunctional Relays Panel, like its technological predecessors, will encourage utilities to develop new application philosophies to maximize grid utilization and further prioritize service continuity. The Open Automation Framework will provide utilities with a new means to thrive in today's challenging operational environment with simultaneous improvments in quality of service and discovery of new efficiencies.

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