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A review on control system management of synchronous generator units based on Internet of Things

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Review Paper

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Abstract:

Many different technologies have been studied in relation to electrical generator control system management and condition monitoring. The ability to plan control systems and monitor them offers benefits for finances, operations, and technology. Electric generator manufacturers are drawn to this area for this reason. The focus of this review paper is on the control system management of synchronous generators, with a particular emphasis on the utilization of Field Programmable Gate Array (FPGA) and microcontrollers with techniques such as Proportional-Integral (PI), Proportional-Integral-Derivative (PID), etc. Furthermore, the monitoring of the synchronous generator's condition has been introduced using Internet of Things (IoT) variable devices. Finally, the paper delves into the classification and thorough analysis of recent research that suggests control systems and monitoring models, including interactions with various kinds of power plants that run on synchronous generators. The survey results included a plethora of relevant articles and papers about the application of control systems to the Internet of Things.

Keywords: Synchronous generator; Control system management; Microcontroller; Condition monitoring; Internet of things

1. Introduction

The industry employed in various control applications, such as machines, power plants, furnaces, heat-treating ovens, factory operations, ship stability, switching in telecommunications systems, and others requiring minimal human intervention, needs automation. In some fields, such as hydraulic, electrical, mechanical, and computer engineering, the majority of processes have been automated and continue to advance. One method of overcoming machine malfunctions is by predicting them beforehand [1]. There are numerous benefits to using three-phase synchronous generators (SGs) for distribution, transmission, and generation. In nuclear power, thermal, and hydroelectric systems, huge synchronous generators are used to generate the voltages. An electrical device called a synchronous generator or alternator transforms mechanical power from a primary mover into AC electrical power at a specific voltage and frequency. The synchronous generator's stationary and spinning components are the stator and rotor. These are the synchronous generator's power-generating parts. The armature conductor makes up the stator, and the field pole is found in the rotor. The voltage of the conductor is caused by the relative motion of the stator and rotor [2, 3]. Every year, there is a greater focus on studies of powered system controllers based on Digital Signal Processors (DSPs). Usually, special development software is used to construct DSP-based controllers on FPGAs or DSP microcontrollers. With the aid of microcontrollers, PLCs, and FPGAs, automation companies need to increase the accuracy, speed, and automation of their systems. Numerous types of sensors are used in the automatic operation and tracking processes of power generator control systems [4–6]. Certain methods, including the artificial intelligence (AI) approach, aid in enhancing the sensitivity of diagnosing techniques. The use of AI in electrical drives and machines is suggested in [7–10]. Several parameters are used as input signals in AI-based systems, including frame vibration, magnetic fluxes, and stator currents and voltages [11, 12]. To enhance frequency and voltage management in microgrids, use a Reinforcement Learning (RL) controller based on PI principles [13]. A novel analytical model is introduced to evaluate the influence of wind power participation on unit commitment risk

(UCR) [14]. The most well-known AI techniques are typically an expert system, an ANN, a fuzzy neural network [9], and their combinations. Over the past 20 years, ANN has been the subject of extensive research and has been successfully used for fault diagnosis [15–17] and dynamic system modeling [18, 19]. The IoT describes a type of wireless network that allows anything to be connected to the internet. It can also be described as a new kind of technology that connects physical objects or gadgets to the internet. The term "Internet of Things" refers to any situation in which machines communicate with one another via the Internet. One excellent tool for bolstering the power system's control mechanism is the Internet of Things [20]. Reducing operating and maintenance expenses is seen as crucial, as fault tracking and monitoring are thought to be efficient methods for early alarms and preventing impending faults. Operating and maintenance expenses can make up as much as 25% of the total levelized cost of power and are largely attributed to unanticipated drive train breakdowns [21]. Two specialized reviews on the use of generator system control for condition monitoring (CM) and fault detection (FD) in wind turbines and nuclear power plants, respectively, were published by [22] and [23]. There are several survey research topics related to the Internet of Things [24–26] and FPGA deployment of the Internet of Things [27–29]. The state-of-the-art synchronous generator CM and FD for several power plant applications is reviewed in this study. By concentrating on the combination of generators, FPGA, and IoT as three fundamental ideas for building smart stations. In this study, recent publications on a wide range of fault detection and monitoring using IoT applications are included. There are nine sections in the paper: section 2: synchronous generator system control overview with subsections; section 3: advanced control techniques using FPGA; section 4: the Internet of Things; section 5: integration of FPGA and IoT for synchronous generator system control; section 6: future directions and research gaps; and section 7: conclusions.

2. Synchronous generator system control

SG is among the most crucial pieces of equipment in the power networks that provide consumers with electricity. Although the SGs are extremely dependable devices, defects are inevitable and have the potential to stop electricity generation. To improve the reliability of power systems, a number of protective strategies have been put forth thus far, with SG reliability being a crucial concern. Redundancy (including another SG as an extra unit) enhances reliability but at the expense of increasing the power-generating system's weight, volume, and cost. Therefore, a suitable strategy makes use of a sensitive and precise fault detection tool to find the flaws at an early stage. The most common failure in large SGs is the stator-winding fault, with the rotor-winding fault coming in second [3, 30]. One intricate and crucial component of power generation is the regulation of synchronous generator systems. It involves a number of different parts, including power system stabilization, voltage and frequency management, and excitation control. Controlling synchronous generators, which are frequently found in wind turbines and power plants, is crucial to preserving grid stability and producing electricity effectively. While a great deal of effort has gone into diagnosing induction machine failures, the identification of SG faults has received less focus. Fig. 1 represents a different type of SG control system that will be described separately for each part.

2.1 Excitation control system

Excitation control is an essential element in synchronous generators, focusing on coping with the excitation modern-day furnished to the sector windings of the generator's rotor. This cutting-edge level dictates the depth of the magnetic subject generated by the field windings, eventually influencing the generator's voltage law, management of reactive power waft, and the overall balance of the device. The excitation system is essential for maintaining stable voltage levels in the generator during load variations or system disturbances. It adjusts the excitation to keep the voltage output constant, typically using an AVR to manage the excitation current and ensure voltage stability under changing load conditions. Excitation control in synchronous generators can be accomplished in a number of ways. The following are some typical ways to accomplish excitation control [31]:

- Static Excitation Systems make use of thyristors or transistors to adjust the excitation cutting-edge to the generator's discipline windings.
- Brushless Excitation Systems do away with brushes and slip rings by employing a rotating diode assembly to rectify the output from a distinct exciter generator.
- AC Excitation Systems utilize a secondary AC generator to energize the field windings of the primary generator. The AC output is converted to DC through diodes or thyristors before being directed to the field windings.
- DC Excitation Systems employ an independent DC

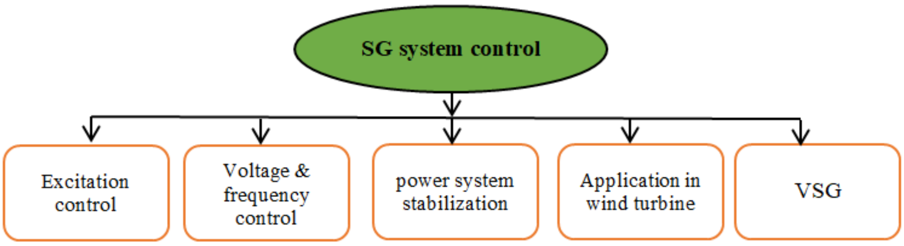

Figure 1. Overview of a different type of SG system control.

generator, referred to as an exciter, to deliver direct current to the field windings of the primary generator.

- Digital Excitation Control is a contemporary excitation systems that frequently integrate digital control algorithms to supervise and modify excitation levels according to system conditions and load requirements. The utilization of these excitation control techniques is vital in guaranteeing the effective functioning and stability of synchronous generators within power systems. See Fig. 2.

2.2 Voltage and frequency control system

The goal of the SGs' voltage and frequency control system is to keep the power grid operating at the appropriate voltage and frequency levels. To do this, the load frequency control (LFC) system, AVR, turbine governor, excitation system, and speed governor collaborate. To maintain the desired voltage and frequency levels, the voltage and frequency control systems communicate with one another as shown in Fig. 3. Time delays, uncertainty, and non-linearity are some of the obstacles that the voltage and frequency management system for super grids must overcome. The voltage and frequency management system for supergrids (SGs) is now performing better because of recent developments in control technologies like robust control and model predictive control (MPC). These developments have improved the system's ability to manage the aforementioned difficulties [35].

2.3 Power system stabilization

A power system stabilizer (PSS) is a control system utilized in synchronous generators to enhance power system stability and damping by issuing additional control signals to the excitation system. The main purpose of a PSS in an SG is to mitigate low-frequency oscillations resulting from disturbances like load variations or faults. So, this control signal helps counteract disturbances and uphold system stability [36]. A power system stabilizer (PSS), which is used to reduce the generator's oscillations, and an excitation control system, which controls the generator's terminal voltage, normally make up a synchronous generator's control system [37]. Contemporary generator controls are built to withstand changes in the active load and nonlinear model components. The PSS schematic is similar to Fig. 3 with replacing LFC by PSS feedback loop which consists of [38]:

- Feedback signals: Rotor speed deviation ($\Delta\omega$), accelerating power (ΔP), terminal voltage deviation (ΔV).
- Damping gain (Kd)
- Washout block
- High pass filter
- Lead-lag compensator

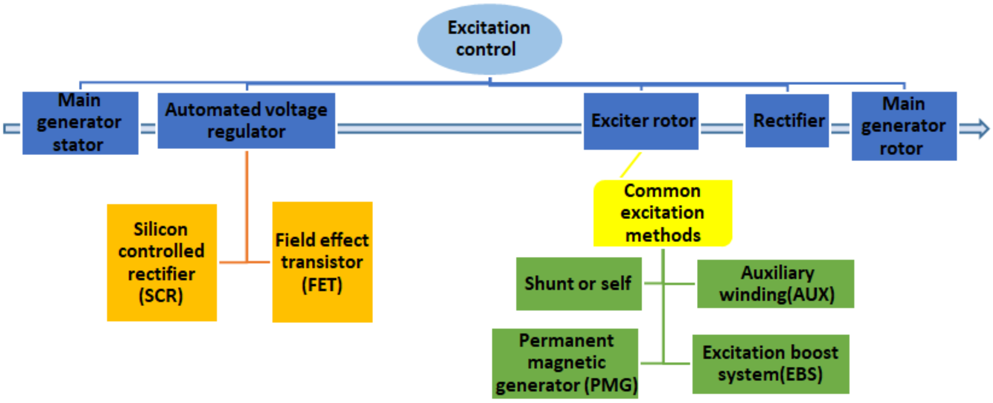

Figure 2. Excitation control methods diagram [31].

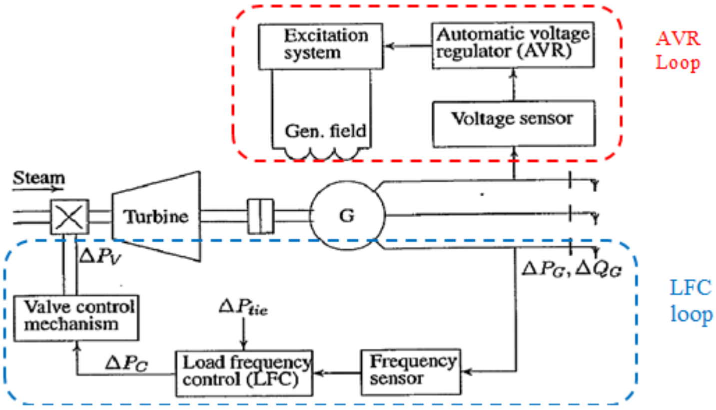

Figure 3. An LFC and AVR schematic for a synchronous generator [32].

2.4 Application in wind turbines

The application of SG system control in wind turbines is essential for efficient and reliable operation. Performing SG control in wind turbines involves implementing various control strategies and algorithms to optimize system performance as shown in Fig. 4. Key steps include designing a control system for regulating output and rotor speed, ensuring grid synchronization, integrating variable speed operation, enhancing fault ride-through capability, improving power quality, and incorporating condition monitoring for fault detection. Utilizing advanced control strategies like vector control and model predictive control can optimize SG performance and ensure reliable operation in diverse wind conditions. By following these steps, wind turbine operators can effectively perform SG control to enhance performance, reliability, and efficiency in wind power generation [22].

2.5 Virtual synchronous generator(VSG)

The Virtual Synchronous Generator (VSG) control system emulates traditional synchronous generators in power systems to provide grid support functions like frequency regulation, voltage control, and fault ride-through capabilities in distributed generation systems. It comprises a power generation part for determining reference voltage based on power requirements and a voltage and current control part for regulating inverter output to maintain grid stability. By mimicking synchronous generators, VSG systems offer inertia and damping effects, support frequency stability, and ensure reliable operation during disturbances, enhancing grid stability and power quality in systems with high renewable energy penetration. As a result of the SG, a genuine flaw may be harmful and result in issues. Because of this, modeling significantly contributes to the SG analysis by lowering expenses and risks. A few review papers using different SG modeling or VSGs were presented [39, 40]. Fig. 5 depicts a typical microgrid configuration with a VSG-based power controller [34].
Research on the management of synchronous generators is also ongoing; technologies like synchronous generator simulation control and virtual synchronous generators are being investigated to meet current technical issues and potential future developments in power systems [41].

3. Advanced control techniques using FPGA

The term "Field Programmable" refers to the capacity to change operations in the field, while "Gate Array" refers to the device's fundamental underlying design. The Field Programmable Gate Array (FPGA) family of reconfigurable hardware falls under this category. Software can be used to build digital computing jobs, which are then assembled into bitstream files. Information regarding the proper wiring of the components is contained in this bit stream file. FPGAs, which are parallel in nature, combine the greatest features of processor-based systems with application-specific integrated circuits (ASICs). The flexibility of software is a benefit of employing a processor that is software-programmed;

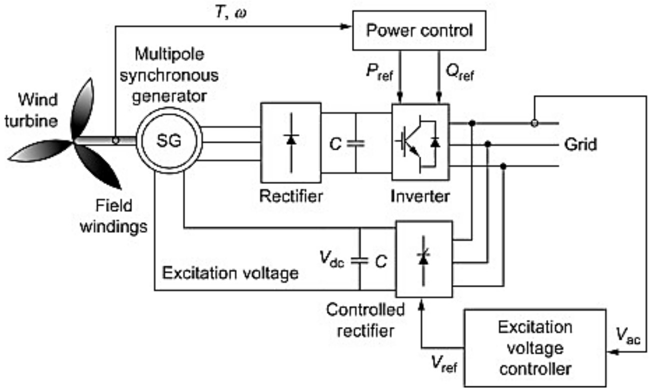

Figure 4. The synchronous generator (SG) in a wind turbine [33].

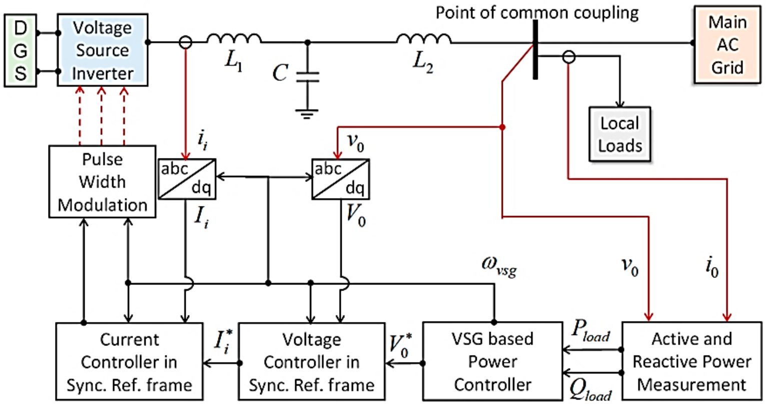

Figure 5. The general configuration of microgrid using a multiloop control system based on VSG [34].

nevertheless, if the processor's clock is not fast, performance may suffer [43]. You may implement a large range of arithmetic and logic functions with an FPGA, which is a two-dimensional array of adjustable elements. Lookup tables (LUTs), registers, tristate buffers, multiplexers, digital clock managers, multipliers, dual port memory, and dedicated DSP blocks are examples of these resources. As seen in Fig. 6, FPGAs are programmable devices that consist of logic cells arranged in a matrix-like arrangement [42]. The Table 1 describes three main applications in various fields. A strong tool for assembling an FPGA program from a high-level Simulink model-based design is the Xilinx System Generator. Furthermore, complex I/O methods found in Xilinx FPGAs are capable of handling a broad range of voltage and bandwidth requirements. Control algorithms can be defined using Hardware Description Language (HDL) (such as VHDL or Verilog) and directly implemented on the FPGA. Fast control algorithm execution and hardware-level parallelism become possible by it. Many times, the System Generator contains all the components required for a design. When a design of this kind is selected, clicking the Generate button causes the System Generator to convert the design to HDL and create the files required for processing the HDL with downstream tools [44].

Because FPGA-based pulse width modulation (PWM) controllers offer significant advantages over classical PWM controllers, their application has grown dramatically in the last several years. It is now utilized in more than just basic DC-AC inverters, DC-DC transformers, and AC-DC transformers. Not to mention more sophisticated ones like the PWM controller for a single-phase five-level inverter and the level-shifted PWM created for asymmetrical converters that are in a triad hybrid multilevel inverter, as well as the space vector PWM (SVPWM) algorithm for a three-phase delta inverter [45–47].

4. The Internet of Things

A type of network called the "Internet of Things" allows anything to be connected to the internet. Another way to describe it is as a new technology that connects physical objects or gadgets to the Internet. [49]. In order to automate industrial operations, controllers and data collection systems became increasingly popular in the power industry during the 1990s. It was an Internet of Things version one. Its duties were gathering information about the underlying process, evaluating the information, and issuing commands

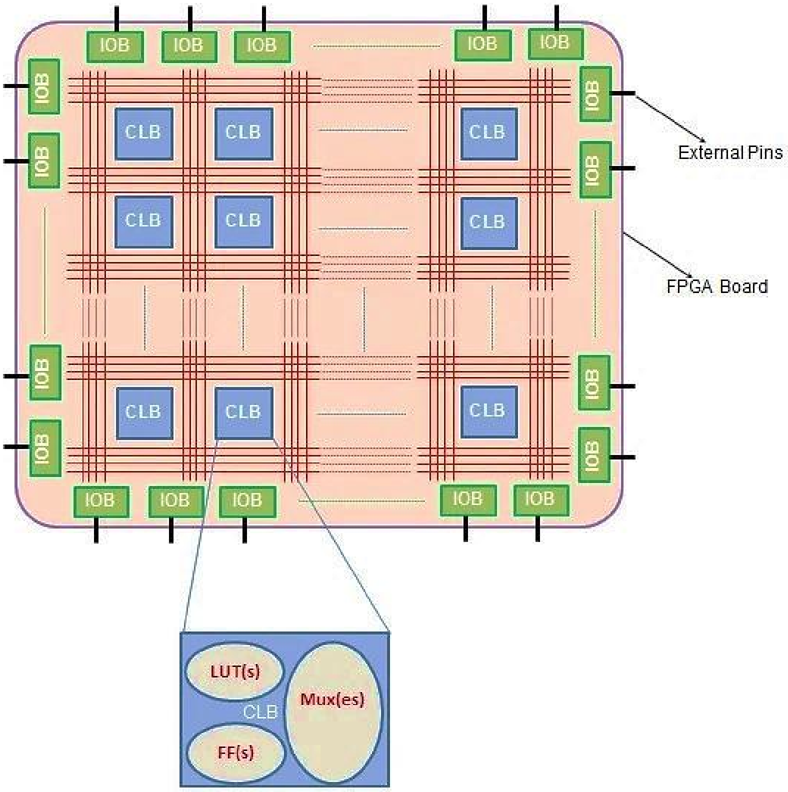

Figure 6. The structure of FPGA [42].

Table 1. Field of FPGA applications.

No	Application	Tasks
1	DSP	Digital signal processing : image and audio processing, filtering, and encryption
2	Embedded systems	Data Acquisition, Control Systems, and Communication Protocols
3	High speed computing	Data Processing, Scientific Simulations, Machine Learning

to regulate the processes in order to supervise the work of programmable logic controllers (PLCs). Another earliest example of the Internet of Things is smart meters, which can connect and detach consumers as well as provide consumption data in almost real-time without the need to visit the customer's location. Both technologies are able to track and control things along the IoT maturity continuum Fig. 7. For an IoT solution to go to a greater degree of maturity, operational technology—such as SCADA and smart meters—often has to be supplemented with information and communication technology (ICT), such as enterprise resource planning (ERP) systems and geographic information systems (GIS). The next section provides an overview of some more developed IoT solutions [50–52].

All IoT modems perform is move data bytes from one format to another (see Fig. 8). Through a variety of communication formats, including Bluetooth, Serial, RS-485, TCP, and other widely used technologies [53].

The following are the essential steps of Internet of Things usage and implementation:

- **Defining utilization:** This is the initial step when the application's purpose and the IoT setup are specified.
- **Equipment selection:** At this point, hardware devices are curated for specific uses.
- **Finalization of protocols:** During this phase, the communication protocols that are compatible with the chosen hardware for a specific application are completed. The communication protocols' comparative research is displayed in Table 2 [48].
- **Storage management:** This phase involves determining the data's mode of storage and enables hardware interaction via completed communication protocols. Storage options include online storage, USB drives, and SD cards.
- **Data analysis management:** it is the last phase of the Internet of Things setup, when a specialized software program is offered for the analysis of the data that has been gathered and stored. It facilitates our ability to regulate and alter the whole setup's functionality as needed.

5. Integration of FPGA and IOT for synchronous generator system control

The Internet of Things (IoT) has recently been implemented using FPGA technology. People and electronic devices are being connected on a scale that was previously unthinkable, thanks to the Internet of Things. Handling the enormous

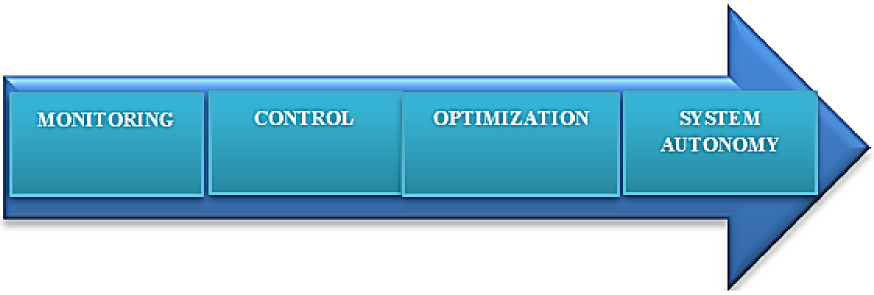

Figure 7. The maturity model of IoT.

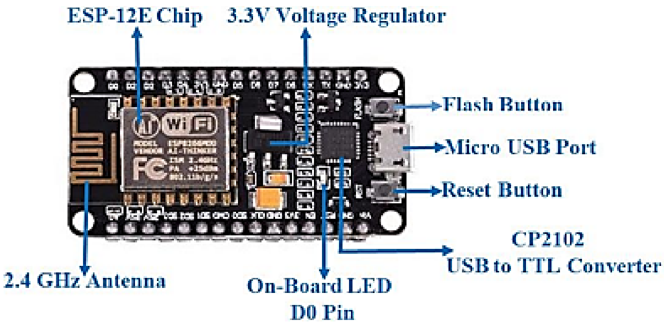

Figure 8. IoT modem.

Table 2. Communication rules comparative research [48].

No	Innovation	Range	Speed	Cost
1	Bluetooth	up to 50 m	1 mbps	low
2	Zigbee	up to 100 m	250 kbps	low
3	LTE-M	up to 200 km	0.2-1 mbps	moderate
4	Satellite	very long distance	10 kbps	high

volume of sensing data produced by smart devices that have limited resources and are prone to missing data from link failures presents another difficulty for the Internet of Things. One way of using low-cost FPGA implementation of the whole IoT subset, including TCP/IP protocol, control system, data acquisition, etc. , as shown in Fig. 9. In the last few years, the research community has paid a lot of attention to IoT applications on FPGA platforms. This method provides a comprehensive, affordable, effective, and user-friendly approach to a remote sensing and monitoring system that operates around the clock [54, 67, 68].

The adoption of FPGA accelerators is limited by integration and programming issues, despite their excellent speed and low power consumption [69].

FPGA and IoT integration in synchronous generator systems can have a number of advantages, including enhanced control, fault detection, and faraway monitoring of parameters in power plants. FPGA or microcontroller-IoT control systems may generally be used to identify power generation defects; several studies have been done in this area, with Table 3 summarizing them. The following is a list of the papers read that discuss the development and execution of IoT applications on FPGA and other microcontroller platforms in power generation with techniques used:

Yousaf H. Khattak et al., [55], developed an intelligent energy management system (IEMS) for effective load control in utility and solar power production systems. The EMC functions as a graphical user interface (GUI) created in LABVIEW for real-time voltage and current data logging and FPGA connection. Wireless radio data transfer is made possible via ZigBee, while voltage and current sensors are interfaced with the FPGA through analog to digital converters. The system's objectives are to monitor and control electrical consumption.

Md. Yaseen et al., [56], addresses the communication between cloud computing and electrical equipment in order to provide real-time generator monitoring. The system collects vital parameters by using a variety of sensors, including temperature, vibration, and current sensors. Field operators receive notifications through a web application when faults are simulated using devices based on the Internet of Things. To find errors, FFT techniques are used to evaluate vibration data from sensors. Local edge analytics have been performed, and an effective early alert system has been developed according to trends seen in online applications.

The application of modern AVR systems for synchronous machines with FPGA has been the subject of recent research. For example, in 2019, the authors of [57] described the design and testing of an AVR system that includes extra controllers for field current and reactive power regulation, as well as safety features like V/Hz limiters and over- and under-excitation limits. Accurate parameter computations

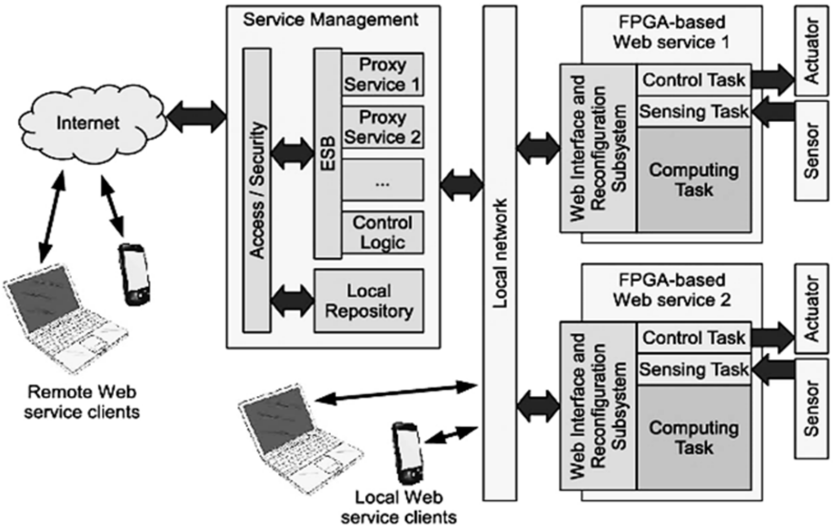

Figure 9. Shows the integration of FPGA and IoT [54].

Table 3. Review papers on power generation control systems with IoT monitoring.

Reference & Year Of Publication	Processing Device	Controller Task	IoT	Power Generation
[55], 2015	FPGA	Current, voltage, and energy management	ZigBee	PV power generation
[56], 2017	Arduino mega	Vibration, temp. and current	Raspberry Pi	Generator
[57], 2019	FPGA with PI technique	Voltage regulator	NI9264 modules	185 kW synchronous machine
[58], 2020	Arduino	current, voltage, and freq.	Bluetooth module	3-phase Generator
[59], 2020	Arduino	current, voltage, freq., power,	NodeMCU ESP8266	3-phase electric power
[60], 2020	FPGA	voltage, speed, Temp., pressure, and fuel	GSM	Thermal power plant
[61], 2021	Arduino Mega	current, voltage, freq., power, P.F, Temp. and fuel	NodeMCU ESP8266	25KV generator
[62], 2021	Raspberry Pi	voltage, current, power, temperature, and light intensity	NodeMCU	solar power generation
[63], 2021	ANN technique	Vibration	ZigBee	Synchronous Motor
[64], 2022	Arduino Mega	Voltage and current	NodeMCU	Hybrid power plant
[65], 2022	Arduino	temperature, voltage, motion, and current.	ESPCAM 32	Photovoltaic power plant
[53], 2022	Arduino nano	temperature, speed, and current, voltage	IoT modem	Hybrid power plant
[66], 2023	NodeMCU	voltage, current, power, energy, and frequency	NodeMCU ESP8266	3-Phase Electric Motor

were ensured by the FPGA's DSOGI PLL, and real-time monitoring and control were made possible via the integration of cRIO modules. These experiments demonstrate how FPGA-based AVR systems can improve synchronous generator efficiency and stability. Under the framework of effective energy management and electrical equipment monitoring, [58] introduced an Arduino-based smart control and protection system for a three-phase generator. The system's integration of Arduino technology allows for real-time monitoring of many parameters, including frequency, load current, and terminal voltage. The data is shown on a mobile application over Bluetooth. The testing findings indicate how well the system works under different stress scenarios and how well it can identify and display anomalous cases. The present study provides significant contributions to the improvement of generator control and protection mechanisms. A system consisting of smart sensors based on hydrostatic/ capacitive measuring principles was established in the study by [59] to track variables like fuel level, run hours, current, and voltage. An Arduino ATMEGA328 microcontroller was used by the system. Users were then able to access the data via a WiFi module, which enabled real-time monitoring. It demonstrated how well the suggested smart monitoring system would work to improve user access to vital information and anticipate system failures. The benefits of FPGA over conventional microcontroller and PLC-based systems were emphasized in [60]. Research has shown that FPGA may be effectively used to monitor and regulate important power plant components. According to the research, FPGA-based systems have better performance, real-time monitoring features, and the capacity to SMS alert users so they may take immediate corrective action when parameters deviate. Similar to [58], the study was conducted in [61], where parameters were monitored through the integration of multiple modules, including the Arduino Mega, PZEM 004T, LM35, and HPT 604-fuel sensors. The findings showed a clear relationship between running time and rising temperatures. According to the study's findings, the suggested strategy provides a reasonably priced and effective solution for small-scale industrial applications, with the potential to lower OPEX costs by utilizing cloud-based alarm control.

In order to maximize the effectiveness and efficiency of solar panels using intelligent monitoring systems, [62] used cloud-based architectures, LabVIEW, Raspberry Pi, and microcontrollers to track various parameters. The results emphasize how important ongoing monitoring is for optimizing solar power generation, identifying problems, and improving performance. In [63] investigated the use of Internet of Things (IoT) technology to establish a remote vibration monitoring and fault diagnosis system for synchronous motors. The two primary parts of the system are a three-tiered model-based Web and database framework and field information gathering and communication. In addition to the diagnostic method, expert services give users precise diagnosis findings depending on the symptoms they have reported. The study emphasizes how critical remote signal processing techniques, such as Java Applet, are to improving fault diagnosis and equipment condition monitoring. For renewable energy systems, hybrid power systems were monitored and controlled by [64] using Internet of Things-assisted SCADA systems. The study highlights how crucial it is to gather and analyze data in real-time in order to manage renewable energy resources effectively. The suggested methodology shows that it is possible to monitor several energy sources and optimize system performance by combining models from simulation with experimental validation. The results demonstrate how well the Internet of Things (IoT)-based SCADA system performs in terms of accurately monitoring, controlling, and making decisions for renewable energy installations.

The photovoltaic system proposed in [65] uses a microprocessor in conjunction with a variety of sensors to check temperature, voltage, motion, and current. Additionally, ESPCAM 32 is employed to connect an Arduino with an IoT controller so that a remote location can monitor the system. The Internet of Things (IoT) makes defect detection and preventive maintenance easier. It also offers real-time monitoring and analysis of historical data. The significance of using efficient fault detection systems to guarantee the stability and effectiveness of hybrid power plants is the focus of this study [53]. The researchers looked into the usage of temperature, speed, and current sensors for problem detection, as well as Internet of Things modems for monitoring. The study effectively discovered defects, processed monitored data, and sent fault information from the hybrid plant to the control center by transferring data to a PC via UART communication. The study's result emphasizes the value of fault diagnosis and real-time monitoring in solar power plants and wind turbines. An Internet of Things (IoT)-based 3-phase electrical energy monitoring and control solution was created in [66] to provide remote energy usage monitoring and control. Measured parameters using the Blynk program and the PZEM-004T sensor. The system effectively monitored a three-phase load with a range of parameters and displayed an error rate of 0.02%. The study's successful implementation of demonstrates how IoT technology can improve energy management procedures.

The key components and advantages of implementing IoT in synchronous generator systems are shown in Fig. 10, which covers topics like energy management, device integration, cloud connectivity, monitoring, data analysis, fault detection, data integration, and security for improved productivity and effectiveness in power generation operations.

As seen in Fig. 11 to apply FPGA in the loop (FIL) simulation to hardware verification on the FPGA board. The HDL and FIL toolbox and utilities are provided by the Matlab/Simulink environment.

FIL's methodology offers advantages for both software and hardware. Throughout co-simulation processing, the FIL made use of Matlab/Simulink's capabilities. When the algorithm is loaded via FIL onto the FPGA board, it operates in real-time. Sensors, power generator models, and other electrical components are among the system components that are simulated on Matlab/Simulink during FIL processing.

Drawing from the comprehensive literature analysis that shows cases of the integration of IoT technologies in synchronous generator systems, the subsequent deductions may

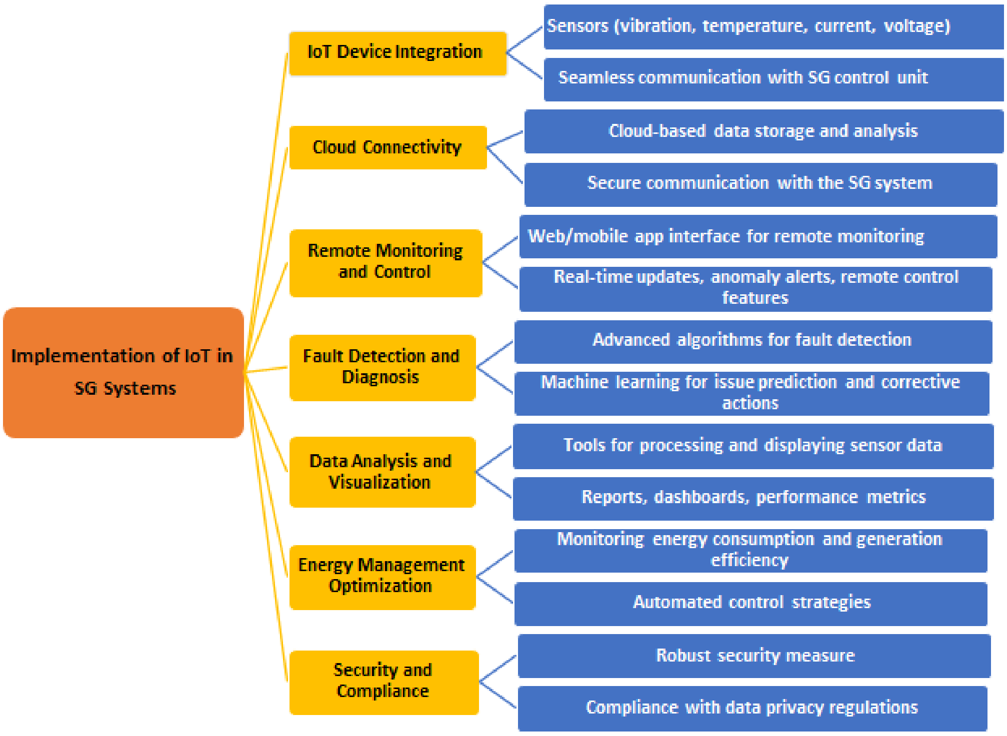

Figure 10. Advantages of implementing IoT in synchronous generator systems.

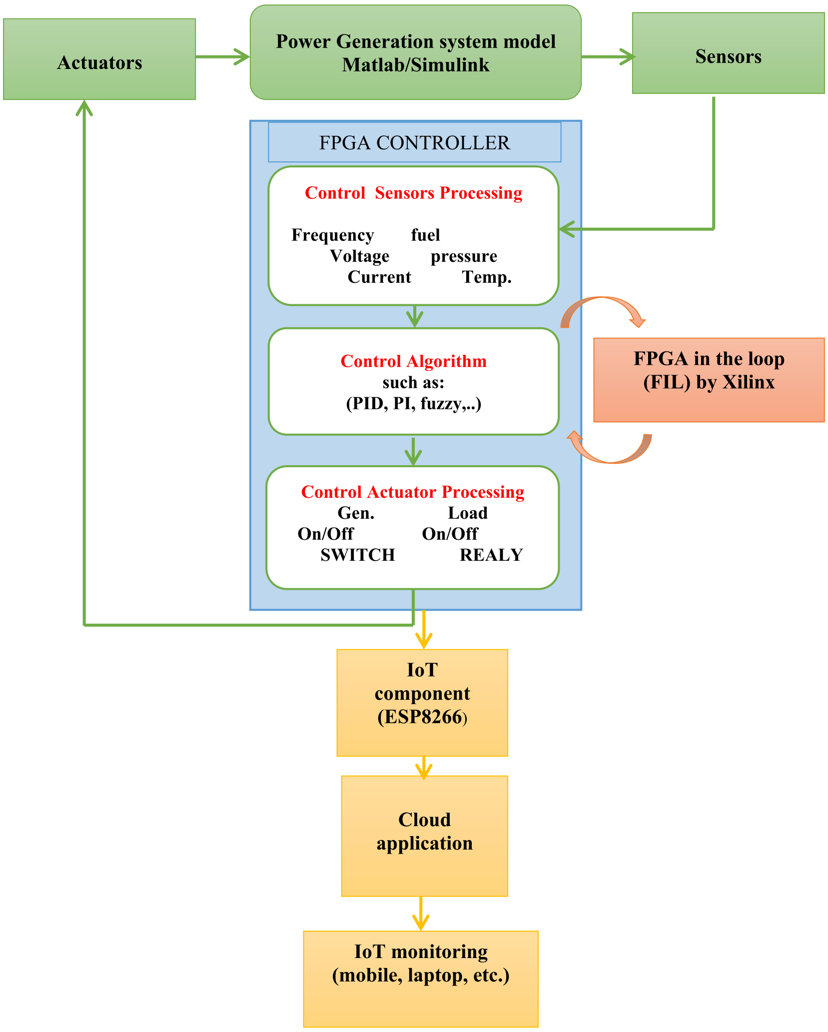

Figure 11. FPGA in the loop (FIL) simulation.

be made: Improved control, real-time monitoring, and fault detection are made possible by the integration of IoT technology—particularly via FPGA—into synchronous generator systems, which boosts power generating efficiency and stability. This enhances energy management and system performance by offering affordable remote sensing and monitoring solutions. Power plant reliability and efficiency are raised by optimizing and modernizing synchronous generator operations through the use of IoT applications running on FPGA platforms.

6. Future direction and research gap

Recent large embedded process control designs depend heavily on Field Programmable Gate Array (FPGA) circuits.

Although there are many advantages to synchronous generator control through the combination of FPGA and IoT technologies, there are certain challenges that must be overcome besides:

- It takes an extensive knowledge of hardware structure and programming, as well as skill with power system management and communication protocols, to integrate FPGA and Internet of Things technology.
- IoT-enabled synchronous generator connectivity raises possible security concerns that need to be addressed with strong security measures including data encryption, access controls, and secure communication protocols.
- Adopting industry standards and creating suitable interfaces may be necessary to guarantee smooth integration and interoperability of FPGA-based control systems and different IoT devices.
- Higher beginning costs associated with integrating FPGA and IoT technology may need to be weighed against the long-term advantages of enhanced performance, dependability, and maintenance optimization.

The integration of FPGA and IoT technologies has the potential to transform synchronous generator system control, enhancing efficiency, reliability, and future-proofing IoT deployments.

7. Conclusion

In this paper, an overview of various topologies of the SG control system is presented along with a description of its structure. The increasing number of complex IoT applications has brought about new challenges in the design of IoT-based embedded systems. FPGAs are currently trending due to the evolution of hardware components and their versatile usage. This paper presents a review of the integration of FPGA and IoT for synchronous generator system control. This approach offers enhanced dependability, efficiency, and monitoring simplicity, marking an important development in generator control systems. For FPGA implementation of IoT applications, various techniques are used for different input description languages, such as C, Simulink, VHDL, etc. FPGA-based IoT implementations may include a physical model on the FPGA or facilitate Wi-Fi connectivity to the internet through dedicated hardware modules. The detailed literature review demonstrates improved data processing speed and efficiency through FPGA-based hardware acceleration, reducing the workload on the main processor and optimizing power consumption. It also highlights the enhanced parallel processing capabilities of FPGAs to manage the vast data streams generated by IoT devices. The ideal method for completing this assignment was to employ an FPGA controller based on IoT monitoring techniques. This paper offers an extensive summary that can help with well-informed choices for particular uses. One can directly reference all of the information and tools that the researchers cited here by consulting the review table. This research opens the way for more advancement in the use of smart technology in power generation systems.

Authors contributions
All authors have contributed equally to prepare the paper.

Availability of data and materials
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] A. Kumar, K. Bansal, D. Kumar, et al. "**FPGA application for wireless monitoring in power plant**.". *Nuclear engineering and technology*, 53(4):1167–1175, 2021.
DOI: https://doi.org/10.1016/j.net.2020.09.003.

[2] B. Kedjar, A. Merkhouf, and K. Al-Haddad. "**Large synchronous machines diagnosis based on air-gap and stray fluxes - a overview**.". *International Conference on Electrical Machines (ICEM), IEEE*, 2020:1384–1389, 2020.
DOI: https://doi.org/10.1109/ICEM49940.2020.9270868.

[3] M. Mostafaei and J. Faiz. "**An overview of various faults detection methods in synchronous generators**.". *IET Electric Power Applications*, 15(4):391–404, 2021.
DOI: https://doi.org/10.1049/elp2.12031.

[4] B. Kedjar, A. Merkhouf, and K. Al-Haddad. "**Large synchronous machines diagnosis based on air-gap and stray fluxes—an overview**.". *International Conference on Electrical Machines (ICEM)*, 1:1384–1389, 2020.
DOI: https://doi.org/10.1109/ICEM49940.2020.9270868.

[5] A.T. Hashmat, T. Tajwar, and A.A. Khan. "**DSP based digital controller design and implementation for energy systems**.". *The 32nd Annual Newfoundland Electrical and Computer Engineering Conference*, 2023.
DOI: https://doi.org/http://research.library.mun.ca/id/eprint/16300.

[6] M. Delgado del Carpio, A. Hilario-Tacuri, and C.A. Hernandez-Gutierrez. "**Modeling and implementation of a specific microprocessor to enhance the performance of PLCs employing FPGAs**.".

Journal of Electronics and Electrical Engineering, 2(2):164–176, 2023.
DOI: https://doi.org/10.37256/jeee.2220233421.

[7] S. Zhang. "**Artificial intelligence in electric machine drives: Advances and trends**.". *Authorea Preprints, TechRxiv*, 2023.
DOI: https://doi.org/10.36227/techrxiv.16782748.v1.

[8] U. Pandey, A. Pathak, A. Kumar, and S. Mondal. "**Applications of artificial intelligence in power system operation, control and planning: a review**.". *Clean Energy*, 7(6):1199–1218, 2023.
DOI: https://doi.org/10.1093/ce/zkad061.

[9] S. Zhang, O. Wallscheid, and M. Porrmann. "**Machine learning for the control and monitoring of electric machine drives: Advances and trends**.". *IEEE Open Journal of Industry Applications*, 4:188 – 214, 2023.
DOI: https://doi.org/10.1109/OJIA.2023.3284717.

[10] A. Karlis. "**Advances in the field of electrical machines and drives**.". *ed. Athanasios Karlis, MDPI-Multidisciplinary Digital*, page 252, 2022.
DOI: https://doi.org/10.3390/books978-3-0365-4286-7.

[11] J. Li et al. "**Automated monitoring of the uniform demagnetization faults in permanent-magnet synchronous motors: Practical methods and challenges**.". *Sustainability*, 15(23):16326, 2023.
DOI: https://doi.org/10.3390/su152316326.

[12] X. Zhang et al. "**Feature engineering and artificial intelligence-supported approaches used for electric powertrain fault diagnosis: A review**.". *IEEE Access*, 10:29069–29088, 2022.
DOI: https://doi.org/10.1109/ACCESS.2022.3157820.

[13] K. SHeida, M. Seyedi, and F. Ferdowsi. "**Adaptive voltage and frequency regulation for secondary control via reinforcement learning for islanded microgrids**.". *IEEE Texas Power and Energy Conference (TPEC), IEEE*, pages 1–6, 2024.
DOI: https://doi.org/10.1109/TPEC60005.2024.10472240.

[14] H. Moradi and M. Geravandi. "**Unit commitment risk evaluation considering load uncertainty and wind power**.". *Journal of Energy Management and Technology*, 7(3):134–41, 2023.
DOI: https://doi.org/10.22109/jemt.2023.311870.1342H.

[15] P. Pietrzak, P. Pietrzak, and M. Wolkiewicz. "**Microcontroller-based embedded system for the diagnosis of stator winding faults and unbalanced supply voltage of the induction motors**.". *Energies*, 17(2):387, 2024.
DOI: https://doi.org/10.3390/en17020387.

[16] K.S.K. Chu, K.W. Chew, Y.C. Chang, and S. Morris. "**An open-circuit fault diagnosis system based on neural networks in the inverter of three-phase permanent magnet synchronous motor (PMSM)**.". *World Electric Vehicle Journal*, 15(2):71, 2024.
DOI: https://doi.org/10.3390/wevj15020071.

[17] X. Wang. "**A fuzzy neural network-based automatic fault diagnosis method for permanent magnet synchronous generators**.". *Mathematical Biosciences and Engineering*, 20(5):8933–8953, 2023.
DOI: https://doi.org/10.3934/mbe.2023392.

[18] M. Zhang et al. "**Dynamic system modeling of a hybrid neural network with phase space reconstruction and a stability identification strategy**.". *Machines*, 10(2):122, 2022.
DOI: https://doi.org/10.3390/machines10020122.

[19] P. Rajendra and V. Rahmajirao. "**Modeling of dynamical systems through deep learning**.". *Biophysical Reviews*, 12(6):1311–1320, 2020.
DOI: https://doi.org/10.1007/s12551-020-00776-4.

[20] G. Bedi et al. "**Review of internet of things (IoT) in electric power and energy systems**.". *IEEE Internet of Things Journal*, 5(2):847–870, 2019.
DOI: https://doi.org/10.1109/JIOT.2018.2802704.

[21] A.M. Costa, J.A. Orosa, D. Vergara, and P. Fernandez-Arias. "**New tendencies in wind energy operation and maintenance**.". *Applied Sciences*, 11(4):1386, 2021.
DOI: https://doi.org/10.3390/app11041386.

[22] N.M.A. Freire and A.J.M. Cardoso. "**Fault detection and condition monitoring of PMSGs in offshore wind turbines**.". *Machines*, 9 (11):260, 2021.
DOI: https://doi.org/10.3390/machines9110260.

[23] C. Lu et al. "**Nuclear power plants with artificial intelligence in industry 4.0 era: Top-level design and current applications—A systemic review**.". *IEEE Access*, 8:194315–194332, 2020.
DOI: https://doi.org/10.1109/ACCESS.2020.3032529.

[24] R.A. Mouha. "**Internet of things (IoT)**.". *Journal of Data Analysis and Information Processing*, 9(2):77–101, 2021.
DOI: https://doi.org/10.4236/jdaip.2021.92006.

[25] M.M. Martin-Lopo and A. Sanchez-Miralles J. Boal. "**A literature review of IoT energy platforms aimed at end users**.". *Computer Networks*, 171:107101, 2020.
DOI: https://doi.org/10.1016/j.comnet.2020.107101.

[26] B. Bekkai, H. Bendjenna, and I. Kitouni. "**Internet of things: A recent survey**.". *International Conference on Recent Advances in Mathematics and Informatics (ICRAMI), IEEE*, pages 1–9, 2021.
DOI: https://doi.org/10.1109/ICRAMI52622.2021.9585953.

[27] F.P.M.D. Bosco and S.R. E. Chitra, Ebenezer. "**A survey of low-latency IoT system using FPGA accelerator**.". *Journal of Physics: Conference Series, IOP Publishing*, 1964(6), 2021.
DOI: https://doi.org/10.1088/1742-6596/1964/6/062014.

[28] A. Magyari and Ch. Yuhua. "**Review of state-of-the-art FPGA applications in IoT networks**.". *Sensors*, 22(19):7496, 2022.
DOI: https://doi.org/10.3390/s22197496.

[29] M. Ibro and G. Marinova. "**Review on low-power consumption techniques for FPGA-based designs in IoT technology**.". *16th International Conference on Telecommunications (ConTEL). IEEE*, 2021:110–114, 2021.
DOI: https://doi.org/10.23919/ConTEL52528.2021.9495970.

[30] R.V. Rocha and R.M. Monaro. "**Algorithm for fast detection of stator turn faultsin variable-speed synchronous generators**.". *Energies*, 16(5):2491, 2023.
DOI: https://doi.org/10.3390/en16052491.

[31] R.L. Damij. "**Development of mechanical coupling and exciter system in synchronous generators**.". *Eastern-European Journal of Enterprise Technologies*, 6(8):114, 2021.
DOI: https://doi.org/10.15587/1729-4061.2021.246619.

[32] A.M. Ali, M. Ebrahim, and M.M. Hassan. "**Automatic voltage generation control for two area power system including GRC nonlinearity based on particle swarm optimization**.". 12:701–709, 2014.
DOI: https://doi.org/10.11591/ijeecs.v2.i1.pp%25p.

[33] O.O. Ajayi, O. Ojo, and A. Vasel. "**On the need for the development of low wind speed turbine generator system**.". *IOP Conference Series: Earth and Environmental Science, IOP Publishing*, page 012062, 2019.
DOI: https://doi.org/10.1088/1755-1315/331/1/012062.

[34] M. Srikanth and Y.V.P. Kumar. "**Improved virtual synchronous generator-based control scheme for enhanced transient response in microgrids**.". *Engineering Proceedings*, 56(1):4, 2023.
DOI: https://doi.org/10.3390/ASEC2023-15390.

[35] C.S. Wong. "**Voltage and frequency control for synchronous generator**.". 2014. URL https://hdl.handle.net/10356/60136.

[36] V. Nazari, M.H. Mousavi, and H.M. CheshmehBeigi. "**Reduction of low frequency oscillations using an enhanced power system stabilizer via linear parameter varying approach**.". *Journal of Renewable Energy and Environment (JREE)*, 9(2):59–74, 2022.
DOI: https://doi.org/10.30501/jree.2021.306909.1265.

[37] M. Shadoul et al. “**A comprehensive review on a virtual-synchronous generator: Topologies, control orders and techniques, energy storages, and applications**.”. *Energies*, 15(22): 8406, 2022.
DOI: https://doi.org/10.3390/en15228406.

[38] J. Ritonja. “**Robust and adaptive control for synchronous generator's operation improvement**.”. *Automation and Control*, 10:239–278, 2020.

[39] Kh.M. Cheema. “**A comprehensive review of virtual synchronous generator**.”. *International journal of electrical power & energy systems*, 120:106006, 2020.
DOI: https://doi.org/10.1016/j.ijepes.2020.106006.

[40] N. Naval and J.M. Yusta. “**Virtual power plant models and electricity markets-A review**.”. *Renewable and Sustainable Energy Reviews*, 149:111393, 2021.
DOI: https://doi.org/10.1016/j.rser.2021.111393.

[41] M. Abuagreb, F.A. Mohammed, and K.J. Brian. “**Overview of virtual synchronous generators: existing projects, challenges, and future trends**.”. *Electronics*, 11(18):2843, 2022.
DOI: https://doi.org/10.3390/electronics11182843.

[42] A.M. Nimase and D.M. Bhalerao. “**Design and implementation of microcontroller in FPGA for IoT**.”. *International Journal of Advance Research, Ideas and Innovations in Technology*, 3(6):1308–1313, 2017.

[43] M.F. Unlersen. “**Field programmable gate array (FPGA)**.”. *Programmable Smart Microcontroller Cards*, 12:179–207, 2021.

[44] V. Chandrasekaran. “**FPGA based hardware-in-the loop controller for electric drives**.”. *PhD Thesis. University of Minnesota*, 2013.

[45] A. Al-Safi, A. Al-Khayyat, A.M. Manati, and L. Alhafadhi. “**Advances in fpga based pwm generation for power electronics applications: Literature review**.”. *11th IEEE Annual Information Technology, Electronics and Mobile Communication Conference (IEMCON), IEEE*, 2020.
DOI: https://doi.org/10.1109/IEMCON51383.2020.9284821.

[46] B. Steinmann. “**Custom PWM modulator implementation in FPGA**.”. page [Online]. URL https://imperix.com/doc/implementation/fpga-pwm-modulator.

[47] A.R. Yilmaz and B. Erkmen. “**FPGA-based space vector PWM and closed loop controllers design for the Z source inverter**.”. *IEEE Access*, 7:130865–130873, 2019.
DOI: https://doi.org/10.1109/ACCESS.2019.2940670.

[48] P. Mhaske and S.K. Sharma. “**Growth of electricity sector in India from 1947–2019**.”. *Government of India, Ministry of Power, Central Electricity Authority*, 2019.

[49] S. Kolhe and P.G. Student. “**Internet of things (IoT) applications in power system**.”. 8(3):39–42, 2021.
DOI: https://doi.org/10.1016/B978-0-12-821204-2.00072-6.

[50] A. Sadeghi-Niaraki. “**Internet of thing (IoT) review of review: Bibliometric overview since its foundation**.”. *Future Generation Computer Systems*, 143:361–377, 2023.
DOI: https://doi.org/10.1016/j.future.2023.01.016.

[51] A.K. Sarika and M.A. Durafe. “**A review paper on internet of things and it's applications**.”. *International Research Journal of Engineering and Technology*, 6(6):1623 – 1630, 2019.

[52] K. Lasse Lueth. “**The 10 most relevant IoT developments of the year .**”. *IoT*, page [Online], 2021. URL https://iot-analytics.com/iot-2021-in-review/.

[53] L.R. Lokhande, M.A. Kale, and S.S. Shinde. “**Fault detection and monitoring hybrid power plant by using IOT**.”. *Int. Res. J. Modernization in Eng. Tech. Sci*, 4(6), 2022.

[54] K. Sharma et al. “**A review of FPGA implementation of internet of things**.”. *Int. J. Sci. Eng. Res*, 8(4), 2017.
DOI: https://doi.org/10.15680/IJIRCCE.2016.0409098.

[55] Y. Khattak et al. “**Design and implementation of FPGA based smart energy distribution management system**.”. *Science International*, 27(4), 2015. URL https://www.researchgate.net/publication/322754407.

[56] Md. Yaseen, D. Swathi, and T.A. Kumar. “**IoT based condition monitoring of generators and predictive maintenance**.”. *2nd international conference on communication and electronics systems (ICCES). IEEE*, pages 725–729, 2017.
DOI: https://doi.org/10.1109/CESYS.2017.8321176.

[57] E. Fjarstedt. “**Implementation of an automatic voltage regulator for synchronous machines on an FPGA**.”. 2019.

[58] A.J. Ali, A.M.T. Ibraheem, and O.T. Mahmood. “**Design of a smart control and protection system for three-phase generator using Arduino**.”. *IOP Conference Series: Materials Science and Engineering*, 745(1), 2020.
DOI: https://doi.org/10.1088/1757-899X/745/1/012027.

[59] S. Varsha et al. “**Load monitoring system for diesel generator using internet of things (IoT)**.”. *International Journal of Scientific Research and Engineering Development*, 3(2), 2020.

[60] A. Kumar et al. “**FPGA application for wireless monitoring in power plant**.”. *Nuclear engineering and technology*, 53(4):1167–1175, 2020.
DOI: https://doi.org/10.1016/j.net.2020.09.003.

[61] G.S. Memon et al. “**An IOT-enabled generator for power ,onitoring and load management with power factor improvement**.”. *Engineering Proceedings*, 12(1):33, 2021.
DOI: https://doi.org/10.3390/engproc2021012033.

[62] S.H. Cheragee et al. “**A study of IoT based real-time solar power remote monitoring system**.”. *International Journal of Ambient Systems and Applications*, 9(1):27–36, 2021.
DOI: https://doi.org/10.5121/ijasa.2021.9204.

[63] X. Yuan et al. “**Remote vibration monitoring and fault diagnosis system of synchronous motor based on internet of things technology**.”. *Mobile Information Systems*, 2021:1–10, 2021.
DOI: https://doi.org/10.1155/2021/3456624.

[64] M.O. Qays et al. “**Monitoring of renewable energy systems by IoT-aided SCADA system**.”. *Energy Science & Engineering*, 10(6): 1874–1885, 2022.
DOI: https://doi.org/10.1002/ese3.1130.

[65] M.D. Bhujbal and M.G. Unde. “**Real time monitoring and security of solar power plant using iot**.”. *IEEE India Council International Subsections Conference (INDISCON), IEEE*, 2022.
DOI: https://doi.org/10.1109/INDISCON54605.2022.9862817.

[66] C.D. Hantoro and S. Setiawidayat. “**Monitoring and control of 3 phase electrical energy internet of things (IoT) based**.”. *European Journal of Electrical Engineering and Computer Science*, 7(3):80–86, 2023.
DOI: https://doi.org/10.24018/ejece.2023.7.3.522.

[67] W. Shang, Y. Yu, R. Droms, and L. Zhang. “**Challenges in IoT networking via TCP/IP architecture** .”. *Named Data Networking Techincal Reports*, page online, 2016. URL https://named-data.net/publications/techreports/ndn-0038-1-challenges-iot/.

[68] A. Magyari and Y. Chen. “**Review of state of the art FPGA applications in IoT networks**.”. *Sensors*, 22(19):7496, 2022.
DOI: https://doi.org/10.3390/s22197496.

[69] J. Hoozemans et al. “**Fpga acceleration for big data analytics: Challenges and opportunities**.”. *IEEE Circuits and Systems Magazine*, 21(2):30–47, 2021.
DOI: https://doi.org/10.1109/MCAS.2021.3071608.