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Self-Healing In Smart Grid: A Review

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Abstract
Today's power systems are based on Tesla's design principles developed in the 1880s and have evolved over time to become the current aspect. Although communication technology is developing very fast, the development of power systems has not been able to keep up with it. Because the structure of the power system used is generally far behind and is unable to respond the needs of the 21st century. With the rapid development of today's technology, it has become possible to make the electricity network better by utilizing the computer and network technologies in the electricity networks. Thus, the electricity networks will provide a sustainable, safe and uninterrupted energy to the consumers by providing bi-directional data and electricity flow. The grids that can do this are called smart grids. One of the most important features of smart grid is that; in the case of a possible outage or fault, self-healing by continuing to provide energy flow.The lower the self-healing time, the less energy will remain in the network and the less time the system will continue to work to renew itself. The methods and tools used to achieve this are discussed in this article.self-healing algorithms and their application areas were surveyed using publications between 2003 and 2017. In the concept of self-improvement, especially transmission, distribution, micro grids, transient stability and cyber attack are explained.

Keywords: Smart Grids, Self-healing , Micro Grids, Cyber Attack, Transient Stability.

Akıllı Şebekelerde Kendi Kendini İyileştirme

Öz
Günümüzün güç sistemleri, Tesla'nın 1880'lerde geliştirilen tasarım prensiplerini temel almış ve zaman içinde gelişerek şimdiki halini almıştır. İletişim teknolojisi çok hızlı gelişmesine rağmen, güç sistemlerinin gelişimi buna ayak uyduramamıştır. Çünkü kullanılan güç sisteminin yapısı genellikle çok geride kalmış ve 21. yüzyılın ihtiyaçlarına cevap verememiştir. Günümüz teknolojisinin hızla gelişmesiyle elektrik şebekelerinde bilgisayar ve ağ teknolojilerini kullanarak elektrik şebekesini daha iyi hale getirmek mümkün olmuştur. Böylece elektrik şebekeleri, çift yönlü veri ve elektrik akışı sağlayarak tüketicilere sürdürülebilir, güvenli ve kesintisiz bir enerji sağlayacaktır. Bunu yapabilen şebekelere akıllı şebekeler denir. Akıllı şebekenin en önemli özelliklerinden birisi; Olası bir kesinti veya arıza durumunda, kendi kendini iyileştirerek enerji akışını sağlamaya devam etmesidir. Kendi kendini iyileştirme süresi ne kadar az ise şebekede enerjisiz kalan kısım o kadar az olacak ve sistemin kendini yenileyerek stabil çalışmasına devam etmesi o kadar daha kısa sürede olacaktır. Bunu başarabilmek için kullanılan yöntemler ve araçlar bu makalede bahsedilmiştir. 2003 ve 2017 yılları arasında kendi kendini iyileştirme ile ilgili yayınlar araştırılarak kullanılan yöntemler belirtilmiştir. Kendi kendini iyileşme kavramında özellikle iletim, dağıtım, mikro şebekeler, geçici hal kararlılığı ve siber saldırı açıklanmıştır.

Anahtar kelimeler: Akıllı Şebekeler, Kendi Kendini İyileştirme, Mikroşebekeler, Sanal Saldırı, Geçici Kararlılık.

1. Introduction

Electricity grids that have been working almost identically since Tesla have become unable to respond to the needs of the 21st century. It is inevitable to use information technology in electrical energy

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production, transmission and distribution technologies in order to be able to respond to today's needs adequately and to provide uninterruptable energy. Until energy production to consumption, real-time bi-directional information flow is obtained at every stage, ensuring sustainable, safe and efficient energy. In recent years, the electricity sector has faced significant challenges such as energy demand, commercial losses and power supply quality [1]. In order to overcome these challenges, it is necessary to transmit energy to consumers in a safe, sustainable and quality way [2].

In addition; despite the large demand for power, the growth rate of the grid has been slow. The rate of electricity consumption is expected to double in the next ten years .Thus, using electric energy efficiently and reliably; is of critical importance. This leads to the need for independent electricity grid operation. As a result, the grid response against the fault must be healed when effective power operation is obtained. To be able to heal it and to provide sustainable energy to consumers, smart grids must be used. Smart grids technologies can be described as self-healing systems that reduce workload and target sustainable, reliable and quality energy to all consumers and can find solutions to problems quickly in an existing system [3]. Although conventional power lines have one-way power flow; smart grid provides two way data and electricity flow by placing various hardware and software in the grid. Smart grids are the most important evolutionary developments in energy management systems as they enable integrated systems, including decentralized energy systems, large-scale renewable energy use, significant improvements in demand side management and sustainable energy [4] . Owing to the integration of distributed renewable energy sources into the system, transmission line losses will be reduced in the near future and more efficient energy consumption will emerge [5].

The US Department of Energy defines the intelligent network as "smart, efficient, adaptive, motivating, opportunistic, quality-focused, flexible network" [6]. Smart grids have been developed for the purpose of providing sustainable energy by combining energy systems and new developments in data and communication technologies [7].

Key elements of the smart grid can be summarized as follows: System integration of renewable energy sources , efficiency and sustainability , integration of electric vehicles into the system and ability to respond to consumer demands [8].

The basic components forming the smart grid is shown in Figure 1.

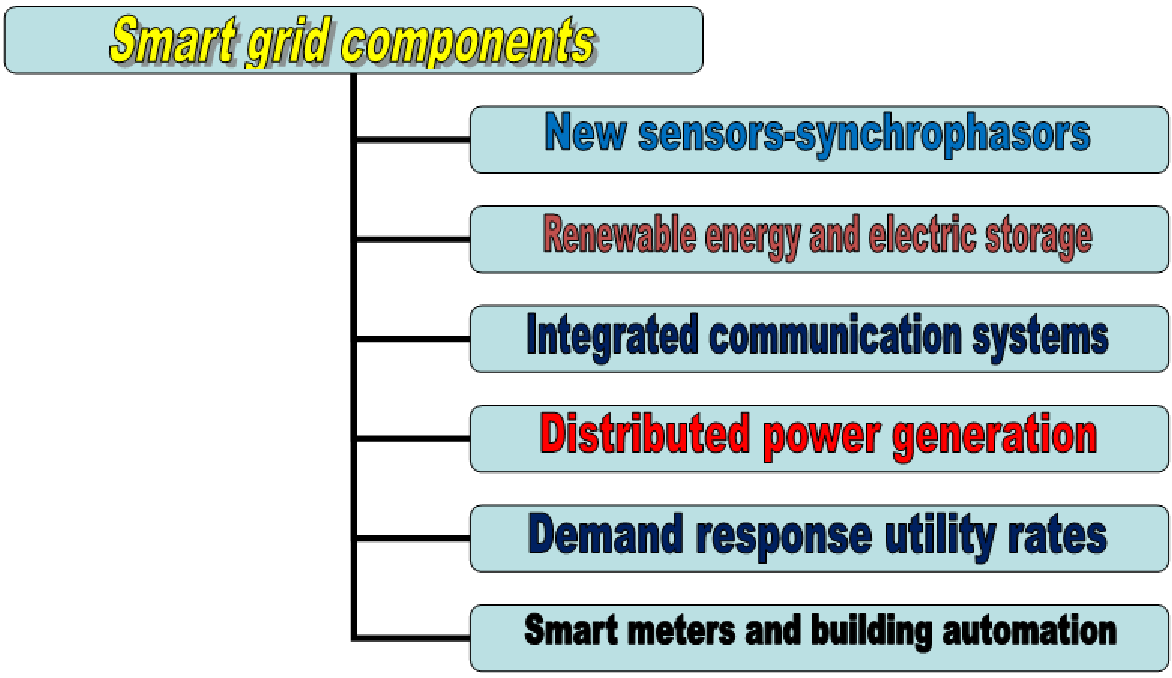

Figure 1. Basic components of smart grid [9]

There are various stakeholders directly or indirectly involved in the smart grid system. Stakeholder ownership can be summarized as in Figure 2.

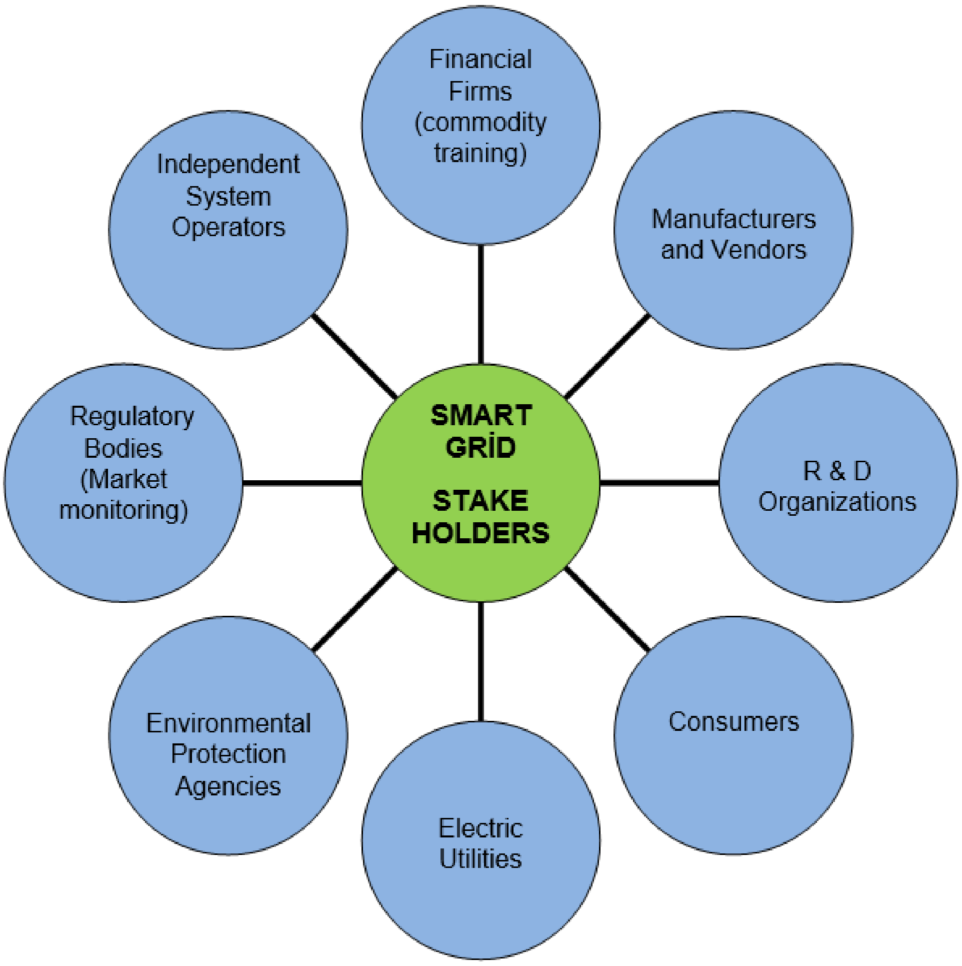

Figure 2. Smart grid stakeholders [10]

The principle of self-healing control is to ensure the reliability and uninterrupted power supply, there are two main meanings:

a) In normal operation, the main purpose of self-healing control is to optimize the operation and eliminate the hidden trouble.
b) The main purpose of self-healing control is to recover the fault as soon as possible,it can be divided into internal and external faults in the control area.It is the main means to quickly remove and recover the faults in the self-healing control area,minimize the outage area and system operating loss,When an irreversible serious fault occurs outside the control area,disconnect the fault network from the external network,the system relies on the autonomous operation of distributed power supply and energy storage device in the region to maintain uninterrupted power supply.

In this article, the information obtained from the literature search on the self-healing feature in smart grid is shared and and how the network self-heals transmission, distribution, micro girds, in transient state and cyber attack situations have been reviewed.

2. Self-healing Grid Applications

As the complexity of the systems increases, it is more expensive and troublesome to correct the system faults and to get the system back to its normal operating state. Self-healing systems must be used to achieve this [11]. The aims of these systems are summarized in Figure 3. The main goal in self-healing is; to be effective against grid faults and at the same time to take protection against grid propagations.

To be able to achieve this, the smart grid must realize the following:

a) Quick and accurate analysis of faults to protect the system from harmful effects.
b) Providing positive or negative situation.
c) Minimization of the service's self-renewal period.

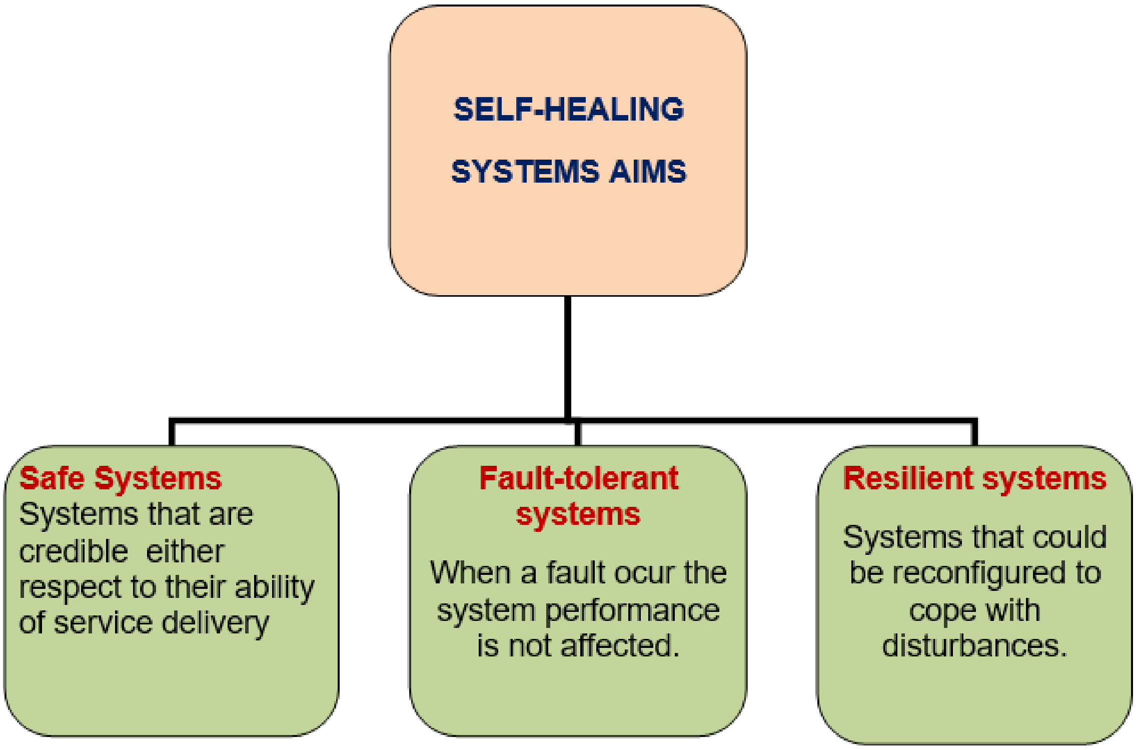

Figure 3. Self-healing System Goals [8]

For a more detailed investigation of the concept of self-healing, it is presumed that the power system in the smart grid consists of three main grids, ignoring the production phase.

2.1 Transmission Grid In Smart Grid Using Self-healing

While today's smart grid system is being constitute, fault detection is very important. The purpose of fault detection is; to increase the quality of the power, to provide reliability and to use the power system's self-healing feature. The use of intelligent sensors and advanced communication technology, which can be used in smart grids, is important in troubleshooting [12].

In a smart grid; In order to continuously determine and monitor the transmission line parameters, developed sensors, signal processors and communication networks must be established in the all transmission grid [13]. However , the transmission line parameters are continuously determined and monitored. Therefore, the sensors will provide critical data such as the sagging of the conductors on the overhead lines , the temperature of the conductors, the conductor current carrying capacity against thermal capacity [14]. Also, the intelligent transmission transformer station must return to its normal case after blackout failures.

One of these solution suggestions is the optimal voltage control based on genetic algorithm. When voltage control is performed, fast and high-quality solutions can be obtained by inserting previous phenomena into the genetic learning algorithm in the system [15]. We need to obtain a comprehensive and planned system for the self-healing of the grid. To ensure this, there is a need for optimally located grid elements, energy storage sources and compensation systems [16]. The network topology will be established through the wired or wireless communication between these systems and the system will be self-healing by sending a warning to the system center in case of any fault [17].

A self-healing method for the smart grid, using a united power flow controller (UPFC) and obtaining a steady power flow under network faults was suggested [18]. In this method to implement the control algorithm; inverse current grid is applied instead of the iterative algorithm, the node analysis method is applied instead of the optimization method and the power flow is rearranged.

In the event of a distributed production increase in the grid, when a fault come off a definite place , both the grid electricity and the grid fault currents flow into the faulty zone. Increasing fault currents can be a problem, especially when the value of the fault current exceeds the power cut off values of the protective devices.

The increased impact of distributed production takes out two problems during fault:

a) Fault current increase.
b) Decrease in the ability of the system to remain on the grid after fault of the system without losing its stability.

FCL is connected between the micro grid and the main grid to decrease the fault current resulting from the jointing of a new generator to the micro grid [19]. An algorithm that monitors and detects overvoltage events is mentioned [20]. To achieve this, the intelligent network's self-healing feature has been exploited and the S conversion algorithm is described in detail.

2.2. Distribution Grid In Smart Grid Using Self-healing

The establishment of a self-healing system in the smart distribution grid is of great importance. For this, a new smart distribution grid based on the travelling wave system has proposed for self-healing method [21, 22]. In this method, a fault is detected when the first measured travelling wave threshold is greater than the threshold value. Fault distance is calculated exactly by using the least squares method . Then the system heals itself with the help of the proposed algorithm and provides a smooth and uninterrupted energy. An analytical method that uses the Markov method was proposed to ensure the reliability of the electrical distribution system [23]. Owing to this method, the electric power distribution grid elements are intelligently followed up , obtained great economic benefits and tested and proven on a real system.

In adaptive overcurrent method, this method, if there is any change in the load level, the relay settings are updated automatically so that the system can cope with the changes [24]. If the distribution grid has distributed generation and has some disruption to the grid flow direction, the islanding can be applied to increase the reliability of the power supply.

In order to connect the distribution system to the rest of the power system, it is necessary to develop active distribution grids and automate the medium and low voltage transformer center. General information on the components and functions of intelligent transformer automation system are given [25]. A multi-agent system and a suitable switching operation was implemented to reconnect the segregated loads [26]. A new protection algorithm was used a wireless token ring protocol (WTRP) [27]. Therefore, data is exchanged between the relays, the appropriate switching operation is performed and the system reliability is increased.

The ant colony algorithm has been proposed so that the distribution network can use the self-healing feature [28]. Thanks to this algorithm, the system responded more quickly to a negative situation and found a solution.

In addition, islanding application was used when the power system confronts a dangerous case [29, 30]. This plan is partitioned into a few small islands that provide fast reconstruction to get the system to the normal state. The load shedding system is then applied according to the drop in frequency. A new multi-agent control system (MACS) is proposed for smart distribution grids [31]. In this system, fuzzy control algorithms are used for decision-making support. Owing to this algorithm, which can reconfigure the distribution network, the voltage irregularities are eliminated and the operation of the reactive power controllers can be controlled. Fault location, isolation and service restoration (FLISR) program in accordance with the latest technology standards has been proposed in smart grids [32]. With the aid of this microcontroller-based program, the fault location in the distribution network is determined and solution proposal is presented.

2.3. Micro Grids In Smart Grid Using Self-healing

The micro grid plays an important role in the smart grid. Because the micro grid can be integrated into the network, it can also feed connected loads in island state. Generally, micro energy sources that generate electricity are named as: Solar panels, fuel cells and wind turbines. In order to create a robust and secure micro grid and to be able to self-heal the network, software-based communication network architecture is presented [33]. A method to maximize the power flow time is considered to build up a micro grid in island conditions, taking into account the availability of renewable resources and stored energy [34].

Disconnection of the grid connection, independent of the grid, distributed production will continue to feed loads connected to the micro grid. Accordingly, reliable use of electrical energy will be ensured if micro grid characteristics are used properly [35].

Integrating micro grids into the distribution grid is useful. Because it makes easier the implementation of many smart grid functions [36]. Accordingly, general system credibleness, efficiency will increase and renewable energy can be integrated into the system. A hybrid DC / AC coupling is used to create a micro grid using a three-phase power distribution system [37]. In this system, an additional DC line is required for the local power distribution system to collect renewable energy resources. Centralized protection strategy for medium voltage micro grids was used [38]. In case of a possible fault, a fault isolation method which provides economical, rapid and selective protection using a minimum number of circuit breakers has been proposed [39].

3. Synchronized Phase Measurement Unit (PMU)

Synchronous phase measurement units (PMUs) were first introduced at the beginning of the 1980s, and since that date, many applications in power systems have been challenging. In large power systems, PMUs are used to get accurate, fast information at blackout. The error rate of information obtained from the PMUs are very low. In case of power fault, thanks to the information received from PMU, interruption can be intervened quickly and safely. The PMU uses the frequency tracking step and estimates the fundamental period of the frequency before determining the phasor. The main task of the PMU is; to distinguish the basic components of the frequency by distinguishing the fundamental components of the frequency, it can be determined which phase is faulty. Figure 4 shows the application of PMU [40].

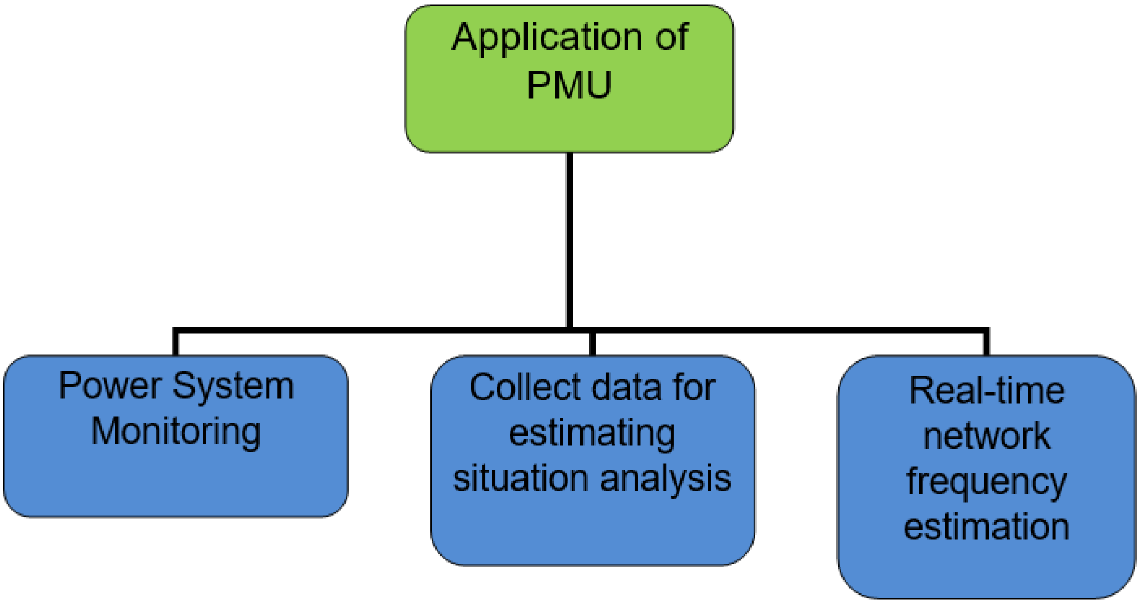

Figure 4. Application of PMU

4. Communication Technology In Self-healing Smart Grid

Owing to the low-cost, collaborative nature of the wireless sensor network, there are reliable and self-improving bi-directional communications to monitor and control the equipment in the smart grid [41]. Wireless sensor networks have features such as ease of installation, scalability, and self-healing [42]. Self-healing hierarchical architecture (SHA) for ZigBee wireless networks was used in smart grid applications [43]. By using this architecture, two-way communication in the smart grid can be made faster and more secure [44].

Generally smart grids have a centralized control system called Control and Data Acquisition (SCADA) to monitor and maintain all data sources. Since the SCADA system does not have a definitive protocol, it can be adapted to any protocol required by the utility program [45]. Unlike SCADA, smart grid fills customer space with smart meters [46].

Smart meters collect data on end-user power consumption, record energy use and automatically send meter readings and meaning an end to estimated bills [47].

Research continues on the role of the real PLC in the smart grid [48]. However, there are two views on the market that may prevent PLC dominance. First, the commercial impact of struggling smart grid applications using inappropriate PLC technology; second, the effect of PLC standardization status [49].

5. Self-healing And Transient Stability

Stability has always been one of the most important aspects of power systems. Stability studies evaluating the effect of faults on the electromechanical dynamic behavior of the power system are divided into two as temporary state and continuous state stability. Transient steady state is the capability of the power system exposed to large disturbance to remain synchronized. Immediate load changes in the transmission system are counted as instances of major failure such as loss of production units, loss of important transmission lines, and line switching. In such faults, the system response causes large deviations in generator rotor angles, load flows, busbar voltages and other system variables. Transient state stability studies involve major errors and do not allow system equations to be linearized. Because of this feature, transient stability analysis is considerably complex.

Several methods have been developed to provide transient state stability in smart grid. Especially one of the recommended methods is the method of islanding. During islanding process; the power system will be divided into small islands and the production-load imbalance in each island will be minimized and the system will be improved in a shorter period of time [50].

Another method is the real-time monitoring of the network using the phaser unit (PMU) following the generator rotor angles. When power fluctuation occurs in the network, the rotor angle of generator / generators connected to the networks will be unbalanced. These unstable generators should be isolated from the network as soon as possible . To achieve this, PMUs that monitor parameters such as voltage and current can be used. Thanks to the PMU, the system can be self-healing more quickly and safely. The time it takes is limited. Since the unstable situation occurs a few seconds after the power surge, an advanced calculation and optimization method should be used [51].

Another method is the load shedding method. The main problem here is which loads are to be shedding from the system. To determine this, the PMU that follows the generator's voltage angle is used. The information from the PMU is compared with the actual values to determine which load should be shedding from the system. Advanced optimization algorithms are used to ensure that the system can self-heal quickly and reliably after the load is shedding from the system [52].

6. Protecting The Smart Grid From Cyber-attack By Using Self-healing

The smart grid is designed to adapt advanced communication / networking technologies to the existing electrical network. Thus, electric networks become intelligent by allowing bi-directional communication. A new communication infrastructure needs to be designed and implemented to convert the available grid into a smart grid . Several solutions have been proposed in recent years to ensure that the smart grid is reliable and potentially resistant to attack by cyber attacks [53].

The standards used in smart grids for cyber security are mentioned [54]. The smart grid has been extensively used to protect against cyber attacks (cryptography, access control, firewalls). The PMU must be reconnected to the system and the observability of the system must be regained so that the network can self-heal in this case. In order to achieve this and to minimize the system's self-healing time , the integer linear programming [ILP] model is used. An intuitional algorithm is used to reduce complexity in calculations [55].

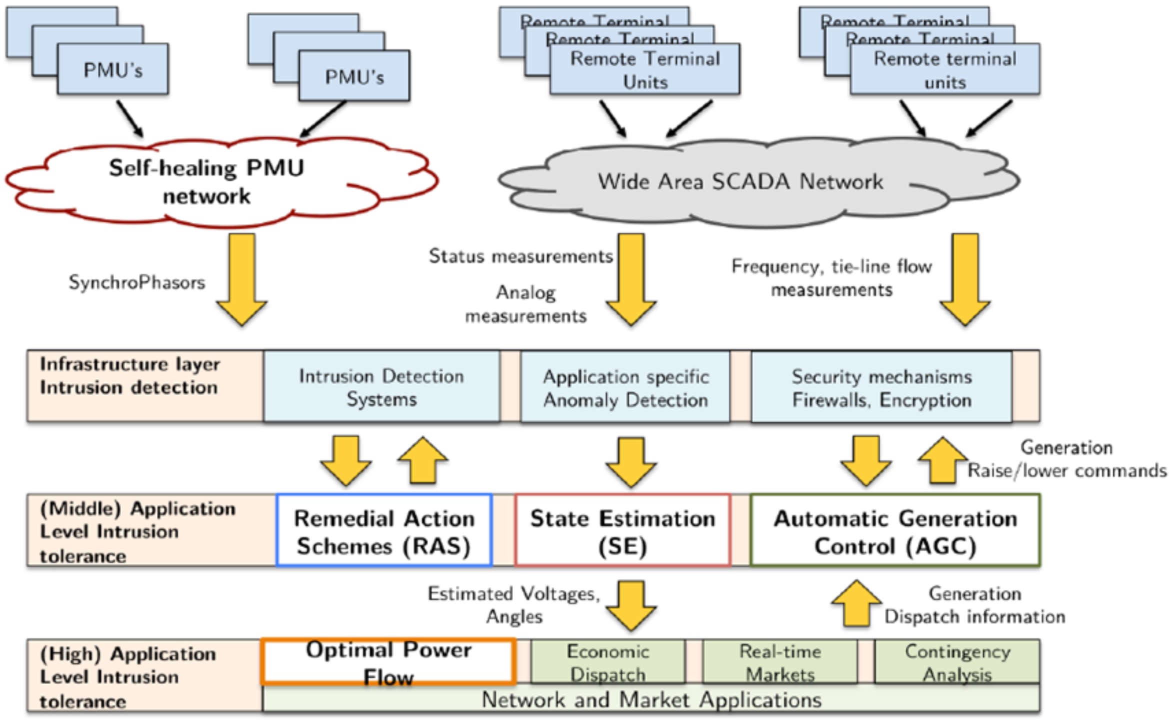

Figure 5. Self-healing flexible security architecture recommended for WAMPAC (Wide area monitoring, protection and control) [56]

Figure 5 shows a self-healing structure for wide area monitoring, protection and control. The main purpose here is; to enable the system to continue to run uninterrupted in the event of a possible cyber attack. For this, the functions and functions of the elements in each layer are seen.

Table 1. Smart grid self-healing methods

Reference number	**Islanding**	**Load shedding**	**PMU**	**Protecting the grid from cyber attack**	**Fuzzy logic control algoritms**
[8]			✓		
[11]				✓	
[24]	✓				
[29]	✓	✓			
[31]					✓
[33]				✓	
[34]	✓				✓
[40]			✓		
[41], [42],[43]				✓	
[50]	✓	✓			
[51] , [52]		✓	✓		
[53] , [54]				✓	
[55]			✓	✓	
[56]				✓	

Table 1 shows the self-healing methods used in the reference of article. When the table is examined, it is seen that the methods of protecting the smart grid from cyber attacks, the methods of islanding, load shedding and working on the PMU are concentrated. In some references we also find fuzzy logic control based self-healing applications.

Looking at the literature review, the change in the number of publications published by the self-healing smart grid in the web of science is shown in Figure 6.

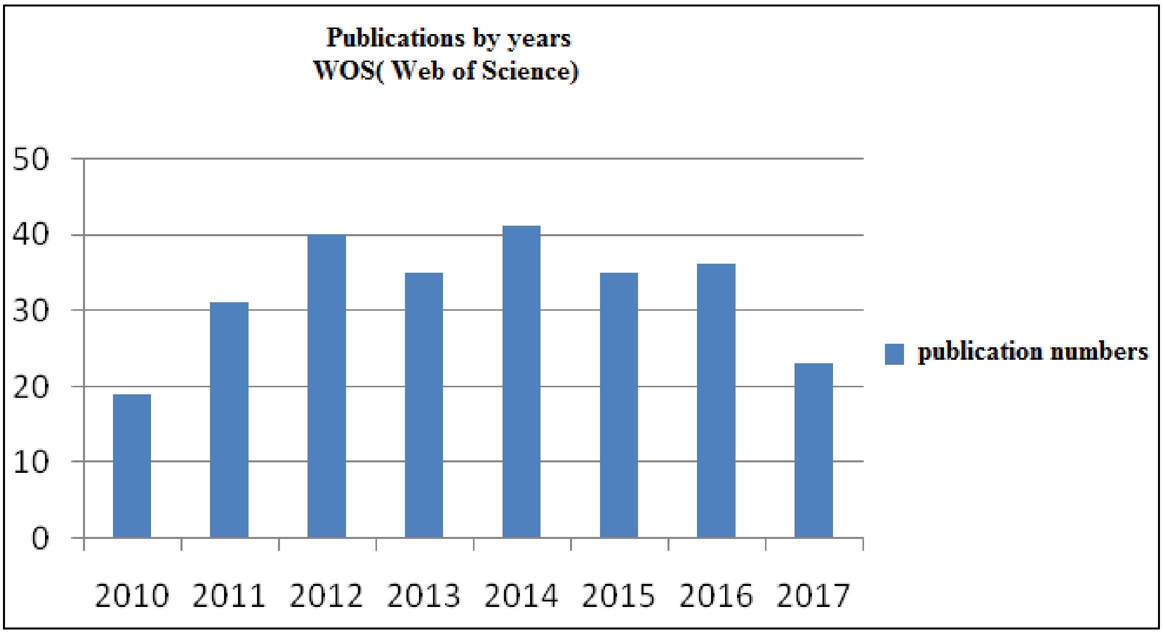

Figure 6. Number of publications based on self-healing smart grid search results in WOS

The number of publications in 2009 and before is 8. What is the concept of smart grid? How to link self-healing? We find several publications on applicability.The number of publications in 2010 is 19. When publications were examined, we find the advantages and disadvantages of the concept of smart grid, publications on the relation of self-healing concept to smart grid.The total number of publications in 2011 and 2012 is 71. When publications were examined, smart grid was tried to be applied to distribution systems together with self-healing concept; different solution proposals have been developed. In 2013 and 2014, the total number of publications is 76. When publications were examined, smart grid communication methods (wired and wireless) were studied and solutions for network security were presented.The total number of publications in 2015, 2016 and 2017 is 94. When publications were examined, micro grid applications, smart grid self-healing can be done in the future, in multi-stakeholder structures, the application of smart grid self-healing concept is emphasized.

7. Conclusion

In this article, the smart grid's self-healing ability, transmission , distribution and micro grids are surveyed. The PMU and communication technology has been researched to determine what the smart grid needs to do in order to be able to self-heal in case of transient state and cyber attack. Main challenges is to incorporate distributed energy into the energy network and to protect the grid against cyber attacks. The major developments in technology that enable communication between different parts of the smart grid will enable us to perceive the smart grid's self-healing concept. Thanks to improvements in the power electronic converter and cyber network security, the self-healing goals of the smart grids are approached step by step.

Especially in case of transient stability and cyber attacks, new algorithms and methods can be developed to reduce the self-healing period of the network and provide reliability. At this stage, wireless communication at short distances and sustainable and uninterrupted energy delivery of the network can be provided by using a satellite communication system at long distances.

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