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Providing Uninterrupted Energy with Fault Detection and Storage Method in Smart Grids

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ABSTRACT

The implementation of smart grids necessitates an upgraded protection system to enhance reliability. When a fault occurs within the electricity network, affecting either transmission or distribution systems, it often leaves a large area without power until the issue is resolved. Identifying and addressing the root cause of such malfunctions is typically a time-intensive process. Fault localization and network repair time are crucial factors for energy companies, as quicker troubleshooting can mitigate manpower demands and economic losses. This study proposes a modernized protection system designed to deliver rapid protection responses and facilitate swift repair operations during both internal and external faults, supported by energy storage solutions. Smart grid technology introduces a bidirectional power system and grid transformation, which streamlines power transmission and expedites the recovery of fault-affected areas. Frequent power outages are a significant concern for both energy companies and consumers. Faults in power systems typically result in voltage drops within the affected regions and are often caused by various disturbances in the transmission and distribution lines. Consequently, addressing failures in smart grids with the aid of storage methods and support from electric vehicles can ensure uninterrupted power supply.

1. Introduction

Smart grids (SG) are defined as an electrical power system that uses information exchange and control technologies, distributed computing, and associated sensors and actuators to provide customer-oriented power and ensure safe, reliable energy [1]. By integrating distributed energy resources, advanced sensing technologies, control methods and communication technologies into the electrical grid, PVs offer the opportunity to operate intelligently with bi-directional power flow and self-healing ability [2,3]. As shown in Figure 1, the AŞ is divided into different areas in accordance with the standard IEC 62913-1 ED2. These areas are described by the Smart Grid Architectural Model (SGAM) defined using the Architectural Approach [4] and include different sections such as mass generation, transmission, distribution, DEC, customer locations and cross-sectional area. Furthermore, the distribution field is divided into three categories: distribution network management, microgrids (MG), and smart substation automation.

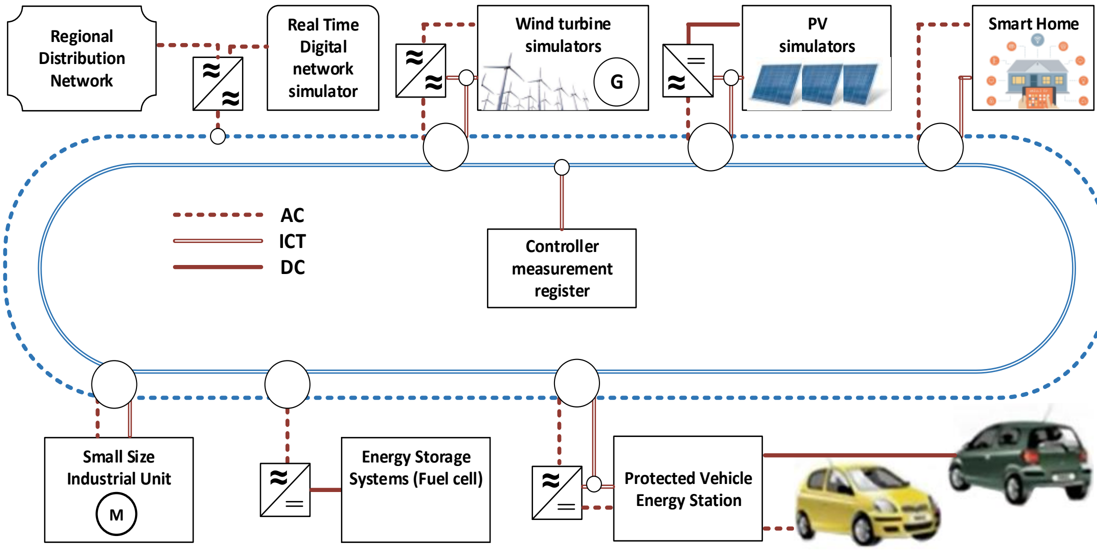

Figure 1. Main components of the smart grid system

The integration of more renewable energy sources (RES), storage systems and control devices into the distribution grid will guarantee system reliability, increase system resistance and keep current and voltage within safe ranges. However, the integration of more and more different technologies into the grid, if not handled appropriately, will lead to an increasing number of significant failure points, subsequently causing cascading failures and power outages [5]. Therefore, an appropriate fault management system [6,7] is necessary to detect, classify, localize, diagnose, isolate and repair faults to restore the system to normal function. One of the key features of PVs is the ability to self-heal by detecting and isolating outages and faults, reducing the frequency of faults, rescheduling grid resources to prevent critical situations, maintaining service continuity of the electric grid under all conditions, and shortening outage repair time [9,10]. To ensure this self-healing ability, stability, and improved system performance, fault diagnosis and positioning are important, as undesirable effects such as power outages and component failures can be reduced [11].

Detection and isolation of abnormal events are the focus of fault diagnosis [12]. The diagnostic process begins after detection. The type of existing problem and its possible causes are determined by diagnosing the severity of the problem. It can also help evaluate whether there is a fault developing that is not yet large enough to threaten the system [13]. The main considerations when developing a fault localization strategy are to locate and intervene in a power outage within the system, to improve the fault detection procedure, and to decide whether an online or offline localization approach will be used [14]. As more generation resources based on inverters, sensors, and communication systems are added to PV systems, more accurate fault location algorithms, fault predictions, and privacy-preserving schemes are needed [15,16]. More dynamic and unbalanced loads, intermittent and unbalanced generation sources, various operating modes (coupled, isolated, interconnected), different topologies (star, ring, mesh or interconnected), different fault points and various conductor sizes make fault localization a critical will make it a duty. Moreover, fast communication, significant fault current biases, and high sampling rates are required for the integration of low line impedance direct current (DC) microgrids [17].

2. Function Phasor Measurement Units to Improve the Protection System of Smart Grid

Phasor Measurement Units (PMU) use time synchronization to take real-time measurements at different remote points of an electrical grid. These devices are considered one of the most critical measuring devices of smart grids [18]. PMUs can be used as standalone devices or integrated into protective relays or other devices. PMUs detect transient waveforms created by faults, providing mathematically defined phasors. A PMU measures 50/60 Hz AC waveforms of voltage, current and phase, typically at a rate of 6-60 samples per second. Analog AC waveforms received from voltage or current signals are converted into analog-digital signal (A/D) for each phase [19]. A GPS-powered phase lock oscillator is used as the reference source to provide high-speed synchronized sampling and operates with an accuracy of 1 microsecond. The resulting time of the phasors is transmitted to a local controller or a remote receiver at rates of 6 to 60 samples per second [20].

Transferring electrical energy from generating stations and units to system end terminals requires overhead lines and equipment at different stages [21]. This process involves increasing and decreasing voltage at subtransmission and substations within the transmission system. Electric power grid systems have been in existence for over 50 years. However, with the increasing power demand, the power system network has become more reliable in recent years and its advantages have begun to be better used. Beyond increasing power demand, several factors have caused changes in power grid systems. First, the increasing interest in distributed energy generation is notable. Secondly, the European Union has turned to renewable energy sources to significantly reduce greenhouse gas emissions in the fight against climate change. According to the Kyoto Protocol, Europe uses more renewable energy than any other region worldwide. Finally, reducing CO_2 emissions, efforts to increase energy efficiency, deregulation or competition, and diversification of energy sources are encouraging improvements in the electric power grid of the future [22].

Substations contain the major electrical equipment used in transmission and distribution systems and are used to monitor and control power fluctuations. In substations, the high voltage carried is stepped down to increase the current while maintaining the same power [23]. The main equipments are:

- Preventive maintenance and Transformers
- Lighting disconnect switches
- Electrical networks and feeders
- Circuit breakers and re-openers for protection systems
- Digital and electromechanical relays for monitoring and controlling network protection
- Fixed VAR compensators and Control building

2.1. Relays in Protection Systems

Relay applications have been used for 100 years to protect power systems. The technology used in making relays has improved significantly in terms of size, weight, cost and functionality. Relays can be classified according to technology and intended use [24]:

- It is the first type of relay used. Since it is based on a mechanical force principle, it is heavier and has lower response speeds than other technologies.
- Emerged in the early 1960s and are based on analog electronic circuits. Although static relays provide advantages over electromechanical relays, they also have some disadvantages.
- Uses analog-to-digital converters (ADC) to sample incoming analog signals and uses microprocessors to define relay logic. High accuracy and multifunctional algorithms are the main benefits of this technology.
- Works with a specific digital signal processor and performs specific digital signal processing applications.

The performance of a relay in a power system is related to the following characteristics [25]:

- It is the ability of the relay to operate correctly. Reliability has two elements: Certainty to act correctly when errors ocur and the ability to avoid unnecessary actions.
- The ability of the relay to ensure continuity of supply by disabling the minimum section required to isolate the fault.

- Ability of the relay to achieve the minimum operating time to clear a fault, thus preventing damage to equipment.
- The ability of the relay to recognize any change or abnormal operating condition exceeding a certain threshold value.

3. Improving the Protection System of Smart Grid

The future of the electric power grid is expected to evolve with the integration of new Technologies [26, 27]. One of the goals of the future smart grid is to improve the protection system to increase efficiency and reliability. In this context, the application of self-healing automation systems in medium voltage (MV) and low voltage (LV) networks is among the steps taken to improve the protection systems of the smart grid [28]. An advanced protection system using a self-healing method in the distribution systems of smart grids is introduced through the application of advanced sensors and Intelligent Electronic Devices (IED) [29]. Optimization of power grid operation is another goal involving protection automation. Reducing loss and downtime increases the reliability of supplying power to consumers with high efficiency and quality [30]. One of the aims of implementing self-healing systems in smart grids is to increase the continuity of uninterrupted power supply [31]. Distribution is the final stage of the electrical power grid and involves the transmission of electrical power to consumers. Power system automation protection includes fault localization, isolation of the area affected by the fault, and restoration of power to unaffected areas. This is the most important technique for improving power networks. When errors occur in the distribution systems of power grids, the change of voltage, current and phase signals can be detected and recorded using smart devices and PMUs (Phasor Measurement Units). These smart devices can be used to locate, update and retrieve data related to grid status in real time. Nowadays, this includes advanced scenarios using protection systems that involve fault detection and quickly isolating the affected area from the mains supply. Circuit breakers are the main cause of outage and power loss and isolate the main supply and feeder to the distribution network. This makes islanded protection systems more complex and requires the use of low-cost advanced electrical devices to integrate appropriate protection algorithms, islanded operation, and reliability [32].

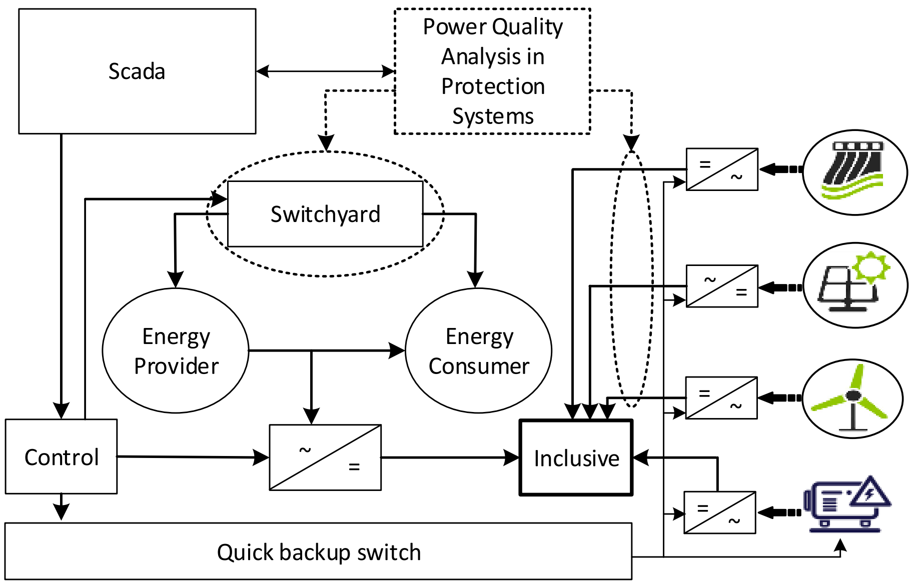

Figure 2. Distributed renewable energy and an integrated protection, monitoring and control system [32]

3.1. System Stability Maintenance and Error Detection Techniques

In order to ensure the stability of the system after the detection of a fault event, it is critical to determine the fault location geographically [33]. In the literature, various techniques are used to determine the location of a fault in the system [34, 35]. While the frequency component and line parameters are used in the phasor-based method, the temporal components of the signals and distributed line parameters are used in the time domain-based method [36]. For example, the phasor-based method relies on traveling waves for the high-frequency components and phasor quantity for the fundamental frequency. The time domain-based method, on the other hand, determines the power outage using expert systems, neural networks or fuzzy logic [37]. Additionally, phasor angle measurements between buses in the system are used in the Gauss Markov method to determine the error [38]. The authors state that examining the lines from one or both ends can detect the fault using the impedances of the source [39, 40].

Measurements of voltage sags and swells can be used to identify faults affecting the system during short circuit events. When a large load is turned off, a large switching capacitor bank is turned on or off, and a transmission line is turned off, the RMS voltage on the faulty line decreases, a phenomenon known as voltage sag. The RMS voltage on the non-faulty line increases to determine the voltage rise [41, 42]. Another method used to find the fault in the system is State Estimation, which is a mathematical method. This method is used to determine voltages at each node in the SG and analyzes only the main grid current, ignoring other sources [43]. However, many of these methods may lack accuracy depending on the size of the power network.

3.2. Smart Grid System Examined

The proposed SG has been validated as shown in Figure 3. This represents a three-line SG supplying electricity to a town and consists of 8 MVA solar power plants, a 4.5 kVA wind turbine, 15 MWA diesel generator, a 100 kilometer transmission line and approximately 10 MVA loads and 4 MW (100*40kW) electric vehicles as storage systems. It has been stated that voltage and current changes should be within ±10% to maintain the stability of the system. In this study, power failure was detected after the current exceeded its rated values at any point. In the faulty case, the position where the current increased the most was accepted as the faulty load. The power fault must be detected within 10 ms - 50 ms and located within three cycles. The faulty load should be isolated after three cycles and the stability of the non-faulty parts of the SG should be ensured.

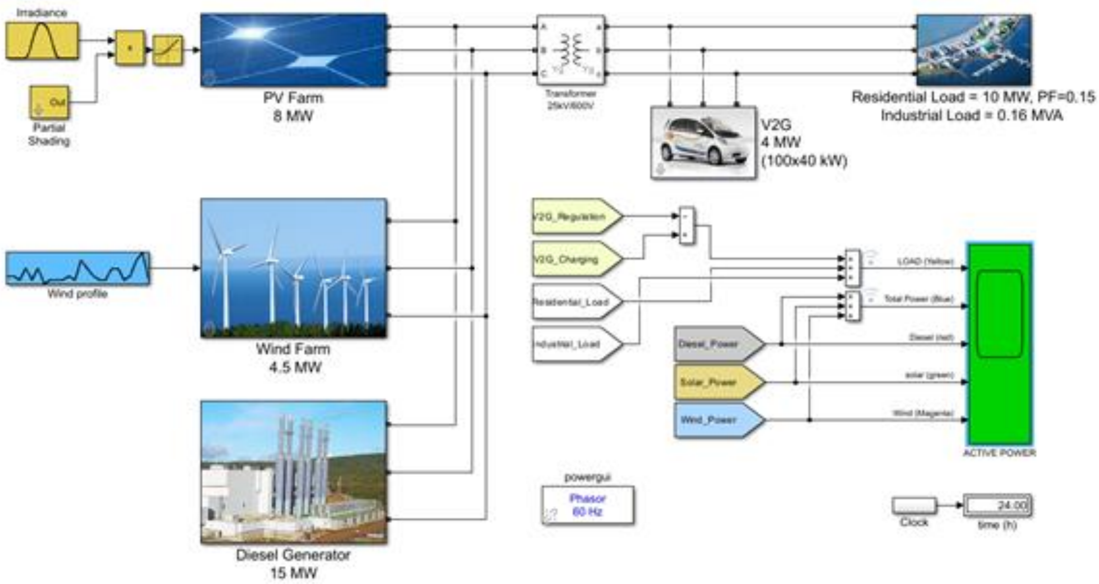

Figure 3. 24-Hour Simulation of V2G System as Storage Model

The first environment allows the user to build the system, compile it, and check for compilation errors. Once the model has been compiled without errors, the model is ready to be executed in the second environment, as a direct working model of the RSCAD software. The electric vehicle battery model used in the first model is used as storage technology to provide an uninterrupted energy system by being activated during line failure. RSCAD has a component library that allows users to control and interact with the simulated model with push buttons, control switches, gauges, and other components. If breakers are used, opening and closing operations are carried out by control switches. The hardware can be a PV or a relay. This feature allows users to connect RTDS to communicate with RSCAD and allows them to implement more complex condition expressions such as loops, conditionals, and looping expressions.

In this study, these features were used to isolate the faulty load three cycles after detecting the power fault in the system. Power failure is determined by the current exceeding its rated values. The following steps were followed to complete this study:

1. Measure the current at the "P" positions and record them in graduations.
2. Apply and save short circuit fault.
3. Detect the fault if the current exceeds its rating at any "P" position.
4. Re-measure the currents in all "P" positions and record as a fault.
5. Calculate the rate of change at all positions and record it as a fault.
6. Find the position where ΔI is maximum (max(ΔI)) and consider it as the faulty position.
7. Use the circuit breaker associated with the faulty line to disconnect the faulty load and remeasure the currents in all "P" positions.
8. Commission the storage system during the outage.
9. Compare the energy supplied to the grid with the energy stored at low prices.
10. Perform a benefit-cost analysis of the designed model.

The test model provides uninterrupted energy to the loads as long as the three-line, 8 MVA solar power plant, 4.5 kVA wind turbine and 15 MWA diesel generator produce energy. With the decrease in solar energy production and wind energy production shown in Figure 4, the supporting diesel generator comes into play. In case of long-term outages where this is insufficient, 100 electric vehicles with a capacity of 40 kW integrated into the system provide uninterrupted and low-cost energy with storage support of 4 MW capacity.

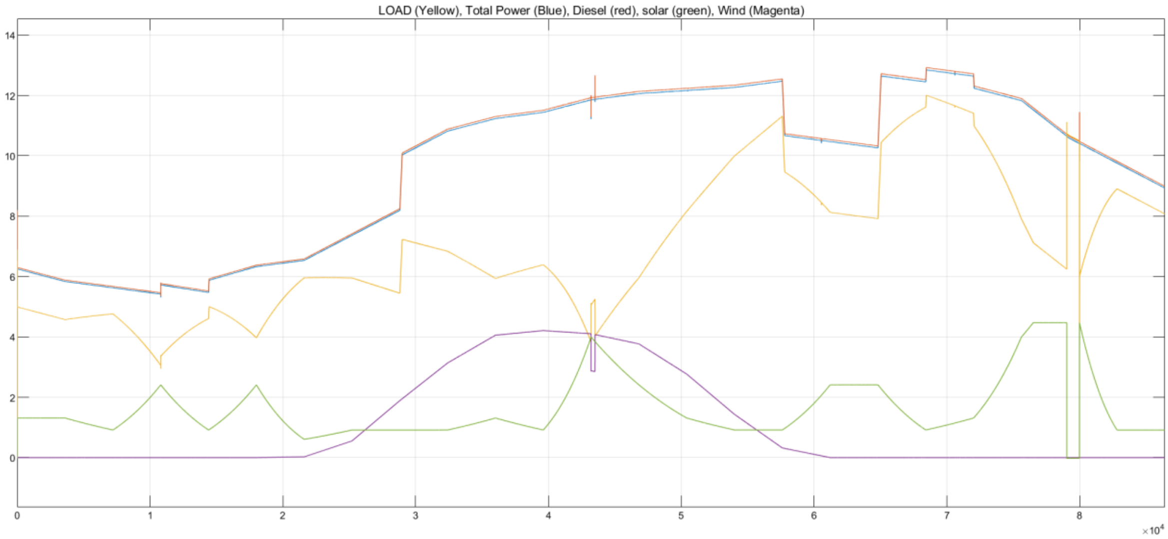

Figure 4. Solar power plant, Wind turbine, Diesel generator energy production change

Indicators P1, P2 and P3 in Figure 5 represent measurement locations defined as station solar power plants, wind turbine, diesel generator, respectively. These measuring units provide measured currents at each location during normal operation, faulty condition and after isolating the faulty load. Indicators S1, S2 and S3 represent circuit breakers programmed in the Matlab file to isolate the faulty load. Matlab/Simulink allows the user to select the fault type and location to be applied to the system. A three-phase earth fault is considered the most severe fault type to the proposed SG and is applied at t = 1 s; The system is run for 3 s while clearing at t = 2 s. The fault location is located in the distribution line of load 4. Additionally, the system was examined in Real Time Digital Simulation (RTDS) to ensure the robustness of the proposed fault management techniques. The RTDS platform allows users to apply faults at any time during operation.

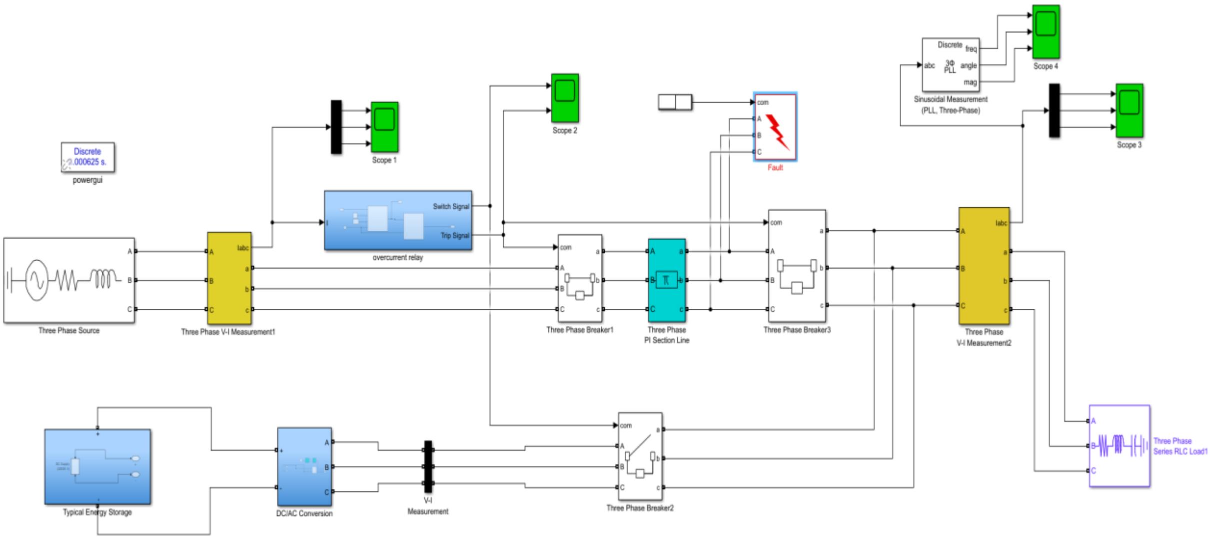

Figure 5. Integration of the Storage Model into the system as an Electric Vehicle

RTDS is a digital power system simulator consisting of advanced computer hardware and software operating in real time [52][53]. It is considered an ideal protection and control tool for the design and development of power systems and SG [53]. RTDS is characterized as a fast processor simulator thanks to its simultaneously executed procedures. RSCAD software has an extensive component library and offers the ability to simulate a large number of components. RSCAD consists of two main interconnected environments and allows users to run and execute the simulated model.

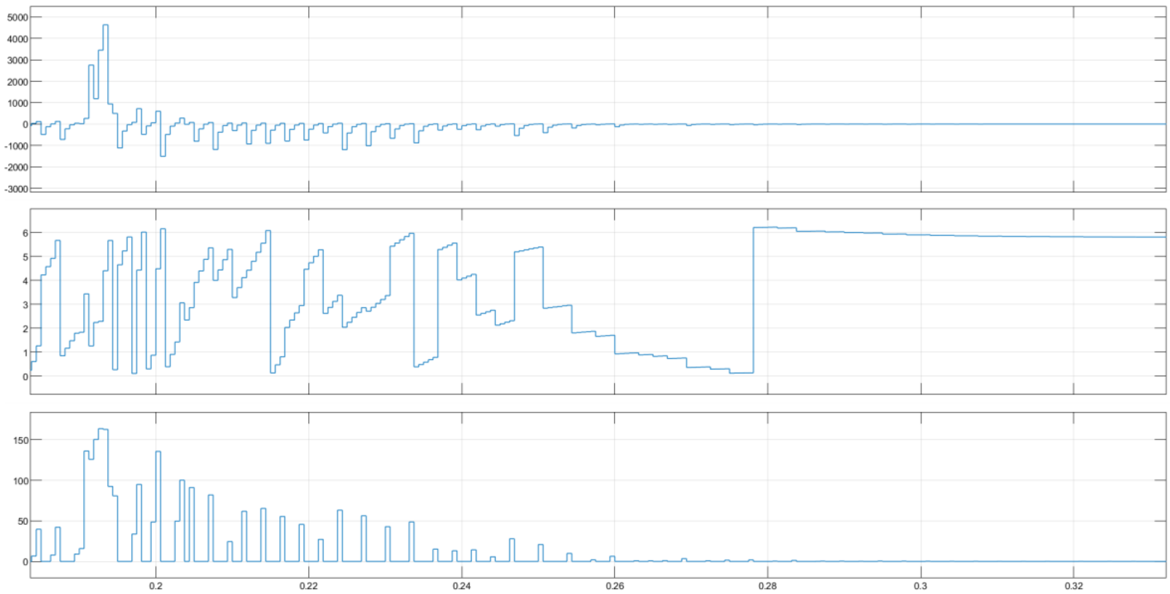

Figure 6. SG allowed error variation between 20 ms and 30 ms

Energy is provided from electric vehicles as a storage system in order to prevent the loads on the 100-kilometer transmission line from being left without energy after a fault occurs in the system between 20ms and 30ms.

The performance of the SG has been comprehensively examined by comparing it with the results of the model designed in the Matlab/Simulink environment. The user was allowed to apply errors during operation between 20 ms and 30 ms, during which time the error was implemented on the model. After the applied error, the current waveform was recorded and this waveform is presented in Figure 6.

Figure 6 shows in detail the error detection time of the designed SG and how the current changes over time. The peak value of the last normal signal was measured at 0.02 seconds, and immediately after this value the fault current exceeded the maximum rated current at 0.028 seconds. This is a sign that there is an abnormality in the system.

By taking the differences of Planned Production (MWh), Actual Production (MWh), Actual Consumption (MWh), the Actual and Planned Production (MWh) value is obtained as 2,059,021 MWh for a month on an hourly basis shown as Figure 7. When the parameter between these two values is multiplied by the system marginal price for the real power system, it is determined that 4.547.563,79 TL of energy is provided by storage. This power value, defined as a large value, will prevent customers from being left without energy.

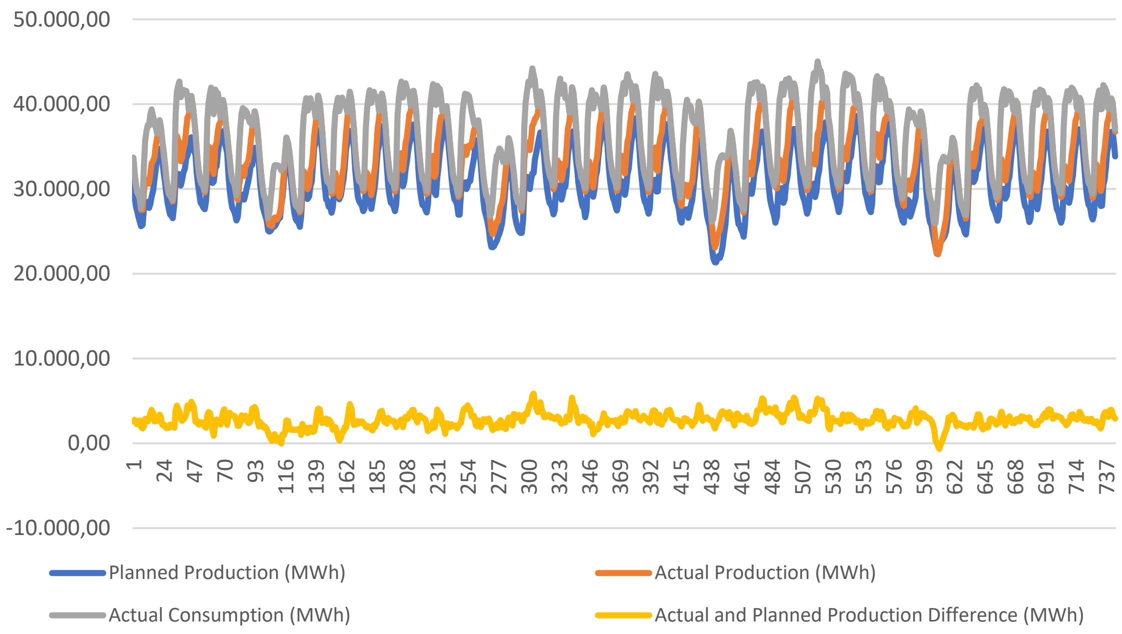

Figure 7. Planned Production (MWh), Actual Production (MWh), Actual Consumption (MWh), the Actual and Planned Production (MWh)S allowed error variation between 20 ms and 30 ms

The time it takes for the system to detect the error after the error is implemented is of critical importance. The designed SG required approximately 8 milliseconds to detect the error. This rapid detection time demonstrates the effectiveness and reliability of SG. This period ensures the system's ability to react quickly and possible malfunctions are quickly isolated and the rest of the system remains stable. These results show that the designed SG is successful in real-time error detection and isolation and is compatible with Matlab/Simulink simulations. The fast response time of the system plays an important role in increasing system reliability and performance by minimizing power outages.

3. Conclusion

This article underscores the critical importance of swift responses to power faults to protect components and prevent outages within SG. The study concentrated on detecting, locating, and isolating faulty lines using Matlab/Simulink and RTDS software. It discusses the application of phase-to-ground short circuit faults in SG and the detection of these faults within milliseconds. Upon fault detection, breakers were used to isolate the faulty line from the system. Simulation results indicate that isolating the faulty load enhances SG stability and ensures customer satisfaction. The processes of error detection, location, and isolation were elaborated using Matlab/Simulink and RTDS software. A phase-to-earth short circuit fault was implemented, and the time required for SG to detect the fault was analyzed. The faulty load was isolated within three cycles. Additionally, electric vehicle batteries were utilized as storage technology to provide uninterrupted energy. These vehicles supplied energy support during extended outages. The performance of SG was compared using Matlab/Simulink results, and the error detection time was found to be 8 milliseconds. This rapid detection time demonstrates the effectiveness and reliability of SG. In conclusion, the paper presents proposed solutions and simulation results for managing and isolating potential power faults in SG. The study's findings are significant for enhancing SG reliability and ensuring customer satisfaction.

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