International Journal of Electrical and Computer Engineering (IJECE)
Vol. 15, No. 1, February 2025, pp. 36~45
ISSN: 2088-8708, DOI: 10.11591/ijece.v15i1.pp36-45

Enhancing the reliance of emergency power supply systems for nuclear facilities using hybrid system

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Article Info

Article history:

Received Jul 3, 2024
Revised Aug 15, 2024
Accepted Sep 3, 2024

Keywords:

Diesel generator
Emergency power supply
Nuclear facility
Photovoltaic system
Safety and critical consumers

ABSTRACT

The performance of an atomic facility depends on the efficient supply of electricity, particularly emergency loads like monitoring and control equipment, radiation safety systems, and emergency lights. Most nuclear facilities rely on diesel generators to supply emergency loads during grid outages. Due to the diesel generator's imperfections, such as its starting time, it may fail to deliver power because it is unavailable due to maintenance, failure to start, or failure to run and supply the load. It cannot immediately supply the critical loads, resulting in a blackout and the release of radioactive substances into the environment. To address the previous issues, this paper proposes an improved method to enhance the reliability of nuclear facilities for providing electricity to safety and critical consumers during normal and emergency operating modes. The approach incorporates a photovoltaic (PV) system/battery, and its robustness and performance are tested using load flow and transient stability analysis. The simulation results demonstrated the effectiveness and speed of the proposed method when compared to the traditional method, as the emergency consumers were successfully powered within a very short time without fluctuations, and the voltage reduction and frequency were within the nominal values. The electrical transient analyzer program (ETAP) is used to validate these results.

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1. INTRODUCTION

The primary goal of nuclear safety is to prevent the release of radioactive substances into the atmosphere, as well as to protect people and the environment from the harmful effects of ionization radiation [1]. An emergency power supply system is critical for nuclear facilities; it provides continuous power supply to critical consumers during unexpected power outages, protecting against serious consequences [2]–[4]. Nuclear facilities' power supplies, especially the emergency power supply, must meet the following requirements: reliability, redundancy, diversity, independence, and capacity [5], [6]. Emergency diesel generators (EDGs) are crucial in nuclear facilities as backup power during offsite power failures or beyond design-based events. However, they require time to start, causing facility blackouts and potentially releasing radioactive substances into the environment if they fail when needed [7].

Several investigations have been made to improve the power sources of atomic facilities to prevent such releases of ionization radiation. For example, Kančev *et al.* [8] investigated diesel generator failure incidents in the nuclear industry over 20 years using four datasets. It identified causes, breakdown mechanisms, failure types, and components of EDGs. The research concluded that maintenance, inspections, systematic risk assessment, and frequent updates are essential for reducing failure chances. Also, the study [9] analyzed the reliability of the prototype Fast Breeder Reactor's diesel generators (DG) during a blackout, identifying a common cause of failure and maintenance issues leading to system unavailability. The most sensitive part was the DG mechanical failure to run. Furthermore, the study [10] explores the use of pumped-storage hydropower plants as an emergency power backup to enhance nuclear power plant safety during station blackouts. However, the main challenge lies in quantifying the safety improvement and integrating the independent electrical connection between the hydropower plants and the nuclear power plants (NPP). Additionally, in study [11], additional steam turbine units were presented as an emergency power supply system for nuclear power plants, and it was found that the proposed system ensures safety, reduces core damage risk, and is cost-effective. Also, the study [12] introduced an integrated fault model for diesel generator failure during startup and operation, utilizing fault tree analysis techniques, and proposed practical solutions for fault elimination and mitigation.

The 2015 twenty-first session of the Conference of the Parties (COP 21) highlighted the importance of converting energy systems to renewable energy for CO_2 reduction. And COP 27 recommended 2030 targets through climate plans to reduce the use of fossil fuels. Moreover, the end of the fossil fuel age was announced at COP 28, with a request for a rapid transition to renewable energy, doubling energy efficiency improvements, and tripling renewable energy capacity by 2030 [13]–[16]. Photovoltaic (PV) energy is one of these renewable resources. It has become the most promising renewable energy option due to its cleanliness, low cost, and quietness. Also, the rapid economic growth in renewable energy, in addition to climate change, has resulted in increased solar PV production in developing countries [17]–[19].

In this paper, a hybrid system (PV/battery) is proposed as an emergency power supply for nuclear facilities to provide an additional uninterruptable power supply to power the safety and critical consumers in the period before the start of an emergency diesel generator, thereby increasing the reliability of a nuclear facility. The proposed system is further compared with the traditional emergency diesel generator. The rest of the paper is structured as follows: section 2 illustrates the functions of the nuclear facility and illustrates the description and requirements for the facility's electrical power supply system. Section 3 outlines the proposed approach, while section 4 includes simulation and result discussions where the proposed and traditional methods are compared, followed by a conclusion in section 5.

2. NUCLEAR FACILITY DESCRIPTION

The International Atomic Energy Agency Glossary defines a nuclear facility as a facility that produces, processes, utilizes, handles, stores, or disposes of nuclear material [20]. Nuclear facilities are classified into several types, including fuel fabrication factories, research reactors, radioisotope production facilities, and spent nuclear fuel storage facilities. This study focuses on the radioisotope-producing facility.

2.1. Description of the radioisotope production facility

The radioisotopes production facility (RPF) is a facility that produces radioisotopes by irradiating low-enriched uranium (LEU) objects. RPF is divided into free, monitored, and restricted areas, the free area such as offices where no radioactive substances are processed, the monitored area where the lowest radiation levels and the restricted areas having the maximum radioactivity level. The facility has 12 hot cells and can produce various radioisotopes, including chromium-51, iodine-125, iodine-131, iridium-192, molybdenum-99, and iridium-192, for medical purposes [21].

2.2. Description of the electrical power supply system at the nuclear facility

The electrical power system in a nuclear facility is crucial for providing reliable electricity to normal operating and safety systems to ensure facility safety [22]. The criteria for power quality, defense-in-depth, and reliability in the electrical power supply for nuclear facilities were highlighted in several studies and standards, particularly the references [23], [24]. The electrical power system at nuclear facilities is comprised of distribution systems and power suppliers. Power supplies contain normal (grid) and emergency power (on-site) sources that are required to keep the facility in a controlled state in all operation conditions [25]. The total loads of the facility are 390 kVA, normally powered by a utility grid and in emergencies by an emergency power supply system, as well as a 100 Ah battery bank, charger, and inverter, which are established as safety requirements to supply the class A consumers. The electrical power supply equipment parameters are described in Table 1.

Consumers are classified into three groups based on what is essential for safety and the equipment's ability to tolerate power supply interruptions. This classification aids in determining which consumers are powered by the normal power supply and which by the emergency power supply. Consumer classifications are illustrated in Table 2.

Table 1. Electrical power supply equipment parameters

Parameter	Value
Grid voltage/frequency	11 kV/50 Hz
Step-down transformer (one working and the other for standby), Power/Voltage ratio	500 kVA - 11/0.4 kV
– Impedance voltage	4%
– Vector group	Dyn11
– Battery bank capacity and autonomy	100 Ah, 2 hours
Charger (AC/DC converter) one working and the other standby	0.4 kV AC/100 A, 220 V DC
Three-phase DC/AC inverter 2:	
– DC input power and voltage	(12.5 kW, 220 V) DC
– AC output power, voltage, and frequency	(12 kVA. 0.4 kV, 50 HZ), AC
– Inverter Efficiency	97%

Table 2. Consumer classifications

Consumers	Description of power requirements	Power sources	Value
Class C	The power supply would tolerate the functions of the assigned AC loads; these consumers are powered by the utility grid.	Utility grid	300 kVA
Class B	They are powered by a utility grid in normal operation and by an emergency power supply in case of emergency.	Utility grid or diesel generator as a traditional method	80 kVA
Claas A	These consumers are critical to safety, monitoring, and control. These consumers are normally powered by the grid but can be powered by an emergency power supply or battery in the event of an accident.	Utility grid diesel generator or battery bank (2 hours of autonomy)	10 kVA

3. PROPOSED METHOD

Due to disadvantages of diesel generators like starting times and potential failure to provide power due to maintenance, failure to start, or failure to supply critical loads, leading to blackouts and radioactive substance release into the environment. Also as fossil fuels become less affordable and climate change concerns arise, renewable energy options like PV are becoming increasingly preferred due to their purity [26]. To address the previous issues, this paper presents an improved method for enhancing the nuclear facility's reliability for providing electricity to safety and critical consumers during an emergency.

In the proposed method, the photovoltaic system/battery is added to the system. Moreover, the PV system can provide power supply to the facility consumers during normal operation, as additional clean and cheap power supply reduces the electricity cost. Furthermore, an inverter and a battery bank with a 1,500 Ah capacity and an 8-hour discharge period are established, as illustrated in Figure 1, to provide electricity during the night.

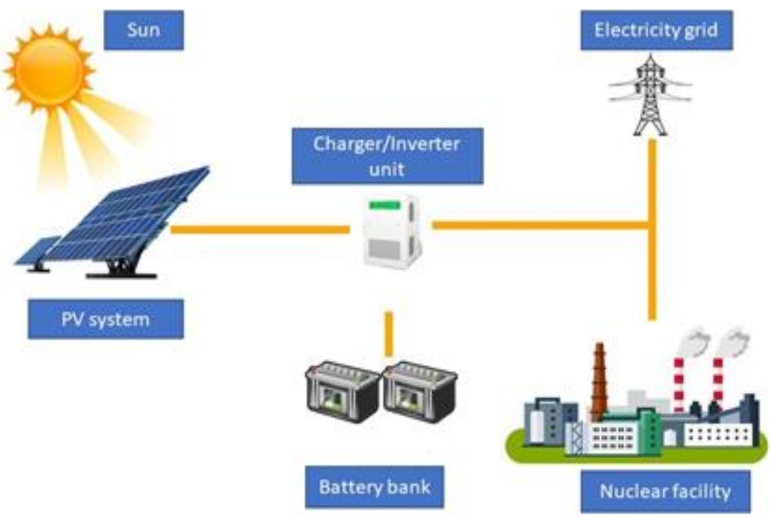

Figure 1. Model configuration

The system is simulated by the electrical transient analyzer program (ETAP) to supply power to the facility in various operation modes, including normal and emergency, as well as different scenarios to test and analyze the system's performance. ETAP is a commercial power system analysis tool that includes various built-in models. The ETAP nuclear license is used globally by nuclear power plants, research facilities, consultancy organizations, and government bodies [27], [28]. The photovoltaic array output power is 500 kW DC with 220 V DC, converted to AC power by a PV system inverter (416 kVA with 0.4 kV and 50 Hz). The PV system size and inverter are chosen to supply facility loads in various scenarios, as shown in Table 3.

A 1,540 Ah battery bank is added to the system to improve its reliability. The battery bank charges from the PV system and discharges for 8 hours at night. The capacity of the battery bank was chosen based on total loads in classes B and A, as well as safety considerations. Table 4 shows typical specifications for this battery bank.

Table 3. Typical PV and inverter system parameters

Typical parameters of the polycrystalline panel		Typical parameters of a PV array		Typical parameters of a PV array inverter	
Parameter	Value	Parameter	Value	Parameter	Value
P (maximum)	206 W	Total number of panels	2432	DC input power	439 kW
V (maximum power point)	28.2 V	Number of panels in series	8	DC input voltage	225 V
V (open circuit)	33.5 V	Number of panels in parallel	304	Efficiency	90%
I (maximum power point)	7.3 A	V DC	225 V	AC output power	415 kVA
I (short circuit)	8.19 A	Rated DC power	500 kW	AC output voltage	0.4 kV
Efficiency	14%			Frequency	50 Hz

Table 4. Typical specifications of the battery bank

Parameter	Value
The total number of cells connected	109 cells
Voltage/cell	2.06 V
Rated voltage	225 V DC
Total capacity	1,540 Ah

4. SIMULATION AND RESULTS DISCUSSION

The proposed method's performance is tested and analyzed through the load flow. The system's ability to react to disturbances is evaluated through the transient stability analysis. The proposed method is also compared to the traditional one in various operation modes and cases.

4.1. Simulation of normal operation conditions (electricity grid)

In a nuclear facility, power is supplied to various consumer classes (C-B-A) via two transformers, one operational and the other on standby. Class A customers are sensitive and demand constant power supply. To achieve that, charger 1 converts AC power from bus B to DC power, then converts DC power to AC power with the desired parameters using a three-phase inverter. Figure 2 shows load flow results and voltage percentages at buses (C, B, and A) are 99.91%, 99.89%, and 100%, respectively, meeting the specified voltage drop values.

4.2. Simulation of emergency power supply systems

In emergencies, power should be available to prevent an accident from occurring. So, power will be provided to safety and critical consumers using traditional diesel and proposed photovoltaics and batteries. Load flow and transient stability analysis are performed for both approaches to test and analyze performance.

4.2.1. Load flow analysis

Case 1 (traditional approach): During utility grid outages, the 210 kW diesel generator was activated to supply safety and critical consumer classes (B and A). This method is considered as traditional because the diesel is commonly utilized as an emergency power supply at nuclear facilities. The load flow results illustrated that these consumers received 100% voltage as shown in Figure 3.

Case 2 (proposed approach): This technique aims to overcome diesel generator discrepancies by providing a power supply for safety and critical loads using a hybrid PV system/battery. In two scenarios, the PV system will supply classes (C&B&A) loads during normal operation and only classes (B&A) loads during emergencies, as shown in Figures 4 and 5. Furthermore, the summary of load flow analysis is provided in Table 5.

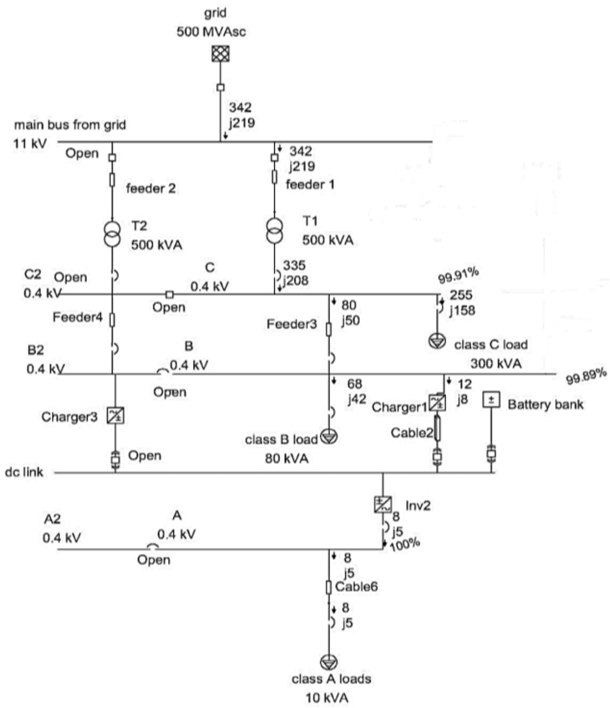

Figure 2. Load flow results in normal operation condition

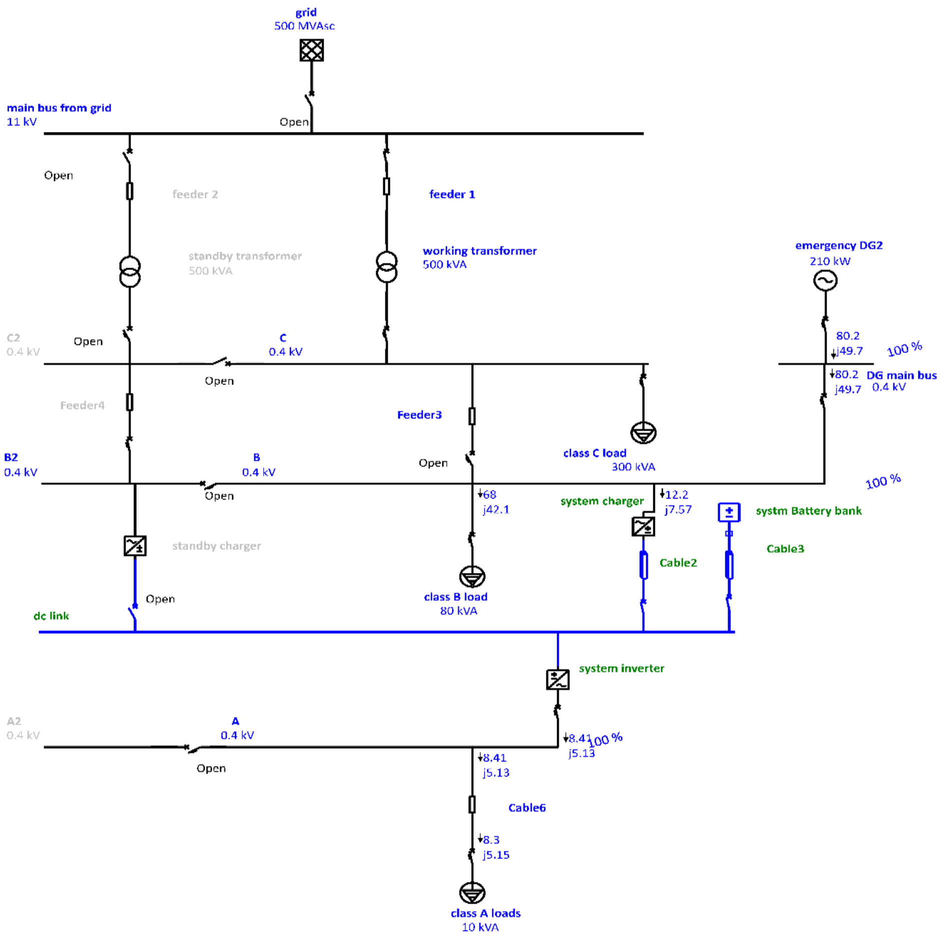

Figure 3. Load flow of case 1

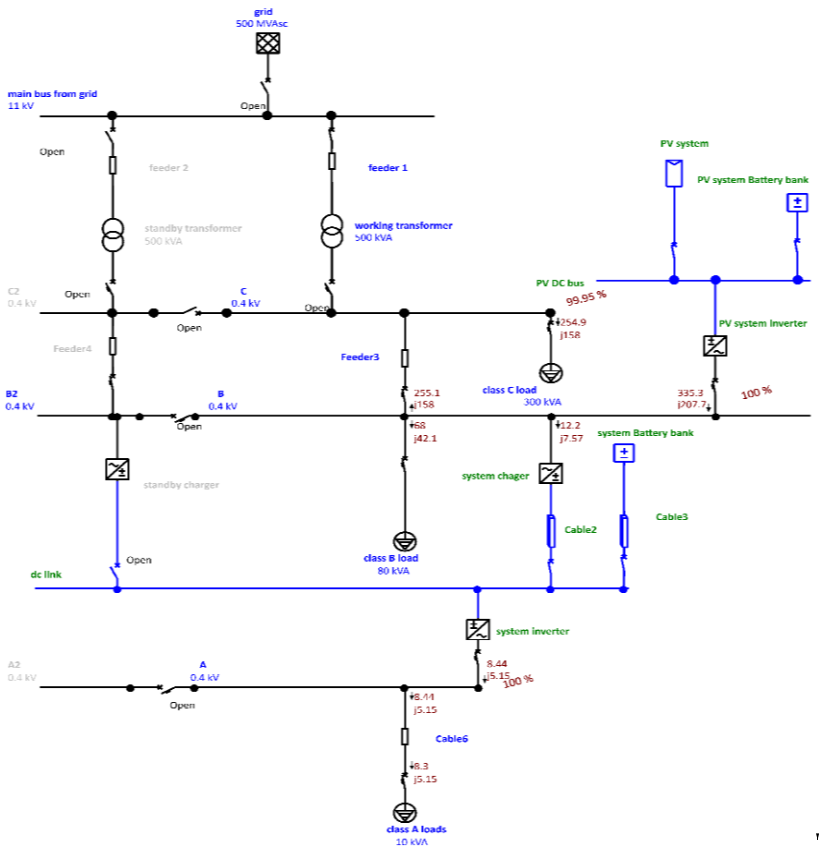

Figure 4. Load flow results for the first scenario of case 2

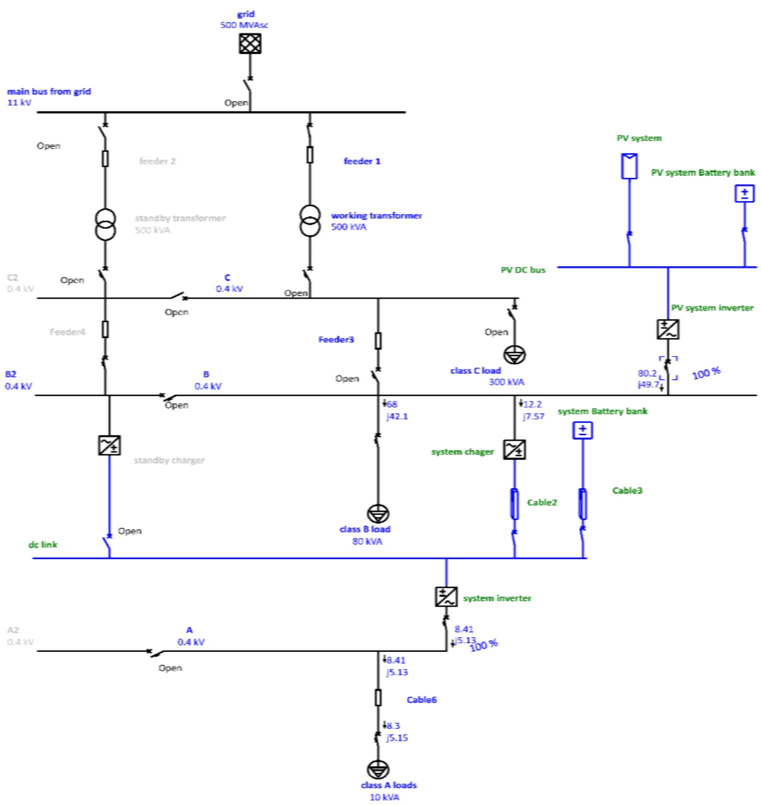

Figure 5. Load flow results for the second scenario of case 2

Table 5. Summary of load flow analysis (√ power supply is active but × power supply is inactive)

Operation mode	Grid	Diesel generator	PV system	Analysis
Normal	√	×	×	A grid will supply all facility loads with the voltage of classes C, B, and A (99.91%, 99.89%, and 100%), respectively.
Normal	×	×	√	The proposed system can supply all facility loads in case of deviation of normal operation or at normal operation to reduce the electricity cost and the voltage of classes C, B and A are (99.95%, 100%, and 100%), respectively.
Emergency	×	√	×	Diesel generators supply only classes B and A and the voltage is 100% for each.
Emergency	×	×	√	The proposed system can supply only classes B and A and the voltage is 100% for each.

4.2.2. Transient stability analysis

The stability study examines the response of traditional and proposed systems to disturbances using a three-phase fault to Feeder 1 at time (0.5) and clearing it at time (0.650) seconds; the simulation time is 5 seconds; the simulation time step (dt) is (0.001); and the plot time step is (20*dt). Table 6 describes the summary of the events. Also, Figure 6 shows the diesel generator speed and power angle. Figures 7 to 10 show the voltage and frequency of buses B and A for the two approaches mentioned also the analysis of the results obtained from Figures 6 to 10 is shown in Table 7.

Table 6. Summary of transient stability events

Event	Event 1				Event 2
Device ID	Feeder 1	T1 LV CB	Feeder 3 CB	Load C CB	Feeder 1
Action	Fault at 50%	open	open	open	Clear fault

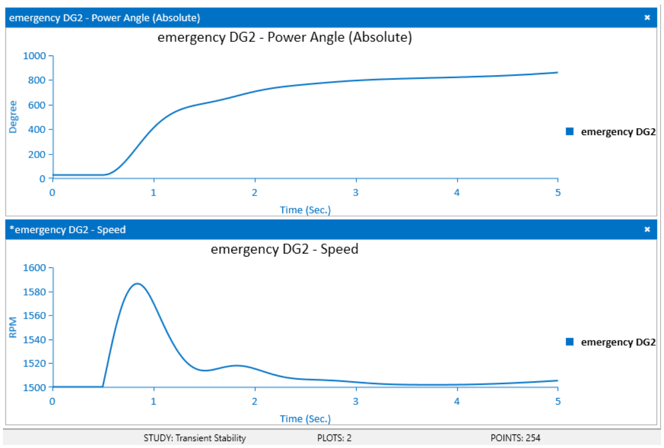

Figure 6. Diesel generator speed and power angel (absolute)

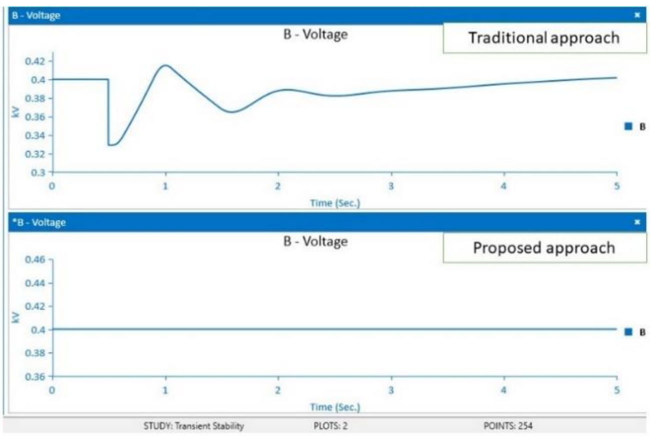

Figure 7. Bus B voltage under the two mentioned approaches

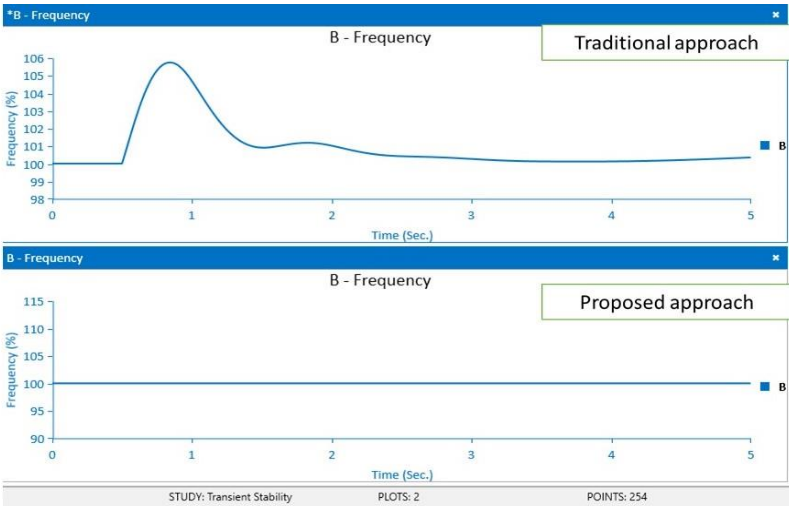

Figure 8. Bus B frequency under the two mentioned approaches

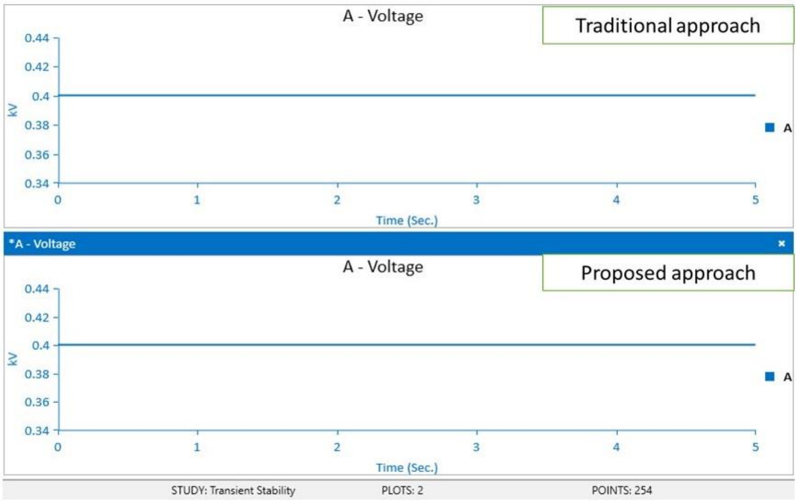

Figure 9. Bus A voltage under the two mentioned approaches

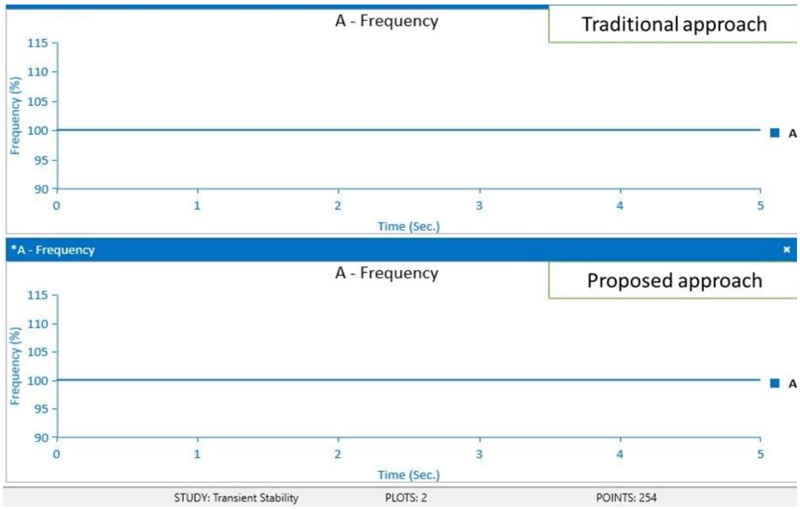

Figure 10. Bus A frequency under the two mentioned approaches

Table 7. Transient analysis Summary (√ power supply is active but × is not inactive)

Traditional approach	Proposed approach	Analysis
√	×	– The rotor speed rapidly increases to 1,580 rpm during the transient, then decreases to its nominal value at time 4 s, impacting the frequency. – During the fault, the voltage of bus B decreased to 0.32 kV, then increased to 0.42 kV. This fluctuation continued until the time of 5 s. The frequency also increased to 106% of its nominal value, then decreased to its nominal value after 3 seconds. – The voltage and frequency of Bus A are stable since they are supplied by the system inverter. – These fluctuations can damage the safety load during this period.
×	√	– The voltage and frequency of Bus B remained nominal during the fault, and Bus A likewise remained nominal.

5. CONCLUSION

The main objective of this research is to eliminate the shortage of diesel generators, which are crucial sources of power during nuclear facility emergencies, to reduce the probability of facility blackout as well as the probability of facility damage by proposing a hybrid PV/battery that can immediately supply safety and critical consumers without requiring a start-up time and with the necessary power quality. Additionally, the load flow and transient stability studies were examined using the ETAP program to test and evaluate the performance of the two approaches. The simulation results demonstrate that the proposed system is capable of supplying the facility consumers in classes C, B, and A with the nominal voltage and frequency during normal operation under certain conditions. Additionally, the performance of the proposed system is significantly better than that of the diesel generator during emergencies, as demonstrated by the voltage and frequency curves for classes B and A, as well as the analysis from Table 7. The system is designed based on nuclear safety, individual safety, and reliability, but the integration of solar, battery bank, and loads presents a design challenge. Future research will focus on optimum battery bank capacity and cost-benefit analysis.

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