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Abstract— This paper discusses the role of protective relaying in a Smart Grid. It outlines the definition, attributes, and benefits of a Smart Grid. The role that protective relays can play in implementing Smart Grid functionality and the impact that a Smart Grid design may have on modern protective relays is discussed. Specific examples of Smart Grid applications that may be implemented using modern protective relays and other intelligent electronic devices are provided.

Keywords— Active network management, Adaptive protection, Advanced metering infrastructure, Communications infrastructure, Condition-based maintenance, Distributed energy resources, Distribution automation, Situational analysis, Smart grid, Transmission Automation

I. INTRODUCTION

In order to modernize America's aging utility infrastructure, the United States Department of Energy implemented the Modern Grid Initiative (MGI) to facilitate the creation of "smart grids." The benefits of a smart grid are numerous for both utility companies and their customers. Key advantages are a more reliable and cost-effective system. Smart grid technology allows system operators to respond to attacks by redirecting power flows and minimizing damage. In addition, it also provides customers with the opportunity to view their consumption in real time while interacting with other "smart appliances" they may have in the home. One of the most important features, however, is the use of protective relay devices (PRDs). Through the use of PRDs, advanced diagnostics during interruptions or events can be quickly obtained providing snapshots of the health of a utility grid. This information plays a crucial role in identifying faults, interruptions and disturbances and correcting those issues in order to minimize the impacts to the customer. This paper will cover several of these topics in detail. It will provide a working definition of a "smart grid" and a comprehensive review of its technological benefits. Also included is an overview of advanced functions and features. Smart grid technology and the role of protection in a modern smart grid will be examined. As this paper will show, the landscape of the grid is changing, and protection does play a crucial role as the move toward the more contemporary grid is realized.

II. SMART GRID DEFINITION

A smart grid uses advanced sensing, communication and control technologies to generate and distribute electricity more effectively, economically and securely [1][2][3]. Also integrated into a smart grid are new innovative tools and technologies from generation, transmission and distribution, including consumer appliances and equipment. A modernized grid will create a digitally-connected energy system that will:

1. Detect and address emerging problems on the system before they affect service
2. Respond to local and system-wide inputs, and have much more information about broader system problems
3. Incorporate extensive measurements, rapid communications, centralized advanced diagnostics, and feedback control that quickly returns the system to a stable state after interruptions or disturbances

Specifically, a smart grid will be able to meet future demand growth and have the following characteristics:

1. Increased use of digital information and controls technology to improve reliability, security and efficiency of the electric grid
2. Dynamic optimization of grid operations and resources with full cyber-security protection
3. Deployment and integration of traditional generation and distributed energy resources (DER) including renewable resources
4. Development and incorporation of demand response (DR), demand-side resources and energy-efficiency resources
5. Deployment of 'smart' technologies for metering, protection, monitoring, control and communications concerning grid operations and distribution automation (DA)

6. Integration of ‘smart’ power system devices
7. Integration of ‘smart’ appliances and consumer devices
8. Deployment and integration of advanced electricity storage and peak-shaving technologies
9. Provision to consumers of timely information and control options
10. Development of standards for communication and interoperability of appliances and equipment
11. Identification and lowering of barriers to adoption of smart grid technologies, practices, and services

III. WHY DO WE NEED A SMART GRID

A. *What is wrong with the grid today*

The electric power grid in North America has historically been reliable. However, the demands placed on the grid have continued to increase and additional investments in the grid may not have always matched the increased performance requirements. Energy losses in the transmission and distribution system have increased dramatically from the 1970’s through the beginning of the new century.

Operational and security risks are present in the design of the grid with centralized generation plants serving distant loads over long transmission lines. Adding more DER presents new operational challenges.

Meanwhile, there has been a rapid increase in the amount of power being traded between regions. In addition, in our digital society, power quality is of much greater importance than it was just 15 years ago, both for household consumers and commercial businesses.

It thus becomes apparent that the current grid is insufficient to serve us in the future.

B. *Problem definition*

Driving forces to modernize current power grids can be divided in the following general categories: increasing reliability, efficiency and safety of the power grid, enabling different ways of employing existing central generation, enabling decentralized power generation, flexibility of power consumption at the client’s side, and renewable energy deployment in the form of DER.

Today’s power systems are designed to support large generation plants that serve distant consumers via a transmission and distribution system that is essentially one-way. The grid of the future will be a two-way system where power is generated by a multitude of small DER in addition to large plants. Power flows across a grid will be network based rather than a hierarchical structure. The smart grid will enable the changes necessary to facilitate the variations in the flow of electrical power.

IV. SMART GRID FUNCTIONS

According to the MGI report, a modern smart grid must be able to heal itself, motivate consumer participation, resist attack, provide higher quality power, accommodate all generation and storage options, enable electricity markets to flourish, run more efficiently, and enable higher penetration of intermittent power generation sources.

A. *Minimize system disruptions*

A smart grid can automatically avoid or mitigate power outages, power quality problems, and service disruptions by using real-time information from embedded sensors and automated controls to anticipate detect and respond to system problems.

B. *Consumer participation*

A smart grid incorporates consumer equipment and behavior in grid design, operation, and communication. An example of which is that real-time, two-way communications enables consumers to better control appliances and equipment in homes and businesses through means of interconnected energy management systems. This results in improved energy management and reduces energy costs for consumers.

C. *Resist attack*

Smart grid technologies better identify and respond to man-made or natural disruptions. Real-time information enables grid operators to isolate affected areas and redirect power flows around damaged facilities.

D. *High quality power*

Using the additional intelligence provided by sensors and software designed to react instantaneously to imbalances, smart grid technology can help to mitigate any degradation of system power quality that may be caused by the intermittent operation of DER.

E. Accommodate generation options

As smart grids continue to support traditional power loads, they also seamlessly interconnect DER technologies at local and regional levels. Integration of localized and traditionally centralized generation options improves reliability, power quality, may reduce electricity costs, and offers more consumer choices.

F. Enable electricity market

Significant increases in bulk transmission capacity will require improvements in transmission grid management. Such improvements are aimed at creating an open marketplace where alternative energy sources can easily be sold to customers wherever they are located.

G. Optimize assets

A smart grid can optimize capital assets while minimizing operations and maintenance costs. Optimized power flows reduce waste and maximize the use of lowest-cost generation resources.

H. Enable high penetration of Intermittent Generation Sources

Political initiatives to address climate change, environmental concerns, and economic drivers are increasing the amount of renewable energy resources, which are often intermittent in nature. Smart grid technologies will help to enable power systems to accommodate larger amounts of such energy resources.

V. SMART GRID FEATURES

Existing and planned implementations of smart grids provide a wide range of features to perform the required functions.

A. Load adjustment

The total load connected to the power grid can vary significantly over time. A smart grid may warn individual customers to reduce the load temporarily or continuously. It is possible to predict how many standby generators need to be used to restore or maintain a stable power system for specific system contingencies. In the traditional grid, the maintenance of a stable local grid for a specific failure can only be achieved at the cost of more standby generators. In a smart grid, the load reduction by even a small portion of the clients may eliminate the problem.

B. Demand response support

DR support allows generators and loads to interact in an automated fashion in real-time, coordinating demand to flatten load spikes. Eliminating the fraction of demand that occurs in these spikes eliminates the cost of adding reserve generators, extends the life of equipment by reducing wear and tear, and allows users to cut their energy bills by telling low priority devices to use energy only when it is low-cost.

C. Greater resilience to loading

Although multiple routes are touted as a feature of the Smart Grid, the old grid also featured multiple routes. Initially, power lines in the grid were built using a radial model. Later, connectivity was achieved via multiple routes, referred to as a network structure. However, this created a new problem, if the current flow or related effects across the network exceed the limits of any particular network element, that network element could fail, and the current would be shunted to other network elements, which eventually may fail also, causing cascading outages. Smart grid techniques can be used to prevent these cascading outages using intelligent reconfiguration following an element failure.

D. Decentralization of Power Generation

Another element of the fault tolerance of smart grids is decentralized power generation. Classic grids were designed for one-way flow of electricity, but if a local sub-network generates more power than it is consuming, the reverse flow can raise safety and reliability issues. A smart grid can help to manage these situations.

E. Price Signaling to Consumers

In many countries, the electric utilities have installed double tariff electricity meters in many homes to encourage people to use their electric power during night time or weekends, when the overall demand from industry is very low. During off-peak time the price is reduced significantly. In a smart grid the price could be changing in seconds and electric equipment would be given a methodology to respond to those price signals.

VI. SMART GRID TECHNOLOGY

Smart grid technology supports the role of PRDs within a smart grid by adapting technology already used in manufacturing and communications. By using inter-operative formats, data pulled from PRDs, can be supported by integrated communications, sensing and measurement, smart meters, advanced components, phasor measurement units (PMUs) and advanced controls with improved interfaces and decision support. Inter-operative formats are being implemented in the forms of IEC 61850, MultiSpeak, IEEE Synchrophasors (C37.118), IEEE 2030 and the UCA International Users Group [2].

VII. INDUSTRY SECTORS AND SMART GRID SEGMENTS

Industry sectors involved in the smart grid include the following: the physical power layer (transmission and distribution), the data transport and control layer (communications and control) and the application layer (applications and services).

Advanced metering infrastructure (AMI) and the field area network (FAN) provide the connectivity between a utility and a customer's home area network (HAN).

Smart grid segments and applications include DR, grid optimization, DER integration, energy storage, electric vehicles (EV) and plug-in hybrid electric vehicles (PHEVs), advanced utility controls systems and smart homes and networks. Utilities benefit from using smart grid segments and applications by avoiding the installation of additional expensive peaking power plants.

VIII. SMART GRID PROJECTS

The following sections of the paper expand on the definition of a smart grid and the technologies presented and provide a list of potential utility smart grid projects. Highlights of possible projects include:

1. Retrofits to transmission apparatus with smart grid capabilities including modifications to both terminal and line equipment
2. Transmission monitoring, control, and optimization including sensors, communications and computer systems and software
3. Distribution monitoring, control and optimization including sensors, communications and computer systems and software
4. Smart grid technologies focused on facilitating the expansion and integration of renewable resources
5. Advanced metering including advanced meters, communications infrastructure and computer systems and software
6. Communications infrastructure to support smart grid including DA and advanced metering
7. Implementation of reliable and resilient microgrids
8. Integration of DA, feeder automation (FA), AMI and microgrids
9. Integrating EV and PHEV into the smart grid
10. Providing consumers with the information, incentives and tools to enable them to participate in energy markets and grid operations
11. Cyber security projects to harden the system and comply with regulatory requirements

IX. ACTIVE NETWORK MANAGEMENT

Active network management (ANM) is intended to dynamically optimize system performance by automatically reconfiguring a network as system conditions change. ANM is generally made possible by using information available from smart-grid components such as relays and other measurement and control devices. Some of the objectives of ANM are described in the full report and an example is provided of one application involving maximizing DER output within the constraints of real-time system conditions [1].

X. IMPACT OF PROTECTION ON SMART GRID FUNCTIONS

Two examples of the impact of protection will be considered: dynamic loading and power transformer asset management.

The installation of new wind generation at the extremes of an existing network could cause the line rating to be exceeded. Rather than costly investment in network reinforcement, it would be more advantageous to adopt an approach of dynamic load management using a dynamic, real-time, thermal rating of the transmission line. Such dynamic line rating techniques can be based on local measurement of current, or on measurement of PMUs, plus input from weather data and settings for conductor material properties. The measurement of PMUs offers much more information on the loadability of the line than the local measurement of line current alone. This form of line thermal monitoring can provide more information to the operators, serve as an early warning system and allow the operators to initiate corrective actions in case of potential overloads. Such real-time condition monitoring enables utilities to make full use of the power transfer capacity of the line without violating the thermal design limits.

Today, the high cost of power transformers, coupled with high in-service network demands increases the need for condition-based maintenance (CBM). In order to schedule CBM the real-time health of the transformer must be known. Maintenance or reconditioning at a time of the asset-owner's choosing is preferable to a forced, unplanned outage due to equipment failure. Today, numerical intelligent electronic devices (IEDs), can incorporate algorithms for condition monitoring, loss of life monitoring and through-fault monitoring. Transformer IED sensor inputs could include top oil measurement, ambient temperature, tap position, etc. Other inputs could include as an example, cooling status. Measured load variation is based on measurement of the transformer load current. Algorithm calculations are then performed to get hottest spot temperature, loss of life, etc. Frequent excesses of overloading will shorten the life-expectancy of a transformer due to elevated winding temperatures and subsequent insulation degradation. Insulation deterioration is not uniform and will be more pronounced at hot-spots within the transformer. Loss of life monitoring is not the proper technique to monitor short-term, large fault currents which flow through a transformer. Through-faults are a major cause of transformer damage and failure, as they stress the insulation and mechanical integrity of the transformer. On through-fault detection, an I^2t calculation can be performed. The calculation results are added to cumulative values and monitored so that users can schedule transformer maintenance or identify a need for system reinforcement.

XI. CYCLIC LOAD SHEDDING

Traditional load shedding makes use of simple under frequency elements. However, these schemes are not always successful for ensuring fast load-shedding, which is mandatory for system stability. While it is a normal practice to trip the less critical loads, if there is a condition where all loads are determined to be equally important, then the load shedding could take place in a cyclic manner to provide equality among the served loads. This is referred to as cyclic load shedding. The cyclic load shedding can be achieved in a numerical PRD by using its programmable logic. The features of the programmable logic can be set to change the order of load shedding so that the occasions when any individual feeder will be removed from service will be reduced.

The basic building blocks of such schemes typically consist of at least the following functions: gate logic, AND, OR, MAJORITY, NOT, timers, pick-up, drop-out, dwell, pulse, and pickup/drop off (out).

In addition to logic functions, many modern relays include math operators, compare, select, flip-flops, counters and memory functions. This system improves on a simple underfrequency scheme to improve the overall customer experience.

XII. ADAPTIVE PROTECTION DURING CHANGING SYSTEM CONDITIONS

Adaptive protection aims to adjust settings of protective relaying to the prevailing conditions of a power system. This can be achieved readily currently with the multiple setting groups that numerical PRDs have.

Power system operating conditions change continuously. This is mainly due to the normal variation of loading at busbars throughout the daily, weekly or seasonal periods. Normally, the PRD settings are calculated for the highest loading conditions to account for a worst-case scenario for the protection. This highest loading scenario is, by definition, not optimized for all system conditions. Using the multiple settings groups and the flexibility of modern PRDs, appropriate settings may be calculated for a wide range of conditions, which would improve reliability, selectivity and fast operation.

There are many other reasons that changes in the loading conditions may result in sub-optimal performance or mis-operation of the PRDs. These reasons could be classified into two main groups:

1. Changes in topology of the distribution/transmission system
2. Automatic feeder reconfiguration of distribution systems

Adaptive setting changes must be carefully considered and take into account operator awareness, technician training and the impact on protection during changes.

XIII. SITUATIONAL ANALYSIS

Situational awareness and analysis are crucial components of the operation of the modern electric grid. Today's generation, transmission and distribution systems provide ever-increasing amounts of data from PRDs, sensors, PMUs, etc. At present, some, but by no means all, of this data is consumed by many different users including energy management systems (EMS), generator automatic gain control (AGC), control center operators, asset management personnel and systems, engineering, etc.

Some of the challenges encountered in optimizing the use of available data from smart grid systems include:

1. Developing communication channels to move data from the points of acquisition to the systems that consume the data
2. Timeliness of data usage: for example, systems may need to move real-time data to centralized modeling systems with sufficiently low latency and then process the data fast enough to provide actionable information during dynamic system conditions
3. Description and organization of data: in many legacy SCADA and EMS systems, raw data is often identified by data tags that are cryptic at best and increase the challenge of tuning data into understandable, useful information
4. Availability of information to the appropriate stakeholders across the enterprise

The report describes some of the components of the smart grid that can be employed to address these challenges. Among the components referenced in the report are [1]:

1. Foundational standards that address data element interoperability and self-description. These attributes make it easier to share data (potentially from different platforms and/or system vendors) between applications and end users, and assist in identifying the data in consistent and understandable ways
2. Ubiquitous high-bandwidth communications: the implementation of a smart grid implies interconnectivity across the enterprise with suitable high-performance communications systems. The capital expenses incurred in implementing these communications systems may enable cost savings and higher performance in many areas across an enterprise
3. Greater penetration of IEDs including PRDs, connected sensors, PMUs, etc: sensing and measurement technologies are a key enabler of the smart grid
4. Improved access to the data available from the base of IEDs, sensors, etc., made possible by improved communications installed as part of smart grid projects
5. Improved utilization of the information available from the base of installed systems facilitated by the application of the interoperability requirements, data structures and conventions defined in the standards that underlie the smart grid. An example of which is the IEC 61850 family of standards having one set of defined data structures, interoperability requirements, etc.

A use case is included that illustrates the potential of applying smart grid concepts to equipment maintenance. The use of CBM may provide a more efficient and lower-cost approach to maintenance than the use of traditional corrective maintenance or periodic preventative maintenance. Modern IEDs can provide real-time performance information in a standardized format. For example, many of the parameters needed to monitor the operational health of a system are already codified in the definitions of IEC 61850 logical nodes, (examples are provided in the report). High-bandwidth communications can convey the information to computer systems in asset management or engineering divisions for analysis and action.

Developing the proper foundation elements, including security and leveraging industry standards helps ensure interoperability between systems and devices and helps to keep costs reasonable over the long term. Finally, the information systems organization needs to be involved in the process throughout.

XIV. USING EXISTING PROTECTION FUNCTIONS

Modern PRDs have the ability to provide information about important circuit measurements, the status and values of digital and analog I/O and convey that information to the smart grid over a variety of different protocols and mediums for further study and use. PRDs are also built to receive information and commands to change settings and operating criteria. System disturbances can be captured, logged and transmitted both in summaries of analog and digital values and as waveforms.

A more recent technology being integrated into modern protection and control devices for conveying important time synchronized information from the power system is through PMUs. Referring phase angle by PMUs to a global reference time is helpful in capturing a wide area snap shot of the power system. Effective utilization of this technology is very useful in mitigating blackouts and learning the real-time behavior of the power system. PMUs raise the possibility of new solutions to power system problems while also bringing forth important issues which need to be addressed.

Utilities utilize smart devices on control equipment such as load tap changers (LTC), line regulators and capacitor controls. These controls can provide important local measurements and statuses. Furthermore, these devices can be used to curtail real-power circuit consumption by strategically reducing the voltage and switching capacitors using a system known as volt/var management (VVM). Some of the same system factors affect power system protection and relaying (PSR) and VVM functions. One of the most important common factors is the "present" circuit (system) configuration. As distribution system circuit switches operate for whatever reason, they change both functions' effectiveness and the "optimum" setting points for the resulting configuration. Another contributing factor for a configuration change is any type of generation operated or changed on the circuit as well as an intertie connection between feeders or to another distribution system. These changes can be communicated to the necessary equipment for inclusion in the function operation by the smart grid communications.

XV. APPLICATION FOR PEER-TO-PEER COMMUNICATIONS BETWEEN INTEGRATED VOLT/VAR COMPENSATION (IVVC) CONTROLS AND PROTECTIVE RELAYS

The primary function of capacitor controls and regulator/LTC controls is to regulate the voltage of the distribution grid while attempting to minimize losses through the reduction of reactive current. In the past, these controls were typically operated in a local automatic mode. Any coordination between controls was performed via local settings including time delays and setpoints. With the advent of robust wireless communications, many are now adding communications from these devices to either a central SCADA system or distributed gateways located in the substations where the circuits originate.

When implementing an IVVC, most utilities have focused on a master/slave relationship. There are several applications where peer-to-peer communications would add benefits. Examples include communications from protective devices such as recloser controls to line regulator controls and PRDs to LTC controls with the paralleling of transformers.

XVI. USING RELAY DATA TO DEFER NETWORK INVESTMENTS

Not having sufficient visibility of network load may lead to assumptions that cause unnecessary network investments. This is due to limited visibility of medium and low voltage networks. With more nodes of actual data in the medium and low voltage networks, it may be realized that sufficient capacity exists and therefore deferment of investment in the network may result. With the inherent monitoring functions present in smart grid PRDs on distribution networks, there is an opportunity to leverage this monitoring to make investment decisions.

XVII. DESIRED FEATURES AND FUNCTIONS FROM UTILITY USERS

Smart grid functions, above protection, are considered an integral part of modern PRDs but these may or may not include all functions deemed useful by electric utilities. Many smart grid functions are part of a SCADA system that may include PRDs or have separate elements. The following features and functions were compiled by a group of utility engineers.

Desired features include:

1. Configurable programmable logic: using graphical logic equations. The ability to use graphical symbols is much preferred to simple "logical equations"
2. Adaptive relaying: using programmable logic or settings groups that are programmable based upon load and system conditions
3. Waveform recording
4. Hardened product - surge immunity
5. Local and remote serial communication
6. PMU functionality for data collection and as a part of a wide-area protection system

Desired functions which may require the above or other advanced features, includes:

1. Monitoring function of the logic elements in order to avoid mis-operation, e.g. the flashover logic in generation protection uses the breaker position as well as the voltage detection in the generator
2. Logic which provides information about the availability of the scheme, e.g. a generator is in service and the breaker is closed, so the voltage is expected to be present, otherwise, an alarm has to be sent showing loss of a logic element
3. Monitor feeders for abnormalities that would most likely result in a permanent outage and thereby alarm and disable automatic reclosing. Substation PRDs and feeder automation PRDs may also share this type of information to make smart decisions in clearing faults and restoring service to customers
4. Integration of cyber security initiatives as required to meet NERC CIP requirements such as password control, access management and implementation of message encryption
5. Improved fault location accuracy using information from PRDs integrated with DA devices, (smart switches, fault indicators, smart meters), to quickly locate faults on the correct lateral

XVIII. INTEROPERABILITY

Many of the functions and capabilities enumerated above are enabled by the inclusion of protocols and systems common across platforms. These include IEC 61850 message and file transfer methods for exchange of information between PRDs and up to integration systems.

Other common protocols include IEEE C37.118 for PMU data transfer and COMTRADE format for event reporting. As the use of these interoperable protocols expands, it becomes more expeditious to expand the use of the information available in the PRDs to more functions.

XIX. CONCLUSIONS

This paper lists many advanced features, capabilities and functions of PRDs that go beyond traditional protection elements. The use of these advanced features will improve overall power system performance.

PRDs are designed such that these additional capabilities do not degrade the primary function of the device. Integration of the device would help ensure that this philosophy is maintained through proper systems engineering.

Some of the goals of a smart grid are to improve the cost, resource and maintenance efficiency of the system by minimizing device count and duplication. By fully utilizing the capabilities of each device, the reductions of connection count, engineering time requirements and failure rates are all possible. Integrating the functionality of modern PRDs within different smart grid applications will help achieve these goals. Organizational challenges are added as these functions increase. These organizational limitations can impact the cost effectiveness of advanced PRD integration.

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