A Technical Review on Self-Healing Control Strategy for Smart Grid Power Systems

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Abstract. The various advanced technologies incorporated in the existing power system to operate in smarter and to provide continuity of power supply without any disturbances. Still, it was few threats that disrupting the electrical network to manage the power demand such as: complexity of the power grid; vulnerability to faults; energy efficiency; and renewable energy integration. The above challenges indicate the perception of smart grid (SG). The smart grid design is economic, competent, intelligent and secured grid was needed to manage the above-mentioned issues. Self-healing is the most essential characteristics of a smart grid. The implementation of self-healing control strategy in the smart grid is one of the prolong challenge. It is the capability of the power system network to restore naturally the network when the fault occurs. It gives primary assurance to the smart grid protection. Apart from this, the implementation of various control strategies assist accomplishing the safe functioning, enhancing the stability of the grid. This paper presents the self-healing control strategy in the context of smart grid power systems. The significant advancements developed in the transmission, distribution, micro grid as a result of power electronics converters presented. Then, the information and communication technologies, software tools and measurements which can be employed for winning crucial smart grid self-healing action will be discussed.

Keywords-Smart grid, Self-healing, Transmission grid, Distribution grid, Micro grid, Distributed Generation, Fault, Protection, Control strategy.

1. Introduction
Smart grid is an automated digital grid is consists of various types of devices, hubs, network stations, and diverse systems [1]. Smart grid commonly having following important characteristics; self-healing, optimization, compatibility, computerization, integration of distributed energy sources [2]. One of the most essential components of the smart grid is self-healing capability. Smart grid self-
healing facility gives the quick return on investment [3]. This behaviour pertains to regularly auto-
evaluation of the grid activity, quick identification, investigation, appropriate segregation of various
faults without intervention of manpower and taken up the appropriate decision to avoid series failure.
Self-Healing control strategy commonly requires reforming the grid within a minimum interval of
time period.
It gives many-adjustable control aspects enabling the power sector to mobilize current conventional
infrastructures and promote to smart grid infrastructure development. The self-healing of smart grid
needs real-time powerful computation systems which supervise, measure, adds prognostic analytics,
acts and prepare quick decisions to diagnose, locate, and separate the different faults, reform and
divert power flow of the distribution system to reduce power outages and interruption. The
management of power outage capital cost a significantly rises in the expenditure from the year 2014 to
2018[4]. Smart grid is suffered many issues it categorized into eight major problems, technological
advancement, transmission and distribution loss, quality of power, integration of renewable energy,
cyber security, interoperability, consumer support, information supervision and control, and self-
healing implementation [5]. Few investigations have discussed in the importance of self-healing for
smart grid [6-8]. Remaining reviews have addressed on the smart grid infrastructure [9]. The self-
healing capability and problems in power grids operation are discussed on [10]. The participation of
consumers was increased on self-healing characteristic of smart distribution grid [11]. Till now no
effective, absolute control methodologies and recovery process to self-healing smart grid distribution
system is proposed. The capability of self-healing in smart distribution network is remain in the
preparatory level only [12].
The occurrence of faults and disturbances in power system is unavoidable, although the possible
hazards predominantly depend upon the fault amplitude, fault type, period, and fault area [13]. The
essential characteristic of smart grid vision is capability to find and minimize faults, forecast the faults,
automatic protection adaptability, and real time control. The build-up of a smart grid involves the
employing of strong infrastructure for assuring continuous and reliable operation. Its gives quickest
return on investment (ROI) [14]. While establishing the smart grid architecture, the design of excellent
self-healing function with multilevel controlling and optimization of the electricity supply is
important.
This permit liberates the all the possibilities of the smart grid by performing advanced measures to
diagnose faults by way of real-time information, assuring reliable and safe operation. Additionally the
diagnosed faults networks will be separated and reducing the amount of affected consumers [15]. The
primary objective of the review paper is giving the advantages of realizing smart self-healing control
mechanism as an important measure to enhance stability and reliability.
2. Objective, importance, and applications of self-healing grid
Self-Healing of smart grid is an approach that provides the detection and segregation of abnormal network and the auto restoration provision of services to end customers delivered by healthier components. This action handled no manpower interference and the purpose is reducing disturbances and escaping additional degradation of reliability. Self-healing of smart grid is performed through Distribution Automation (DA), especially smart switching, protective equipments that reduces the...
count of disrupted clients under emergency situations by segregating fault elements automatically and moving the consumers to an alternative supply while the normal source has been absent. As the complexity of the systems increases, it is more costly and difficult to clear the system faults and to return to its original operating state. Self-healing methodology must be implemented to achieve this [15]. The block diagram of self-healing smart grid systems is summarized in Figure 3. The primary objective in self-healing methods is; to be more powerful tackling the faults in smart grid and simultaneously to maintain the security over grid dissemination. The following factors must be analyzed to achieve the smart grid self-healing:

- To protect the smart grid from adverse impacts, fast and precise fault analysis must be done.
- Minimization of the functions during self-renewal period.
- Considering the positive or negative state.

The smart grid self-healing system consists of smart sensors, self-acting intelligent controllers, and sophisticated software tools. It utilizes real-time information to identify and disconnect faults and to reform the system to reduce the affected customers. Another main aim is to enhance the reliability. It can be achieved through reconfiguration of switches, reclosure connected on the distribution lines. Reconfiguration method rapidly separate faulted section of the feeder as well as continuing functions to many consumers through alternate feeder lines. Distributed Automation (DA) which includes feeder, substation, and user automation are prominent tools to accomplishing the self-healing, power quality, reliability and enabling the integration of renewable energy resources. DA control forces are needs of smart grid selfhealing relating to reliability, power quality, regulatory incentives, penalties, optimize operations and pressure to cut costs. Major application of DA is detection, Isolation of faults and Service Restoration (FLISR) that can considerably minimize power outage time period to the end users.

3. Smart grid self-healing in transmission systems

Smart transmission system is used to supervise the functions of transmission lines, transformers, circuit breakers, smart sensors. The smart sensors gives information essential for the functions of the transmission system namely: temperature of transmission line conductors; current carrying capacity, thermal ability of conductors, identifying the location of faults in lines, mechanical sag, ice loading, failure of insulators and towers, forest in near vicinity, diverse services considered for self-healing in the transmission systems.

While designing of current smart grid, diagnosis of fault is most essential for smart grid system. The main objective of fault diagnosis is to; improve the power quality, maintain reliability and make use of self-healing benefits of power systems. The various technologies is adapted to trouble shoot the faults in the transmission system such as smart sensors advanced ICT tools etc [16].

In order to regularly take a decision and supervise the transmission line parameters, signal processors, communication networks and developed sensors must be entrenched for all transmission systems [17]. However, line parameters are regularly estimated and supervised. The smart sensors will sense and give the crucial information namely: conductor temperature, conductors sagging, current carrying...
capacity of conductor against thermal capacity [18]. Also, the intelligent transmission transformer station must come to its original state after blackout failures.

The genetic algorithm (GA) based optimal voltage control is one of these solution suggestions. When implementation of voltage control, rapid and superior solutions should be attained by adding past event into the GA Optimization [19]. To achieve planned, comprehensive self-healing need the energy storage sources, system compensation [20]. The establishment of network topology via wireless or wired communication between these networks and the system will be self-healing during occurrence of any faults its send the signals to the control center [21]. Author in [22], was proposed that to achieve the self-healing control and normal power flow under network faults through unified power flow controller (UPFC). He analyzed the inverse control algorithm instead of the iterative control algorithm, tested node analysis instead of the optimization algorithm and reordered the results of power flows data.

In occurrence of an increased the integration of distributed generation, while a fault occurred a definite location, both fault currents and power flow enter into the faulty zone. Increasing the magnitude of a fault current create an issue, particularly magnitude of the fault current more than the interrupt rates of the fault protection instruments.

The increased effect of distributed generation brings down following issues during the occurrence of fault:

- Prevent increasing the magnitude of fault current.
- To enhance the stability and maintain the synchronism

In order to minimize magnitude of fault current resulting from the increasing an additional sources to the micro grid, Fault current limiter (FCL) was interconnected between the main grid and the micro grid [23]. It was utilized with the additionally added energy storage devices connected into the grid to retain stability during the occurrence of faults and to help the grid. The S conversion algorithm used to monitors & identifies overvoltage events [24]. To reach this, the intelligent network's self-healing control feature can be used.

Transmission grid self-healing strategy by using UPFC maintained steady power flow in the transmission systems. The probability of contingencies in fault-location for a multi-generator system is achieved by employing computational intelligence techniques and wavelet multi-resolution analysis (MRA) is presented in [22]. The Global positioning system (GPS) along with Multi Agent systems (MAS), phase measurement unit (PMU) presented the conception of urban power grid's self-healing. It consists of four control modes such as: healing, contingency, defensive and remedial control [22].

4. Smart grid self-healing in distribution systems

Distribution smart grid systems have a bidirectional communication between customers and grid. Its affect the power quality, reliability and efficiency if any fault or disturbance occurred. Distribution systems can be categorized into following perspectives namely: power quality and reliability.

The primary perspective is the power quality. It is described as ability of grid's to provide a stable power to the customer and maintain the supply voltage, frequency under the prescribed limits. It is determined through various factors such as fluctuation in voltage, flicker, phase unbalance, harmonics etc. The operational problems, terrorist attacks, natural disasters directly affect the distribution system. Its leads to affect the supply voltage, power outage, all substations.

Second perspective is reliability which defines the providing the continuous supply to the customers. It is calculated using two indexes namely: system average interruption frequency index (SAIFI), average interruption duration index (SAIDI). Exceeding limits of above indexes leads to more economical loss. Author in [20] was reported, According to the history of U.S. energy's report the reliability rate is 99.97%, and this costs around 150 billion dollars in each year. Its takes huge time to restore the system to achieve the stable operation. So, the quick and high quality research in needed for giving a persistent results to assure the reliability and power quality in distribution side. The main objective of self-healing distribution grid includes to minimizes power outages, enhance the power quality and reliability of supply, reduces the problems created by the natural disasters, external attacks.
The implementation of a self-healing control strategy in distribution grid is very essential. In paper [25, 26] is projected travelling wave based self-healing control in distribution grid. Whenever the threshold value of initial measured travelling wave exceeds the fault is identified and used the least squares method to estimate the fault distance is accurately. Then this above proposed methods heals itself and its gives the stable and continuous power supply. Author in [27] suggested the markov analytical method to achieve the reliability of distribution grid. This system verified and tested on real time environment and it gives more intelligence, considerable rate of economic features. In paper [28] implemented the adaptive overcurrent method. In this method any variation in load level setting of the relay are automatically restored and then system can cooperate the modification. Then if any disturbance is occurred in the distributed generation the islanding mode can be activated to enhance the reliability of the grid.

To interconnecting the distribution grid to the rest of the system, it’s mandatory to automate the transformer hub and expand active part of distribution system. Common data’s on the elements and features of intelligent automation in transformer are given [29]. A multi-agent system and with an appropriate, switching operation were implemented to reconnect the segregated loads [30]. Author in [31] proposed the protection algorithm for wireless token ring protocol (WTRP). Here, the information is interchanged between the relays and reliability is improved through execution of appropriate switching operation. In paper [32] is suggested the ant colony optimization algorithm to achieve the self-healing in distribution grid. Then he is reported that this algorithm behaves fastly to a negative disturbance and gives the best solutions.

In [33, 34] the isolating application was used when the power system withstand a hazardous case. This plan is split into some mini islands it gives quick reconstruction to return to the original state. According to the decrease in frequency the load shedding algorithm is used. Author in [35] was reported the multi-agent control system (MACS) for the distribution grids. Then used the fuzzy logic algorithm for decision-making. In this algorithm, reconstructed the distribution systems, reactive power controllers can be controllers and the voltage irregularities are ignored. Fault location, isolation, and service restoration (FLISR) algorithm in correspondence with advance automation tools have been suggested [36]. Then he proposed the microcontroller-based program for detection of faults in distribution network and presented the solution methodology.

4.1. Architecture and functions of self-healing smart grid in distribution systems

Smart grids are susceptible to disturbances and faults of several attributes. Such interruptions produce power blackouts, incremental damage, huge revenue loss and productivity loss [37]. During the occurrence of faults in smart grid, various performance parameters variation values can be diagnosed and recorded through IEDs, intelligent sensors, PMUs and various devices that are installed. The primary goal of the selfhealing mechanism in smart grid is to maintain steady state during various abnormal situations, to prevent the occurrence of faults, not eliminating essential supplies under contingency conditions and maintain power security.

Self-healing in distribution systems classified into two types of control namely; direct control and conditions control [38]. Direct control is the main scheme it is operating on closed-loop to analyze the entire assessment of grid such as fault recovery, prevention and maintaining optimal control in the smart grid. Condition control indicates the total logic control system of grid dependence on assessed from several elements from bus and takes appropriate measures on the fault section immediately. This control mode is also called as emergency control. Its coordinate the protection control functions between customers and its utility.

The main objective of the self-healing protection control is support to all power distribution devices, data acquisition instruments and software system which responsible for decision making, control and all analyzation. Self-healing architecture of smart grid distribution systems is shown in figure.4. It’s supervise and control the all the possible real-time data’s. This data is correlated to execute the decision making and self-healing.
Self-healing control consists of various functions. Mainly it is divided into following two conditions:

4.1.1. **During normal conditions;**
- Enhance the stability margin and performance of wide area power grids, tolerate diverse interruptions and maintain the optimum control of smart grid.
- In real-time environment effectively supervise, diagnoses, detects and eradicates the cascade failures, incipient issues, faults and taken preventive control measures.

4.1.2. **During faulty operations;**
- Providing the stable functions, control loads automatically during fault environment in grid-connected and islanded modes.
- Restore the faults, outages, blackouts rapidly through restoration control strategy.

![Figure 4. Architecture of self-healing smart grid](image)

**4.2 Control methodology for smart grid self-healing in distribution systems**

Self-healing in distribution systems intents to enhance the controllability and observability of the smart grid to reach optimal functions of the system by means of minimizing outages and load balancing. In this portion shows a methodology for self-healing in distribution grid. The following operations are presented in this system such as supervising, diagnosing, predicting, analysing, isolating, mitigation and restoration. Figure 5. shows the control methodology flow chart for self-healing in distribution systems.

The preeminent stages of self-healing control in distribution grid are represented as follows:

4.2.1. **Monitoring and analysis state**
All the grid elements are revealed to various conditions as follows: deterioration because of maintenance and aging, weather conditions, abrupt abnormal behaviours it’s create faults start to arise during this time. Monitoring stage is capable to detect all the interruption and it needs intelligent and accurate technical facilities. These facilities consist of smart sensors, smart meters, distributed energy monitoring device, condition monitoring device, switches etc. This stage is gives required data’s of the grid components. The following features must be considered for this stage to attain self-healing [39].
- Capability to predict and detect the various faults.
- Capability to be controlling from the management and control center and grid compatibility.
- Ability to restore and enhance reliability.
- Accomplish a very fast communication, secure, accurate information.
All relevant information is collected and correlated to ready to analyze any fault. And take control and predictive actions during normal and emergency conditions. In these stage based on the typical features, size and type of data, control algorithm, computing difficulty.

4.2.2. Fault isolation state
The diagnosing the fault in isolation part and identifying the key reason for this fault is a very difficult task. The disturbances, sounds, faulty alarms, errors create several issues.

4.2.3. Fault diagnosis state
The functions of this stage are to diagnose the grid conditions in fault location, type and severity. Main challenge of the fault diagnosis algorithm is two various faults occurs its leads to similar performance of the grid during diagnosis. It’s difficult to understand.

4.2.4. Fault assessment state
Assessment stage is targets on real-time risk assessment when normal and faulty environment including the effect of the status of utility, peak hours and surroundings status, uncertainty and demand load. Also it includes vulnerability, dynamic risk analysis and their assessment.

4.2.5. Fault tolerant state
The functions of this stage are regularly supervising the performance of smart grid during various contingency conditions. The objective of this stage is to response around mseconds to seconds time period. The task of all the levels entities is not depending on another entity. The data’s are moved from each entity and take appropriate action in every level.
5. Self-healing in smart microgrids

Microgrid is consists of collection of confined power sources, energy storage components, various static and dynamic loads. It is playing a vital role in the background of smart grid. It may be grid connected and also supply to several interconnected loads under autonomous conditions. The commonly used sources of power generations are Distributed Generations (DGs) such as: solar photovoltaic; fuel cells; and also wind power generator. During normal operating conditions is integrated in to the traditional grid. When, it’s disconnected from the conventional grid it will be an autonomous microgrid, the DGs is sustaining to supply the microgrid interconnected loads autonomously from the traditional power grid [40]. Correspondingly, if appropriate usage of the microgrid sources is implemented the reliability of the grid maybe achieved.

Figure 5. Flow chart for distribution smart grid self-healing control
To maintain the reliability of the grid the continuity of supply is maintained during contingency conditions also. So, the make use of DGs continuous supply maintained by purposely isolating from the power grid. However, the bidirectional communication happened with the power grid [41]. It must be necessary to supervise the performance of the micro grid, so that if any disturbance disappeared it is disconnected from power grid [42]. To increase the features and benefits of the smart grid the integration of microgrids in distribution side is very necessary. Consequently, the entire grid reliability, system efficiency will be improved. The net results are varied for islanding and grid connected mode [43].

Author in paper [44] was proposed the three-phase power distribution system based hybrid AC/DC connection micro grid. This method needs extra DC conductors for the localized power distribution system to accumulate the distributed generating resources. Author in paper [45] proposed the centralized protection approach for low and medium voltage micro grids. Author in paper [46] was proposed the rapid and selective protection scheme to isolate the faults through minimum number of circuit breakers.

6. Various tools for self-healing smart grids

Software tools in all grid stages (electrical equipment, instrument, control…etc.), synchronized assessments of various parameters, and communication lines between different devices that are all important agents for self-healing in smart grid.

6.1. Software tools

Software tools are performing various functions through communication between the grid equipments [47]. It’s executed through computer programs. The classification of these tools as follows [48]:

6.1.1. Grid component tools: This tool regulates the grid elements functions such as transformers, protective relays and circuit breakers.

6.1.2. Distributed resource tools: In this tool is responsible for regulating the load flow between microgrid and utility grid.

6.1.3. End-user tools: This tool is responsible for calculate power demand from customers. Consequently, this tool regularly track and assess the customer power consumption. To maintain the continuous supply needs bidirectional communication linked between distributed energy agents.

6.1.4. Fault control tools: The role of this tool is supervising and predicting the conditions of grid component. If any fault in components is identified, immediately information was reported to supervisor agents through this agent. Consequently, supervisor agents take decisions to prevent from the fault occurrence.

6.1.5. Data analyse tools: This tools is responsible for gathering the following data’s: grid components condition, power demand, and generation capacity. The collected data is submitted to the superior agents to achieve the effective performance. If any fault in components is identified, superior agents analyze the data and take the proper decision.

6.1.6. Graphical visualizations tools: In this tools visually monitor, forecast and analyze grid performance.

6.2. Synchronized phase measurement unit (PMU)

Synchronous phase measurement units (PMUs) were first popularized at the starting of the 1980s, and since that day, many applications in electric power systems have been challenging. In complex power systems, PMUs are used to get fast, exact information at blackout. The error rate of information received from the PMUs is very less. In case of power failure, thanks to the information obtained from PMU, disturbance can be interfered rapidly and safely. The PMU uses the frequency tracking step and calculates the fundamental period of the frequency before calculating the phasor. The main job of the PMU is; to differentiating the basic components of the frequency by differentiating the fundamental components of the frequency, it can be calculated which phase is faulted.

PMU is a digital instrument that calculates the time stampings with respect to frequency, phasor magnitude [49]. The more phasor values are needed simultaneously for wide area measurements to achieve effective synchronization. The functions and communication of PMUs is shown in Figure.6.
6.3. Information communication technology (ICT)

ICT it is an important element in the smart grid architecture. The best decision is achieved based on analyzing the performance parameters of power grid. The functions are collecting real-time conditions in power grid, interchanging and compiling the collected data’s, executing results and takes the best decisions. An ICT are classified into wireless and wired systems are shown in Figure.7.

To remotely monitor and process the data in power grid Supervisory Control and Data Acquisition (SCADA) tool is play a vital role. In smart meters has been used in the customer location to record the real time information of smart grid [50]. It is an modern digital meters, can be capable of

• To Collecting real time power consumption data from customers
• To Transferring the collected information to local power grid customers, and
• To calculate the tariff for real time power consumption and send the information to the customers [48].

Currently power line communications (PLC) is most commonly used for the smart grid communications [51]. Many debates are raised by the researches for the actual function of PLC in smart grid. Even though many investigators think that PLC can efficiently use in various applications, another group believes wireless communication is an appropriate and powerful tool. However, it is two visible features found PLC domination in the market. First is PLC standardization status. The second is PLC technological status [51].
7. Statistics of publications related to smart grid self-healing research outcomes in web of science

Viewing the several reviews, the publications count is increased in the smart grid self-healing research. The statistics of publications numbers is shown in table 1.

The total paper published in the year 2009 and before year are 8. After that, the many researchers published the articles in different perspectives related to the smart grid self-healing research. The total papers published in the year 2010 are 19. While inspecting the publications we are identified benefits and drawbacks of the self-healing in smart grid.

The total papers published in the year 2011 and 2012 were 71. Again inspecting the publications, we are identified many research methodologies was developed for self-healing concepts applied in distribution smart grid.

In the year 2013 and 2014, the total paper published was 76. Again inspecting the publications after 2014, many research articles presented in the context of smart grid ICT.

The total papers published in the respective years 2015, 2016 and 2017 were 94. While inspecting the publications after 2017, many articles published related to the application of smart micro grid multi-stakeholder structures and its self-healing methodologies was presented. Total number of paper published in year 2018, 2019 and 2020 is 116.

Table 1. Statistics of publications related to smart grid self-healing research outcomes in web of science

| S.No | Year of publication       | Total number of publications |
|------|---------------------------|----------------------------|
| 1.   | 2009 and before           | 8                          |
| 2.   | 2010-2011                 | 19                         |
| 3.   | 2011-2012                 | 71                         |
| 4.   | 2013-2014                 | 76                         |
| 5.   | 2015, 2016 and 2017       | 94                         |
| 6.   | 2018-2020                 | 116                        |

8. Conclusion

This article presented the concepts of recent advancements on smart grid self-healing. The self-healing smart grid methodology is explained under the classification of three grids such as: transmission smart grid, distribution smart grid, and smart microgrids. The task of software tools, Synchronized phase
measurement unit and ICT tools in smart grid are reviewed. Still, many challenging improvements need to develop in smart grid roadmap. The major challenging issues are accommodating more distributed generation, participation of customers to be more enthusiastic into the smart grid context. To achieve the smart grid self-healing required an enormous usage of power electronic converters and ICT tools between several parts of the smart grid. This will satisfies the duties of self-healing control. The effective restoration is an important step to promote a smart grid self-healing. Restoration gives a flexible and optimized control to maintaining smart grid reliability. And also in this article outlines selfhealing control of distribution network in five stages explained. In all stages operating together able to achieve the reliability and security of smart grid. Finally concluded that self-healing control is the essential for the smart grid to provide reliable and secure power to our community.

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