# Smart Grid – The Present and Future of Smart Physical Protection: A Review

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## *Abstract*

*Smart grid is regarded as the next generation power grid, which provides bi-directional flow of electricity and information, with improving the power grid reliability, security, and efficiency of electrical system from generation to transmission and to distribution. As smart grid continues to develop, realization of a reliable and stable system is necessary. This article reviews on the current state-of-art technology in physical protection. This article also focuses on the system reliability analysis and failure in protection mechanism. In addition, the challenges of both the topics are also presented along with the suggested solution.*

**Keywords:** *Smart grid, physical protection, system reliability analysis, failure in protection mechanism*

## 1. Introduction

Reliable and affordable electrical power is essential to the modern society. The modern electrical power systems cater the demands in wide range of areas which include the major components such as generators, transformers, transmission lines, motors and *etc*. The availability of new advanced technologies has made a smarter, more efficient and sustainable grid to ensure a higher reliability of electrical power supplied to mankind. Regarded as the next generation power grid, smart grid has transformed the interconnected network between electricity consumers and electricity suppliers. The smart grid system involves transmission, distribution and generation of electricity. In a smart grid, the operation of power systems infrastructure has evolved into a dynamic design instead of a static design. The overview of smart grid is discussed in Section 2.

As smart grid technology and its adoption are expanding throughout the world, realization in smart grid protection is important. Protection plays an important role to ensure realization of power grid reliability, security, and efficiency in generation, transmission, distribution and control network. It is a subsystem of Smart Grid which provides advance grid reliability and security analysis in physical protection and information protection services. In view of the enhanced capability of Smart Grid with its smart infrastructure and management, the role of Smart Grid in a protection system which supports the failure protection mechanisms effectively and efficiently. In Section 3, the physical protection in smart grid is discussed, along with the review of the current-state-of art. Section 4 is the discussion on the protection in general. Finally, Section 5 makes the conclusion.

## 2. Smart Grid Overview

Smart grid is defined as an intelligent grid which provides bi-directional flow of electricity and information, with improving the power grid reliability, security, and efficiency of electric system from generation to transmission and distribution. It is driven by the need to provide a more robust, flexible and efficient electric system to overcome the increasing demand of electricity, uprising treat from green house gases emission, depletion of energy resources and other rising issues in traditional grid [1, 2]. With comparing to a traditional power grid [1, 3], smart grid enables the (i) integration of renewable energy resources (such as PV, wind turbine and *etc.*) at distribution network, (ii) supervisory control and real-time status monitoring on the power network, (iii) self-monitoring and (iv) self-healing feature, adaptive response to fault and *etc.*

### 2.1 Smart Grid Structure

A typical smart grid structure is illustrated in Figure 1. It contains four subsections which are generation, transmission, distribution and control network [1]. Each network interconnected from various locations, information exchange and communicates through smart communication subsystem such as an access point with wired or wireless communication infrastructure. Raw information on the network healthiness or performance is obtained from smart information subsystem such as a smart meter, sensor and phasor measurement unit (PMU). Real time network monitoring, management and control are performed at the control network such as the electric utility control center. Besides that, a distribution network can be an individual when dispersed generation (DG) (renewable energy resources) is embedded, that allowing electricity supply from both DG and utility.

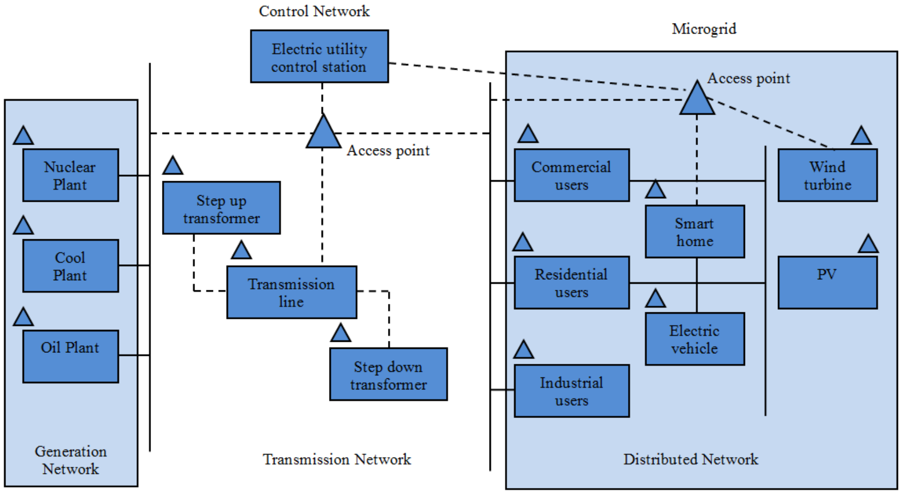

**Figure 1. Typical smart grid structures**

### 2.2 Smart Grid Characteristic

This subsection describes three smart grid characteristics namely grid self healing ability, formation of Microgrid system and enable embedded distributed generation (DG).

**2.2.1 Grid Self-Healing Ability:** According to the National Institute of Standards and Technology (NIST), the ability to "self-heal" in the event of failure which is an important characteristic of Smart Grid [5]. Self healing is the ability of allowing the grid to reconfigure itself or restore automatically to permit an uninterrupted power flow during occurrence of outage [6]. However, it does not mean that the grid can repair by itself. An effective approach for self-healing is to divide the power grid into a small and autonomous islanded network like Microgrid, which can work well in normal operation as well as during outages.

**2.2.2 Formation of Microgrid System:** Microgrid is an emerging paradigm for smart grid in distribution network [4]. It has two boundary namely normal and islanded operations. A Microgrid is connected to the electric utility network during normal operation, whereas in islanded operation Microgrid operates on its own, with electricity supply from DG or storage devices. It has the ability to operate during loss of main, islanded operation and isolate Microgrid from electric utility disturbance. Thus it provides a reliable electricity supply. This characteristic allow smart grid to be able to maintain its stable operation and deal with emergency problems [7].

**2.2.3 Enable Embedded DG:** Smart grid has the characteristic for DG which has been embedded into distribution network. This characteristic encourages the use of green energy sources from renewable and also enables customer interaction. In addition, DG also serves as the main supply during islanding operation for Microgrid.

### 2.3 Smart Grid Standard

According to the Energy Independence and Security Act of 2007 (EISA) and Cabinet-level National Science and Technology Council (NSTC) report [5], the standards for Smart Grid help to ensure that the investments in the Smart Grid remain valuable in the future which include to catalyze its innovations, to support consumer choice, to create economies of scale to reduce costs, to highlight best practices and to open global markets for Smart Grid devices and systems. Smart Grid standards are developed by groups of experts, namely as standards-setting organizations (SSOs) or standards development organizations (SDOs). These groups of experts from each industry come together from different nation to discuss, to develop new standards and to update the current standards.

At the present, there are hundreds of standards in both technical and non-technical aspects, over 25 SSOs and SDOs are involved. These SSOs and SDOs include institutions such as The Institute of Electrical and Electronic Engineers (IEEE), International Electrotechnical Commission (IEC), International Organisation for Standardisation (ISO), National Electrical Manufacturers Association (NEMA), International Telecommunication Union (ITU), American National Standard for Protocol Specification (ANSI) and etc. IEEE 2030 (approved by the American National Standards Institute (ANSI) in 2011) and its associated standards which addresses Smart Grid interoperability, is the standard that provides a roadmap at establishing the framework on cross-cutting technical disciplines in power applications and information exchange and control through communications. IEEE 2030 provided the guidelines for defining Smart Grid interoperability in the necessity of integrating energy technology, information and communications technology as a whole.

IEEE 1547 (approved by ANSI in 2003) and its associated standards address the distributed resources (DR) interconnection standards. It is a DR interconnection standard which provides technical and interconnection test specifications that help to decrease the time and effort associated with DR interconnection developments. With IEEE 2030, both standards support the expansion of Smart Grid and realization of the revolutionary benefits in Smart Grid such as greater consumer choice, improved electric-system reliability, and increase reliance on renewable energies [8]. Besides that, some other standard such as IEC 61850 for electrical substation automation and ANSI C12.22 for smart metering are emerging in adoption [3]. IEC 61850 and its associated standards address the interconnecting and interoperability of intelligent electronic devices (IEDs) that support the emerging favorites of data communication technologies such as wide area network (WAN), ethernet based local area network (LAN) and TCP/IP networks. In addition, ANSI C12.22 and its associated standards define the specification for interfacing of smart infrastructure to data communication networks that enable the new generation smart meters to communicate simultaneously with other smart meters and corresponding substation gateways. IEC 61850 has been adopted and in practice [9] in the developing countries such as Malaysia.

## 3. Smart Grid Physical Protection

Physical protection is defined as the protection of physical infrastructures in Smart Grid. It addresses the inadvertent which compromises of grid infrastructure due to the failures of equipment, system and network, human errors, natural disasters and unexpected phenomena. This section starts with the review of system reliability analysis and followed by the discussion on failure in protection mechanism. In each subsection, the problem is revealed and some potential solutions are also addressed. The work carried in this section is classified in Figure 2.

### 3.1. System Reliability Analysis

In the context of bulk power system, North American Electric Reliability Corporation (NERC) define system reliability as the ability of a system to meet the electricity needs by maintaining continuity and stable supply of electricity, even when unexpected equipment failures or other factors occurred [10]. System reliability is a topic that cannot be neglected, it is important in power grid research, design and development. A major blackout incident was happened in Malaysia (13 January 2005) due to circuit breaker failure in protecting the busbar, resulting 6,230 MW (54%) total load loss in the affected region and 3.5million customers were affected in this incident [11]. Hence, there is an emerging need in improving the system reliability, and it is expected that the future smart grid will provide enhancement with better system reliability operation and smarter failure protection mechanism.

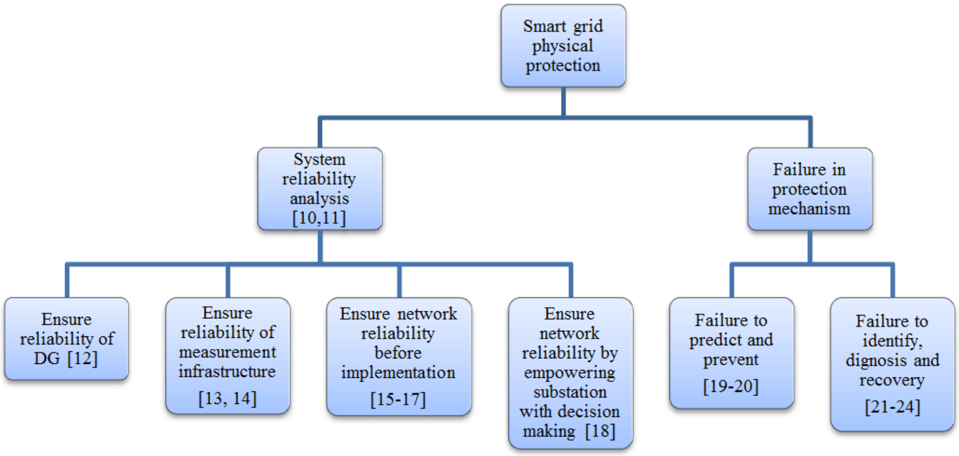

**Figure 2. Classification of Smart grid physical protections**

There are several methods in ensuring system reliability, (i) by ensuring the reliability of distributed generation (DG) in distribution network, (ii) by ensuring the reliability of measurement infrastructure and (iii) by ensuring the network reliability before implementation. Besides that, (iv) by enabling substation to have the ability to perform decision-making is also another key to ensure system reliability.

**3.1.1 Ensuring Reliability of DG:** It is expected that the embedded or dispersed or distributed generation (DG) such as small scale generation from renewable energy resources, will be widely be used in smart grid. As the integration of DG into distributed network increases, the risk in distributed network increases. The risk compromises of distribution network reliability and stability, resulting from the use of fluctuant and intermittent renewable resources. To analyze the reliability of DG, Chen *et al.*, [12] proposed a method that use simulation model which gradually increase of local generators in smart grid, to mitigate the cascading failures resulted from DG. The model concept is, as loads in distribution network are being served locally by individual local generators (similar to Microgrid architecture), less power flow interruptions within entire power grid, this enhances the reliability and stability of smart grid. They obtained satisfactory result which dramatically reducing the likelihood of cascading failures in smart grid.

**3.1.2 Ensuring Reliability of Measurement Infrastructure**: To enable smart grid operation, a smart measurement infrastructure is required. It served as the input for smart grid with monitoring and sensing ability, to observe network healthiness, reliability and stability. A phasor measurement unit (PMU) is one of smart measurement unit. PMUs have been widely used in wide-area measurement system (WAMS) for monitoring, control and protection function in smart grid. To analyze the reliability of WAMS, Wang *et al.*, [13] presented a quantify reliability evaluation method for WAMS, using combined Markov modeling and state enumeration techniques to evaluate WAMS reliability. The proposed idea of reliability evaluation covers the backbone communication network in WAMS and also the overall WAMS from a hardware reliability viewpoint. For verification, the WAMS evaluation method was demonstrated in the IEEE 14-bus system. It was proven that the evaluation method to be dependable in providing useful information to improve the reliability of WAMS and recognize the reliability of WAMS-based control scheme which require different information set.

Besides that, Vaiman *et al.*, [14] introduced a Region of Stability Existence (ROSE) concept, which could continuously and automatically monitor system condition in real-time by computing the power system stability margins accurately. Their approach is illustrated in ISO New England's transmission network, with data set of (i) State Estimator (SE) data, (ii) Supervisory Control and Data Acquisition (SCADA) data and (iii) PMU measurements, used in ROSE computation. Their results of study indicated that the approach is effective and efficient in improving the reliability in ISO New England's transmission network and could be used to prevent major blackouts.

**3.1.3 Ensuring Network Reliability before Implementation:** The more accurate and precise a simulation platform can be used to emulate the actual case. Therefore, the behavior and performance of smart grid can be understood better. Simulation of system reliability provides the preview of the system advantages, weaknesses and potential short coming before implementation. This ensure the system to be implemented is reliable and stable, through the evaluation and decision making based on the simulation results. But the question is how to create a simulation system which is accurate, precise, wide, flexible, adoptable and scalable? Godfrey *et al.*, [15] proposed a wide modeling method of targeting in smart grid applications with co-simulation, which focuses on communication and power network in smart grid to provide the means to examine the effect on communication failures. Their simulation method enables the investigation of wide range of smart grid issues with high capability and accuracy in addressing the communications latency adversely impact to the expected behavior later in power system.

In addition, Ghosn *et al.*, [16] designed an agent-oriented architecture for simulation, primarily focuses on self-healing problem, with an incremental method that begins with simulating a local Microgrid. Their architecture enables scalable and adaptable design that grows hierarchically into a more complete model. Such architecture also enables smart grid developer and designer to understand the weaknesses, potential short coming issues and identify the way to improve the electrical grid. With their agent-oriented architecture, they able to present software design issues that must be considered in producing a system that is flexible, adaptable and scalable.

Yusof *et al.*, [17] presented a teleprotection simulation lab which enhances the learning process of the teleprotection system and it allows proactive measures to be taken before any unwanted incidents occur. The overall reliability and performance of the teleprotection system has been improved. With the simulation lab, it allows their R&D team to test and evaluate the performances of various telecommunication aided protection schemes comprehensively under a controlled lab environment.

**3.1.4 Ensure Network Reliability by Empowering Substation with Decision Making:** By empowering substation with the ability to perform decision making, the system could response by itself first without waiting for instruction from control network. This enables the substation to resolve the issue in the shortest possible time and ensure the reliability of the network. However, safety and precaution is necessary, the failure in performing the right decision is crucial. To ensure network reliability while minimizing failure in decision making, Overman *et al.*, [18] defined a multilevel framework trust model with reasonable compromises in both the failure and reliability. They suggested that distributed decision making ability to substation and/or field devices, by pre-load the substation and/or field devices with sufficient information for autonomous action, in the event of system failure without having to wait for instruction from control network. In their research, they have proven that by pre-loading the substation and/or field device with a set of "next actions to be taken" instructions, when attached in distributed rather than hierarchical communication architecture, the proposed model could significantly increase the grid reliability, while at the same time reduce real time impact from loss of reliable control.

### 3.2 Failure in Protection Mechanism

Protection mechanism can be divided into two topics, (i) prediction and prevention of failure and (ii) identification, diagnosis and recovery of failure. Prediction and prevention of failure are the actions of attempting to predict failure location and prevent failures from occurring. If fail to prevent failure from occurring, identification, diagnosis and recovery are required to restore network from failure to normal operation, in the fastest possible time. In this subsection, both the protection mechanism briefly reviewed.

**3.2.1 Failure to Predict and Prevent:** For smart grid to operate efficiently and effectively, accurate in predicting the failure location and preventing failure from occurring is important. One approach to predict the failure location is to locate the weak points in smart grid. Chertkov *et al.*, [19] have developed an approach to efficiently predict power grid weak points, and identify probable failure mode in static load distribution. They applied the approach into two system, Guam's power system and IEEE RTS-96 system. In each of the system, its static power flow is modeled and analyzed. Their finding concluded that this technique could provide an accurate predictive capability in locating the problematic links based on different failure mode of load operation. In addition, they also observed that this approach has an improved reliability in the respective power system.

Besides accurately predicting the weak point, accurate forecasting of short circuit fault and predicting its magnitude in smart grid are also important in preventing network failure. Chen [20] introduced the artificial neural network (ANN) to perform short-circuit current prediction in power distribution systems. The formulated model was verified through computer simulation and the algorithm was demonstrated on hardware system based on TMS320F2812-DSP. The algorithm was proven to be effectively in predicting the magnitude of short circuit in the shortest possible time.

**3.2.2 Failure to Identify, Diagnose and Recover**: If failure occurred, it must be identified quickly in the shortest possible time, to avoid further damaging or cascading of event. Once the failure has been located, it must be diagnosed in order to search for the root caused and response to the failure by recovering. When the fault is cleared, the network must be resynchronized and restored the failure region back to normal operation. Calderaro *et al.*, [21] presented a method to identify and localize failure in smart grid, based on the design of Petri Net (PN) theory. This method detects the failure in data transmission and fault in distribution network, through means of matrix operation, from the captured modeling data in distribution network. In their research, they have verified the method with two case studies. Through the verification, they demonstrated its effectiveness and discovered the method is able to remove a lot of complexity associated in data analysis and permit quick assessment and evaluation of information, while avoiding occurrence of cascading failures in power system protection. They also added on that the proposed detection strategy is consistent with the current trend and direction in smart grid development. Therefore, they were looking forward on the model to be adopted in smart grid protection.

**3.2.2.1 Failure diagnosis:** Cai *et al.*, [22] realized the critical step in distribution fault diagnosis, comes from the proper selection of features to identify the root cause of failure. Hence, they carried out the literature reviews on some popular features of selection methods such as (i) Hypothesis test, (ii) stepwise regression, (iii) stepwise selection by Akaike's Information Criterion, and (iv) LASSO/ALASSO, and evaluated these methods with real world datasets to identify each method advantages and limitations for fault diagnosis. They concluded that there was no single method that was best for all cases, but each of the method had its own potential in the particular case. Nevertheless, the features selection method can be served as a meant of failure diagnosis for engineers to find out information that may be hidden under the massive data rather than producing some feature that cannot be understood or explained.

**3.2.2.2 Failure Recovery:** The ability of self-healing in the event of failure is an important feature in smart grid. When failure occurs, a self-healing reconfiguration in smart grid splits the power network into a self-sufficient islanded network to stop the propagation of failure and avoid cascading event. For failure recovery within the islanded network, Li *et al.*, [23] presented a self-healing system reconfiguration technology with proposed of an area partitioning algorithm, to minimize the power imbalance between generation (DG) and load in islanded network. From their research, they found that the algorithm is computationally efficient, and by appropriately control the system reconfiguration the overall efficiency in system restoration can be improved.

On the other hand, to enable smart grid operation, smart meter is another main smart infrastructure for smart grid. Failure due to load data loss or corruption in smart meter might likely to occur. Thus, recovering of these missing or corrupted data in smart meter is necessary and is important, because the data contained vital information for daily system analysis, decision making and smart grid operation. Chen *et al.*, [24] addressed the issue by presenting a B-*Spline* smoothing and *Kernel* smoothing based techniques to automatically cleanse the corrupted and missing data. They evaluated the method on real British Columbia Transmission Corporation (BCTC) load curve and they demonstrated that their method is effective.

## 4. Discussion

Section 3 reviews and discusses the current state-of-art of physical protection in terms of system reliability analysis and failures in protection mechanism. Ensuring of system reliability is important in realizing effective and efficient means of smart grid operation. The development of protection mechanism to resist the attacks and failure is also necessary in order to maintain the continuity of supply as well as ensure stability and reliability operation of smart grid. Although realization of the importance in each of the topic is essential, its challenges must also be addressed. Therefore, the challenge in each of the topic is discussed and some possible solutions to overcome the challenges are provided.

Ensuring system reliability is important, but it poses the increase in system reliability risk. Moslehi *et al.*, [25] critically reviewed the reliability impacts of major smart grid resources and he observed that an ideal mix of these resources could lead to a flatter net demand which will eventually accentuates reliability challenges further and making it more susceptible to failure. Flatter net demand implies that the grid is operating close to its near peak load condition at most of the time; operating close to the boundary of saturation or breakdown. These consequences are from the impacts of increasing consumption of energy and asset utilization, which is an unavoidable situation if the development of smart grid continues. Since in flatter net demand, grid is operating at the boundary of breakdown, we can address this issue by developing an effective approach, to construct and compute the margin before the boundary. And with a real-time monitoring system, the margin level can be known instantaneously, and we could response in advance to minimize system reliability risk. Besides that, maximizing asset utilization could lead to reduction in the margin level, thus we must ensure the balance in asset utilization to guarantee the maximizing level provide a reasonable margin.

On the other hand, ensuring proper protection mechanism is important, but it poses the increase of complexity in decision making process. Assuming in smart grid, there are millions and millions of node. In order to process the failure, smart grid have to solve a lot of complex decision problems in the fastest possible time to avoid any further damage or cascading event. To address this challenge, a possible solution is to introduce more decision making systems into the network, so that each system focuses in processing its respective region locally. This can decrease the complexity in decision making process and also reduce the failure response time. Each of this system will also communicate with one another, to ensure an optimum decision making in the global network.

Throughout the literature review, two lessons were obtained. Firstly, system reliability is a topic that cannot be neglected, it is important in power grid research, design and development. Consequences of low system reliability may result network failure (endangering human), and possibly even blackout of whole network (bringing discomfort to consumer and affecting industrial and commercial progress). To ensure system reliability, adaptive protection mechanisms in detecting failure play an important role. Because these adaptive protection mechanisms are the one to sense and response to the failure; if a weak protection mechanism is use, the reliability and stability will also be weak. Therefore proper consideration between protection mechanisms for reliability of system is required, to ensure the operation of smart grid to be effective and efficient.

Next, another lesson learnt is that new technology and infrastructure are introduced and deployed for smart grid, the possible risks and challenges must also be assessed. This is to ensure an efficient and effective operation of smart grid with higher security, reliability and stability. For instance, although ensuring system reliability is important, however the increase of system reliability risk may be introduced from the mix of sources in smart grid. Besides that, we also observed that the usage of smart metering itself although enable fast tracking of customer power usage, it may also introduce failure. Therefore, a throughout assessment on the new technologies and infrastructure is necessary.

Last but not least, there is no doubt that the fast growing of smart grid will enable many new paradigms, achieving a sustainable and environmental sound future, with the improve services of power supply and eventually transforming human ways of living. It is still a long way to go before the whole picture is puzzled up. In the meantime we need to continue explore and search for reliable method and ways to make this new paradigm vision come true.

## 5. Conclusion

In this article, the literature review of current state-of-art in physical protection is presented. In order to realize a reliable and stable smart grid operation, the article also focuses in system reliability analysis and failure in protection mechanism. Although smart grid enable power grid to be empowered with intelligent and advanced capabilities, it also opens up many new challenges and risks. Hence some challenges and risks in both topics are also briefly discussed, along with possible solution to overcome it. However, more in depth and throughout research in the physical protection system is required to ensure the operation of smart grid to be reliable and stable.

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