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EVALUACIÓN DE LA INTRODUCCIÓN DE BESS EN LA OPERACIÓN DEL SISTEMA INTERCONECTADO NACIONAL DEL ECUADOR COMO ESTRATEGIA PARA ENFRENTAR LA CRISIS ENERGÉTICA

EVALUATION OF THE INTRODUCTION OF BESS IN THE OPERATION OF ECUADOR NATIONAL INTERCONNECTED SYSTEM AS A STRATEGY TO ADDRESS THE ENERGY CRISIS

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Resumen

En este estudio se examina la aplicación de un sistema BESS para la estabilidad de sistemas eléctricos en situaciones de emergencia, como la disminución de la producción o la interrupción de cargas industriales. El estudio se basa en el creciente uso de fuentes de energía renovables, cuya imprevisibilidad amenaza la estabilidad del sistema. El objetivo principal es comparar el rendimiento de la red eléctrica en escenarios de falla catastrófica con y sin asistencia de BESS. El método se basa en el uso del software Power Factory para modelar y simular un sistema eléctrico de nueve nodos. La pérdida de una planta de gas y la interrupción de una carga industrial, tanto con como sin BESS, son los cuatro escenarios de contingencia examinados. Los hallazgos indican que, en la situación 1, la frecuencia disminuye a 59,43 Hz, mientras que en la situación 2, con BESS, se mantiene en 59,85 Hz. En la situación 3, la frecuencia aumenta a 60,6 Hz, mientras que en la situación 4 se mantiene estable en 60,12 Hz. Esta información demuestra que BESS aumenta la estabilidad de la frecuencia y reduce las oscilaciones del sistema, lo que prueba su eficacia como recurso de apoyo ante contingencias.

Palabras clave: BESS, Almacenamiento de energía, Contingencias eléctricas, Red eléctrica, Estabilidad de frecuencia.

Abstract

The application of a BESS system in the stability of electrical systems in emergency circumstances, such as decreased output or interruption of industrial loads, is examined in this study. The study's foundation is the growing use of renewable energy sources, whose unpredictability threatens the system's stability. Comparing the electrical grid's performance in catastrophic fault scenarios with and without BESS assistance is the primary goal. The method is based on utilizing the Power Factory software to model and simulate a nine-node electrical system. The loss of a gas plant and the interruption of an industrial load, both with and without BESS, are the four contingency scenarios that are examined. The findings indicate that, in situation 1, the frequency decreases to 59.43 Hz, whereas in situation 2, with BESS, it remains at 59.85 Hz. In situation 3, the frequency increases to 60.6 Hz, while in situation 4 it remains stable at 60.12 Hz. This information demonstrates that BESS increases frequency stability and reduces system oscillations, proving its effectiveness as a contingency support resource.

Keywords: BESS, Energy storage, Electrical contingencies, Electric grid, Frequency stability.

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1. Introduction

Energy storage has been essential to the development of electrical technology from its creation. The global electrification trend has made efficient management of energy production and consumption crucial [1]. The technology known as a battery energy storage system (BESS) makes it easier to store energy and release it when needed. This technology has emerged as a key component in the transition to a more sustainable energy matrix, encouraging the use of renewable energy sources and enhancing electrical grid reliability [2].

From the early use of lead-acid batteries to the development of state-of-the-art lithium-ion technology, energy storage technologies have evolved dramatically throughout time [3]. Despite its limitations in terms of energy density and cycle life, lead-acid batteries, which were developed in the 19th century and were among the first rechargeable battery models, are still utilized in many applications. New batteries with better performance characteristics have been found over time because of research and development [2].

Lithium-ion battery innovation has played a major role in the revolution in energy saving. Compared to their predecessors, these batteries, which went on sale in the 1990s, have a higher energy density, a longer lifespan, and a lower rate of self-discharge [4]. These characteristics have established them in a variety of ways, from portable electronic devices to electric vehicles and, more recently, large-scale energy storage systems [3]. Reduced production costs and increased efficiency have made lithium-ion batteries a viable alternative for a variety of applications [5]. The progress of BESS has not only been driven by the need to store energy for future use, but also by the growth of renewable energies, such as solar and wind, which are intermittent in nature, generating energy irregularly throughout the day and under various weather conditions [6]. BESS provides a response to this intermittency, facilitating the storage of surplus energy generated during periods of high generation and its release when generation is low or demand is high. Not only does this promote the use of renewable energies, but it also increases the stability of the electricity grid [7].

Furthermore, BESS plays a crucial role in the management of the electricity grid, which faces ever greater challenges due to the increase in electrification in areas such as transportation and industry [3].

In this scenario, one of the challenges facing current electrical systems is how to respond to contingency situations, such as unexpected loss of production or the disconnection of significant loads. These occurrences may result in significant frequency and voltage instability, endangering the dependability of the electrical supply [5]. The operational security of the grid is still at risk due to the inability to react quickly to these occurrences, despite efforts to fortify generation systems [8], [9].

Implementing BESS systems is a practical way to improve the resilience of electrical systems in the face of this difficulty. They can act as dynamic assistance at crucial times [10] by responding quickly and supplying active power when needed. As a result, BESS not only lessens frequency oscillations but also eases the burden on generators, enhancing their functionality and lowering wear and tear brought on by abrupt movements [3]. The necessity to quantitatively show the benefits of a BESS is the basis for analyzing system stability both with and without its involvement. Even though its use has grown in sophisticated systems [5], many emerging environments still face technological and financial difficulties. To support planning and investment decisions, it is essential to conduct comparative evaluations under actual contingency scenarios, such as the closure of a producing facility or the disruption of a significant industrial load [5], [11].

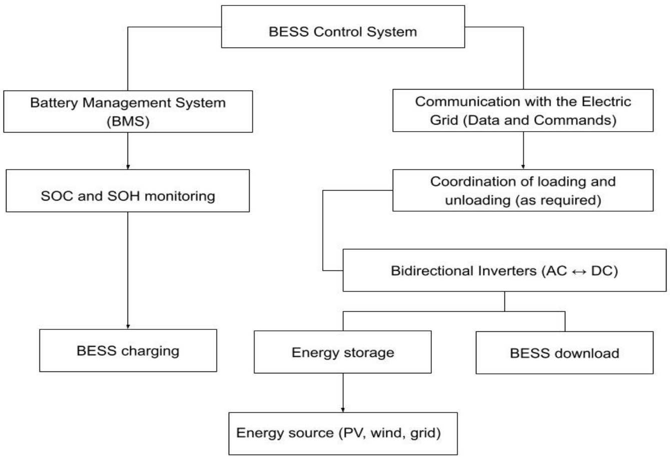
The importance of BESS in integrating renewable energy, boosting grid resilience, and meeting energy demand is becoming more important as the globe transitions to a more sustainable future. Therefore, scenarios with and without storage will be compared to evaluate the impact of BESS on the stability of electrical systems exposed to operational contingencies [12]. Fundamental factors like frequency, voltage, and operational power will be taken into consideration when analyzing events like reduced gas production and the disconnection of industrial loads [13]. The objective is to show how BESS can enhance the electrical system's resilience, efficiency, and dependability, particularly during times of high operational demand.

2. Materials and Methods

2.1. How a BESS Works

A BESS facilitates the charging, storing, and discharging of electrical energy through a few processes and energy flows. This system contributes to backup power, renewable energy integration, and grid stabilization [14] [15].

Figure 1. *Below describes the elements of how a BESS works.*

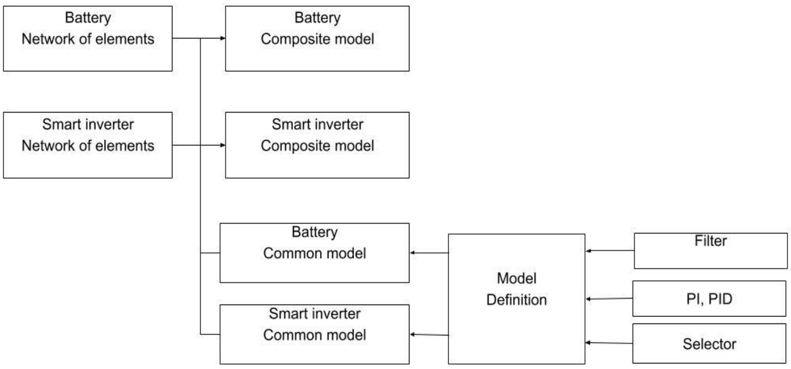


To ensure safe operation, the Battery Management System (BMS) regularly checks the cells' state of charge (SOC) and state of health (SOH). Alternating current (AC) can be converted to direct current (DC) for battery charging and from DC to AC for grid draining thanks to bidirectional inverters [16], [15]. The BESS can participate in services like voltage control and frequency regulation by communicating with the electrical grid [17]. The BESS can be directly powered by the grid or by renewable energy. This system enables it to operate in a few applications, including energy incorporation, grid stabilization, energy backup, and lowering electrical expenses [10].

2.2. Modeling a BESS in Power Factory

DIgSILENT is a consulting software that created a program perfect for industrial network analysis and power generation, transmission, and distribution. It integrates mathematical ideas with the ability to model systems. The BESS model [10], which incorporates smart battery and inverter models, was constructed in this study using the model. Figure 2 shows the diagram.

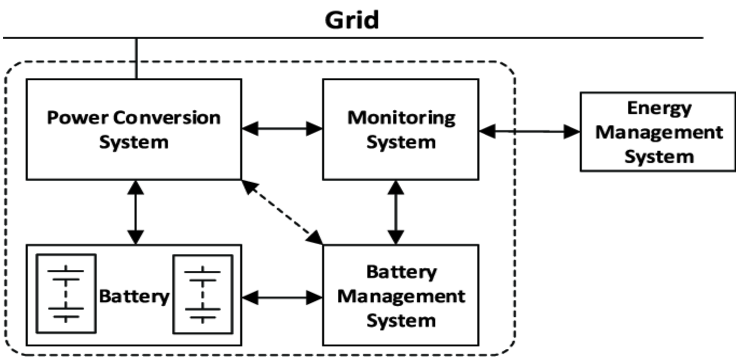
Fig. 2*. Model of a BESS in PowerFactory*



2.3. BESS Model

The BESS arrangement utilized in this investigation is depicted in Figure 3. A battery, an energy conversion system, a BMS, and an energy management system (EMS) make up this system. Every one of these components contributes to the efficient administration and oversight of the system [18], [10].

Fig. 3*. Diagram of a BESS model*



The charging and discharging procedures are made easier by the smart inverter's ability to convert direct power into alternating current that is compatible with the grid and the reverse [10]. According to this study, the BESS can improve temporal stability, control frequency, and system voltage [12], serving as an essential resource in the event of disruptions. When a breakdown or production loss occurs, the battery runs in discharge mode, supplying energy to the system. The oscilloscope outputs are filtered to gather the measurement signal, which enables a more exact comparison with the reference value and guarantees precise control. The PID and PI controllers work together to fix the found defects by dynamically altering the BESS response to system conditions [19].

2.4. Models for BESS stability analysis

It is essential to employ mathematical models that appropriately depict the dynamic and stable behaviour of the electrical system while conducting electrical stability evaluations in the event of load or generation losses. In order to evaluate the performance of parts like generators, loads, and storage systems like BESS, these models allow the modelling of both normal and dependent conditions [20]. The basic formulas and equations that underpin this kind of analysis are included in this document, along with an explanation of each one's role in the framework of electrical system analysis both with and without BESS.

2.4.1. Power flow

Utilized to determine the voltages, active, and reactive powers that are present in each system busbar when it is at rest. It serves as the foundation for confirming post-fault and operating conditions. according to Equations 1 and 2.

$$P_i = V_i \sum_{j=1}^{n} V_j\left[G_{ij}\cos(\theta_{ij}) + B_{ij}\sin(\theta_{ij})\right] \quad (1)$$

$$Q_i = V_i \sum_{j=1}^{n} V_j\left[G_{ij}\sin(\theta_{ij}) - B_{ij}\cos(\theta_{ij})\right] \quad (2)$$

2.4.2. Power balance

It makes it easier to confirm whether the system keeps generation, demand, and losses in balance [21] [22]. It is essential for calculating power deficits or overloads following a contingency in Equation 3.

$$\sum P_{generación} - \sum P_{carga} - \sum P_{pérdida} = 0 \quad (3)$$

2.4.3. BESS frequency control

The capacity of BESS to operate as a frequency regulator in the event of changes in the electrical system, such as load loss or generation, is one of its core features [23], [7]. Equation 4 provides a mathematical example of this function.

$$P_{BESS} = k_f(f_{ref} - f) \quad (4)$$

In this line, P_BESSrepresents the power that the system needs to inject or absorb, f_refis the nominal frequency of the system (such as 60 Hz), f is the true measured frequency, and K_fis a proportional constant that determines how intense the BESS reaction is to frequency deviations [24]. This equation is a component of a proportional control that makes it easier to respond quickly and instantly to unforeseen circumstances. Similarly, the BESS absorbs power if there are a load loss and the frequency rises [25]. By assisting the electrical system in swiftly regaining equilibrium, this gadget helps avoid more significant issues like disconnections or disconnections of sensitive devices.

2.4.4. PID and PI control

To achieve more precise regulation, the BESS system can employ more complex controllers as PID or PI in addition to basic proportional control [26], [27]. Equation 5 represents these controllers:

$$u(t) = K_p\, e(t) + k_i \int e(t)dt + k_d \frac{de(t)}{dt} \quad (5)$$

Therefore, *u(t)* represents the control signal transmitted to the inverter, while *e(t)* represents the error between an evaluated variable and its reference value [2]. The figures K_p, K_i y K_d refer to the proportional, integral, and derivative gains. This kind of control helps to balance deviations with more stability in an electrical system that employs BESS by altering the system's response to changes [4].

2.5. Overview of the electrical system

It is crucial to employ mathematical models that appropriately depict the dynamic and stable behaviour of the electrical system while conducting electrical stability evaluations in the event of load or generation losses. To evaluate the performance of parts including generators, loads, and storage systems like BESS, these models allow the modelling of both normal and dependent conditions [20]. The electrical system under examination is a major component of Ecuador's National Interconnected

System (SNI), notably a topology with nine critical nodes that cover hydraulics, storage via a BESS system, and heat generation in addition to significant industrial loads [7].

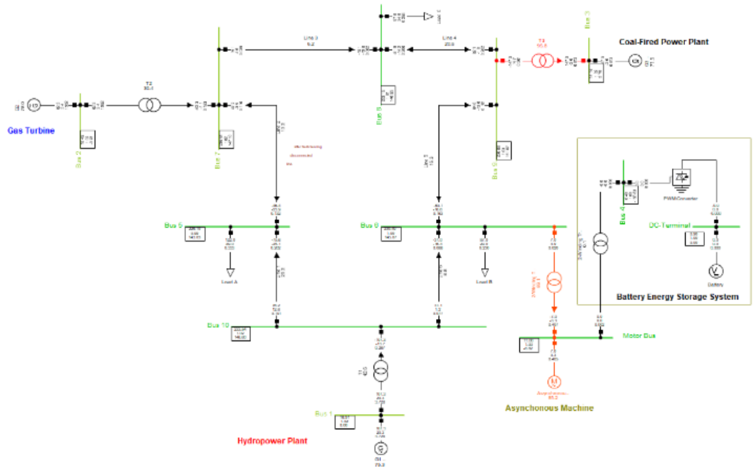
The National Electricity Operator (CENACE) and the Agency for the Regulation and Control of Energy and Non-Renewable Natural Resources (ARCERNNR) provided technical data that was used to model this system [10]. To determine the system loads, monthly averages of energy consumption were used, adjusted to a typical power factor of 0.92. The industrial loads represented symbolize the coastal provinces of Ecuador: Guayas, Los Ríos, Milagro, and El Oro, where the active and reactive power values are detailed in Table 1 of the report.

Table 1. *Determination of the load on the electrical system*

Load (CNEL)	Energy – Jan 2024 (MWh)	Energy - Feb 2024 (MWh)	Energy – average (MWh)	Active power (MW)	Reactive power (MVAr)
Guayas	306,064.61	300,999.54	303,382.07	422	180
Los Ríos	98,893.94	300,999.54	95,113.86	127	54
Milagro	50,893.99	49,512.10	50,203.04	70	30
El Oro	151,761.59	145,843.09	148,802.34	207	88

The system shown in Figure 4 was designed to examine contingency situations, whether due to generation or load disconnection, both with and without the BESS. The effect of the BESS on system stability in the event of interruptions and its ability to function as additional support is analysed.

Fig. 4. *General system with 9 nodes*



2.6. Case studies

To complete the analysis, we will begin by explaining the case studies detailed below:

2.6.1. Case 1 (Gas blackout using BESS)

Analysis is done on an electrical system with nine nodes connected under a gas-fired power plant's disconnection plan. To evaluate the system's capacity to lessen the effects of decreased production, the BESS is integrated.

Event 1: After 60 seconds, the switch that connects the gas plant to bus 7 is unlocked. Event 2: The coal plant's speed is changed to 1.35 pu for 480 seconds. how well the BESS maintains voltage and frequency stability in the face of major disruptions.

2.6.2. Case 2 (Blackout without BESS)

The same 9-node system is investigated in the same gas plant disconnection scenario sans BESS. After 60 seconds, the switch shuts off, reducing the amount of active energy produced by 40 MW. The limitations on frequency regulation and generation adaptability are highlighted by the system's behaviour and the generators' response in the absence of BESS support.

2.6.3. Case 3 (Disconnection of industrial load with BESS)

The reaction of the BESS-backed system during the disconnection of an industrial load at point 6 is analyzed.

- Event 1: At 60 seconds, the load is disconnected at node 6, causing excess generation.
- Event 2: Modification of the speed control of the coal generator to 1.15 pu for 480 seconds.

The BESS capacity to retain a steady frequency while absorbing surplus energy.

2.6.4. Case 4 (Industrial load disconnection without BESS)

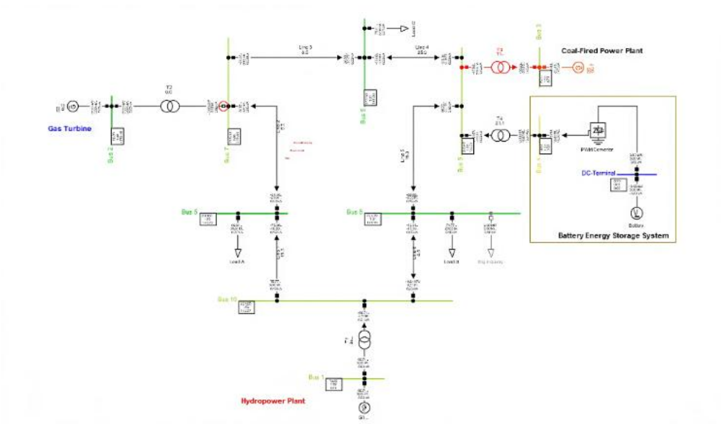
To assess system performance, a comparable load disconnection scenario is encountered without BESS. The industrial load disconnects at node 6 after 60 seconds, which results in an increase in frequency because of extra energy. the way generators respond to sudden load drops and determining how well frequency control works.

3. Results and Discussion

3.1. Gas blackout using BESS

9 interconnected nodes make up the system examined in Figure 5. In this case, a gas-fired power plant's disconnection has been planned, which is a big event that has an impact on the system's operation. To lessen the effects of this disconnection, a BESS must be implemented in this system. In this case, an electrical simulation is performed on a 9-node system with the aim of examining the effects of certain critical events and how a BESS can mitigate their effects.

***Fig. 5**. Gas blackout using BESS*



3.1.1. Opening of the switch connecting gas generation to busbar 7 at 60 s

A gas-fired power plant will be cut off from the system in this scenario, which will drastically lower the amount of active electricity produced. The BESS's capacity to react to this loss will be the focus of the investigation. To avoid variations and keep voltage at appropriate levels, the capacity to provide power instantly will be assessed.

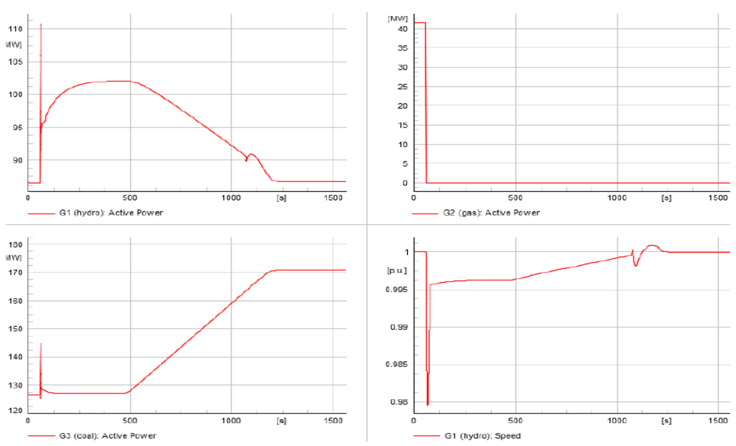
3.1.2. Modification of the speed regulator of the coal-fired power plant at 480 s, increasing it to 1.35 pu

The coal-fired power plant, which is connected to the same bus as the BESS, will operate differently because of this second incident. The speed regulator's responsiveness and contribution to frequency management will both enhance because of the modification. This modification is essential for analyzing how the BESS and the coal-fired power plant can respond to the loss of the gas-fired power plant and maintain system stability.

3.1.3. System response 60 seconds after the disturbance

The supply of active power is noticeably interrupted when the gas-fired power plant (G2) disconnects after 60 seconds, which results in a shortfall in the system's production capacity. The hydroelectric generator (G1), which is essential to preserving the stability of the system frequency, responds to this disruption by increasing its speed to make up for the decline in generation. The hydroelectric generator (G1) makes a significant effort by increasing its active power production by roughly 15 MW, but it is insufficient to compensate for the 40 MW loss resulting from G2 disconnection. However, the coal plant (G3) continues to produce at a steady level, which suggests that its capacity to act swiftly to cut back on the usage of more costly resources is limited. By providing the extra 25 MW needed to balance the system in this scenario, the BESS plays a critical role in keeping the coal generator (G3) from raising its production, which would be more costly and inefficient. In addition to satisfying the immediate requirement, the BESS's action also encourages frequency stability, demonstrating its efficacy in situations where production is unexpectedly lost (Figure 6).

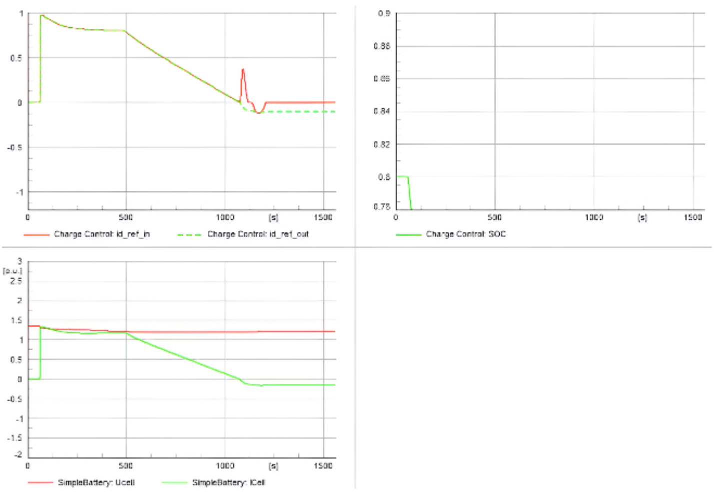
***Fig. 6**. System response 60 seconds after the disturbance*



3.1.4. Modification of the speed controller of the coal generator at 480 s

The coal generator's (G3) speed controller is modified, increasing the speed reference to 1.35 pu. Consequently, during a duration of 1200 seconds, the coal plant progressively expands its capacity from 125 MW to around 170 MW. This gradual increase in load is a strategy to control frequency and partially compensate for the active power shortfall without producing abrupt changes in the system. The hydroelectric generator (G1) sustains a slight speed increase during this time, stabilizing at 1 pu. This improves its operation to avoid overexertion and enables it to adjust its production more precisely for frequency management while also lowering its load. At the same time, the BESS continues to provide energy and power, albeit at a reduced level, as shown by the U_cell and I_cell curves. This involves strategic management of the BESS load to ensure its availability throughout the disturbance event and its recovery, ensuring constant system stability and preventing the excessive use of more expensive or less adaptable resources. This study emphasizes the significance of BESS in handling electrical system eventualities, offering backup during crucial times as well as encouraging more economical and efficient functioning of other generating units (see Figure 7).

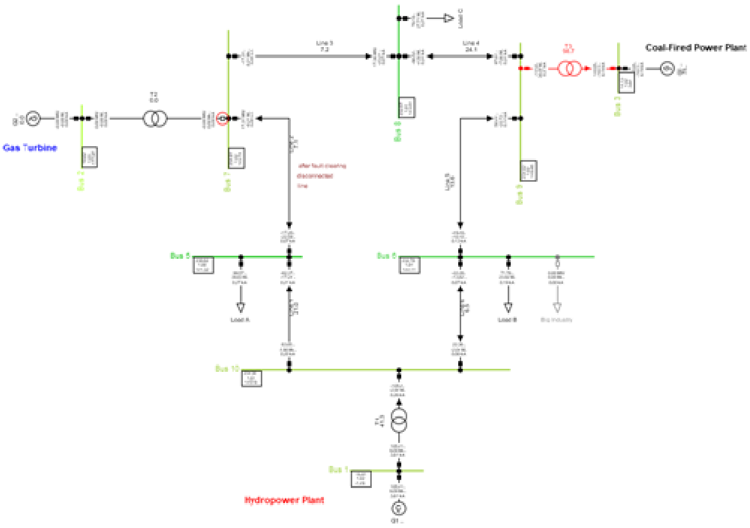
***Fig. 7**. Modification of the coal generator speed controller to 480 s*



3.2. Blackout without BESS

9 interconnected nodes make up the system examined in Figure 8. In this case, a gas-fired power plant's disconnection has been planned, which is an important event that will have an impact on the system's operation.

Fig. 8. *Blackout without BESS*



To investigate the consequences of critical events and how generation systems can lessen their effects, an electrical simulation on a 9-node system is conducted in this study. These generators' capacity to provide electricity instantly will be assessed, assisting in preventing frequency fluctuations and preserving voltage at appropriate levels.

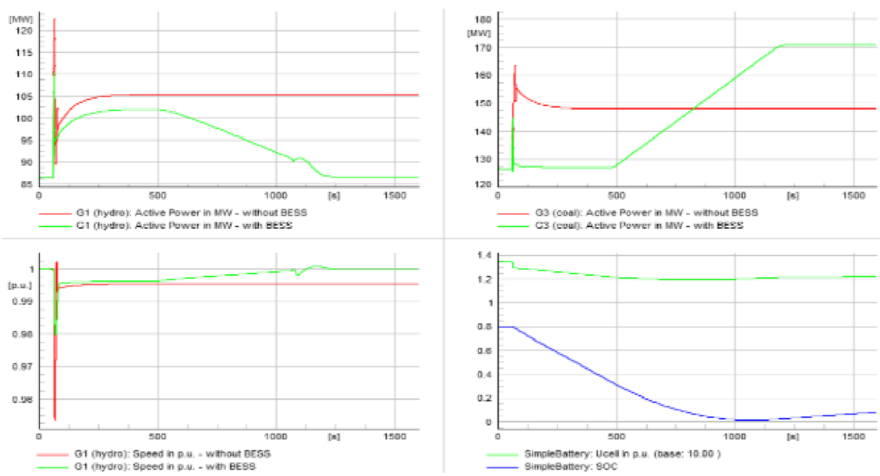
3.2.1. Opening of the switch connecting gas generation to busbar 7 at 60 s

The disconnection of a gas-fired power plant from the system will result in a decrease in the amount of active electricity generated. How generation systems can react to this loss will constitute the focus of the study.

3.2.2. System response 60 s after the disturbance

The system experiences a significant active power deficit when the gas-fired power plant (G2) disconnects after 60 seconds. A critical situation for the stability of the system frequency is created by this abrupt drop in generation. To offset the shortfall, the coal-fired (G3) and hydroelectric (G1) generators speed up their output. The hydroelectric generator (G1) contributes an additional 20 MW, increasing its active power generation from 85 MW to 105 MW. Although this increase is a quick and substantial response, it is still insufficient to make up for the 40 MW of electricity lost because of G2 disconnection. Concurrently, the coal generator (G3) contributes an additional 20 MW and raises its output from 127.5 MW to roughly 147.5 MW. This rise in production necessitates the intense use of increasingly costly and inefficient resources. Without the assistance of a BESS, the system's response reveals some flaws, such as the requirement for generators with longer response times and the usage of more expensive and environmentally harmful energy sources, which raise operational expenses and carbon emissions. Additionally, the lack of a BESS limits the system's capacity to control frequency regulation and inertia, raising the possibility of instability in situations including unforeseen generation loss (see Figure 9).

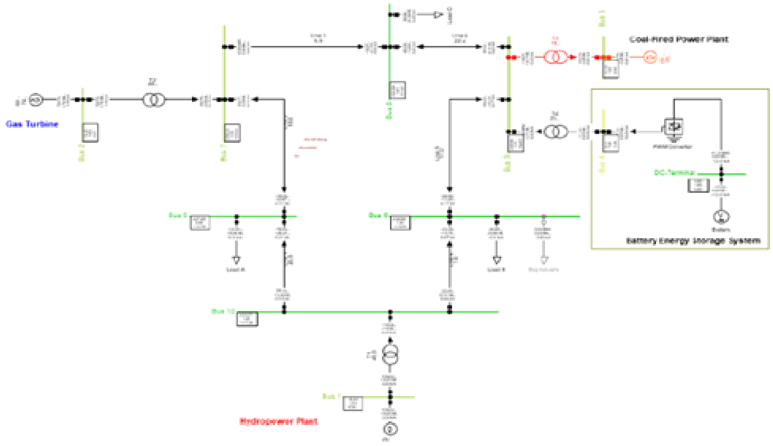
Fig. 9. *System response 60 seconds after the disturbance*



3.3. Disconnection of industrial load with BESS

9 interconnected nodes make up the system examined in Figure 10. In this case, an industrial load at node 6 has been designed to disconnect; this is a major event that has an impact on the system's functionality.

***Fig. 10**. Disconnection of the industrial busbar with BESS*



To lessen the effects of this, disconnect, a BESS must be implemented in this 9-node. To investigate the consequences of occurrences and how can lessen them, an electrical simulation is run on a 9-node system in this case study.

3.3.1. Opening of the switch connecting the load at node 6 to 60 s

This will result in the disconnection of a load at node 6, which will significantly reduce the active power load. How the BESS can react to this loss will be the focus of the investigation. To prevent over frequency and maintain voltage at appropriate levels, the BESS capacity to instantly capture power will be assessed.

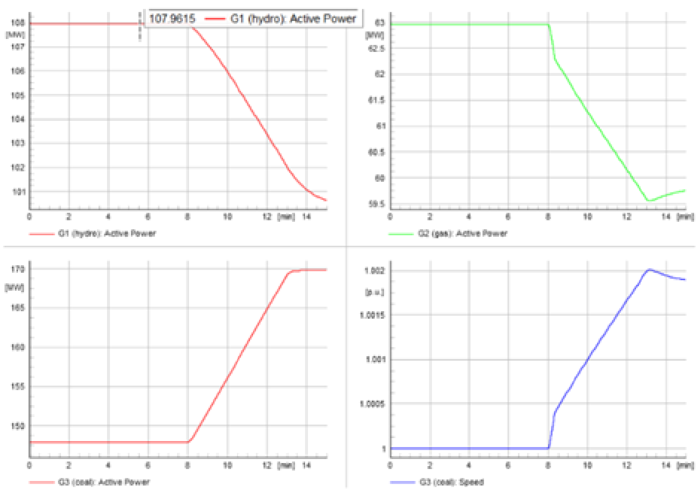
3.3.2. Modification of the speed of the speed regulator of the coal-fired power plant at 480 s, increasing it to 1.15 pu:

The coal-fired power plant, which is connected to the same bus as the BESS, will operate differently because of this second incident. The speed regulator's responsiveness and contribution to frequency management will both enhance because of the modification. Analyzing how the coal-fired power plant and the BESS may respond to the loss of the gas-fired power plant and maintain system stability depends on this modification.

3.3.3. System response 60 s after the disturbance

The system experiences a power imbalance that could change the frequency if the gas production facility (G2) is disconnected. Nevertheless, the BESS successfully controls the imbalance brought on by excess generation, which makes it simpler to keep the system frequency within typical operational bounds and lessen abrupt swings. In this case, the BESS (SOC) is kept at about 0.8 pu, showing that it is successfully absorbing the extra energy generated and making up for the gas plant's production loss. To avoid frequency changes that could harm the equipment, this behavior is crucial. Despite the disruption, the hydroelectric (G1), gas (G2), and coal (G3) generators continue to produce power at steady levels, producing approximately 108 MW, 63 MW, and 146 MW, respectively. The BESS intervention, which has assumed the function of load balancer and allowed the generators to continue working without necessitating significant adjustments to their output, is responsible for this generation stability (see Figure 11).

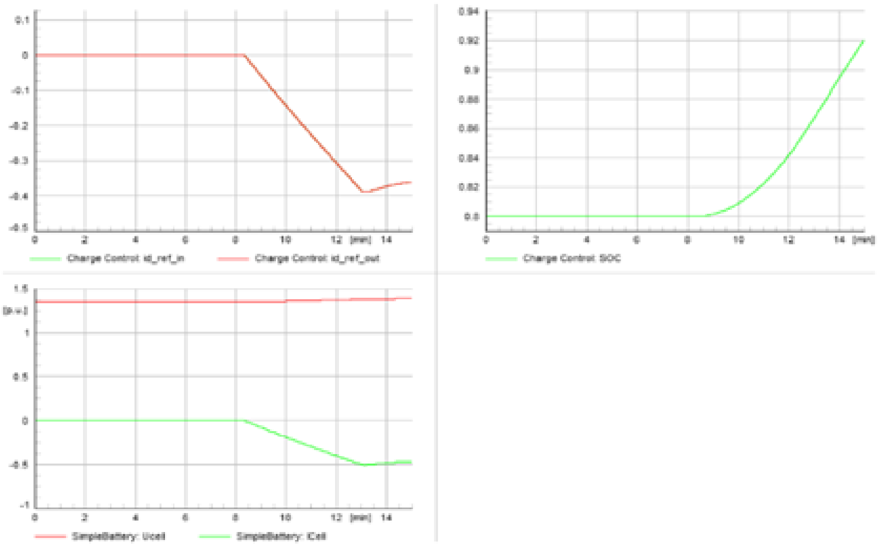
Fig. 11. *Disconnection of the industrial busbar with BESS*



3.3.4. Modification of the speed controller of the coal generator at 480 s:

An adjustment is made to the speed controller of the coal generator (G3), raising the speed reference to 1.15 pu. The goal of this modification is to improve the coal generator's reactivity so that it can more easily handle a larger load in a controlled way. In just 13 minutes, G3 output rises from 146 MW to almost 170 MW. To avoid negative consequences on system stability, this load increase is managed carefully. To meet the growing demand, a balanced supply, both the gas generator (G2) and the hydroelectric generator (G1) start to reduce their energy production at the same time. To maximize system efficiency, this coordinated adjustment is essential. On the other hand, the BESS begins to recharge, as indicated by the variations in the U_cell and I_cell curves. To maintain the continuity and stability of the electrical system without turning to the overuse of more costly or less flexible generators, this recharge process is carefully controlled to guarantee the BESS availability to respond to future disruptions (Figure 12).

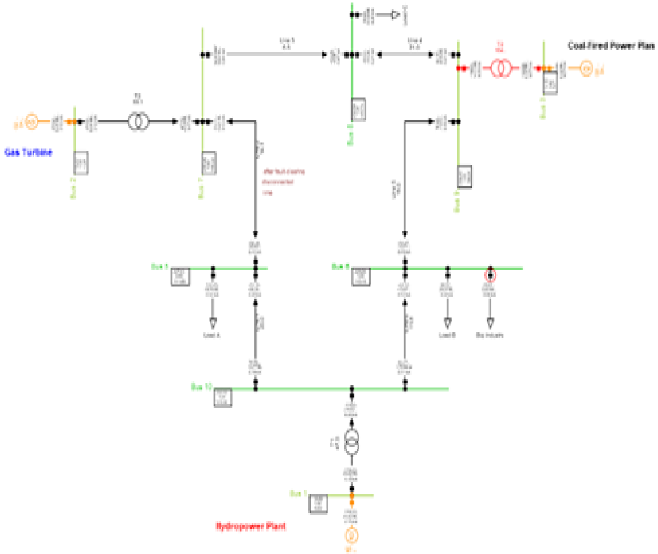
Fig. 12 *Modification of the speed controller of the coal generator 480 s*



3.4. Industrial load disconnection without BESS

9 interconnected nodes make up the system examined in Figure 13. An important event that has an impact on the system's functionality is the planned disconnection of an industrial load at node 6.

Fig. 13 *Industrial load disconnection without BESS*



systems can lessen them, an electrical simulation is run on a 9-node system in this case study.

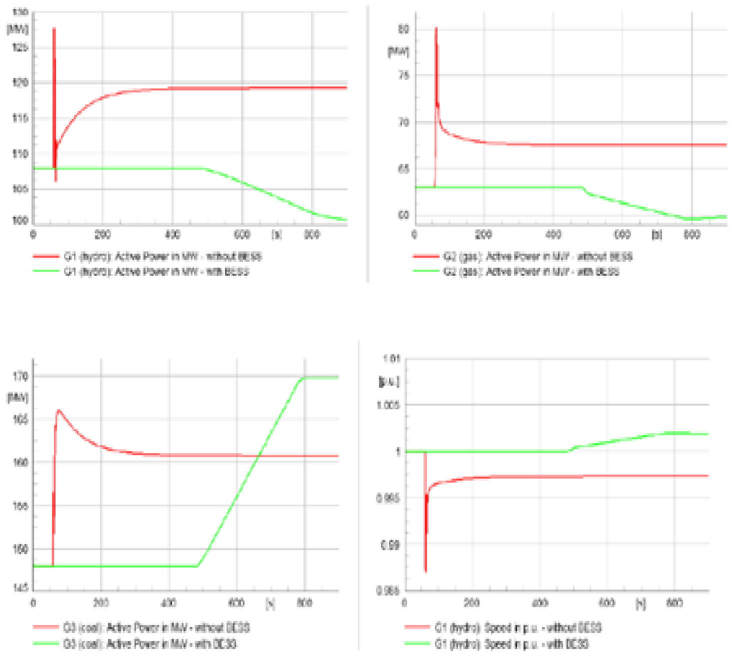
3.4.1. Opening of the switch connecting gas generation to busbar 7 at 60 s

This will result in a significant decrease in active power generation since an industrial load at node 6 of the system will be disconnected. How generation systems can react to this loss will be the focus of the study. These generators' capacity to provide power instantly will be assessed, assisting in the prevention of frequency swings and the maintenance of acceptable voltage levels.

3.4.2. System response 60 seconds after disturbance

The system's available active power increases significantly because of excess generation when a big industrial load at node 6 is disconnected for 60 seconds. This causes an imbalance between the supply and demand for energy. Because overproduction might result in an increase in frequency if improperly handled, this unforeseen interruption poses a key scenario for system frequency stability. In reaction to this incident, the hydroelectric generator (G1) dramatically reduces its active energy production from 127 MW to roughly 109 MW to respond to the fall in load. Nevertheless, after 300 seconds, this initial decline stabilizes at about 120 MW, suggesting a continuous adjustment to balance the system frequency. This behavior of G1 demonstrates the ability of the hydroelectric generator to quickly modify its output in response to variations in demand, although not ideally in terms of frequency stability. At the same time, the coal generator (G3) increases its output from around 147 MW to a maximum of 167 MW, then stabilizes at 162 MW after 300 seconds. This increase shows the resilience and reaction of the coal generator to the disturbance, in which greater system resilience facilitates more efficient absorption of excess generation. However, this response is neither instantaneous nor ideal, due to the time required to stabilize production. In contrast, the gas generator (G2) exhibits an immediate response to the increase in system frequency, raising its output from 62.5 MW to about 80 MW. This rapid response is a characteristic of gas generators, which can quickly modify their output. However, G2 also decreases its output to about 67.5 MW to keep the system frequency stable during the same 300-second period. This study demonstrates that frequency stability cannot be adequately maintained by the combined response of gas and hydropower generators to overproduction. Before the system reaches a new equilibrium, there is a fluctuation in frequency because the adaptation of energy production is not instantaneous nor proportionate to the disturbance. It is seen that the BESS can swiftly absorb extra active power, minimize abrupt frequency changes, when compare this reaction to the system's operation with a BESS. Without needing significant changes to generation, the BESS provides a nearly instantaneous response to changes in load. In addition to improving system stability, it also permits more economical and efficient operation, lowering generator wear and the consumption of more costly and environmentally harmful resources (Figure 14).

***Fig. 14** System response 60 s after disturbing*



4. Conclusions

The results of the study demonstrated that the installation of a BESS system directly improves the electrical system's reliability in emergency scenarios, such as production loss or an interruption in industrial load. The analysis of the electrical system's stability in emergency scenarios, both with and without a BESS system, has shown significant differences in the system's dynamic behaviour, especially in frequency response and transient stability. It was confirmed that the frequency displayed more notable variances when BESS was not used. For instance, in scenario 1, the frequency dropped to 59.43 Hz due to the loss of a production plant, however in case 3, the frequency increased to 60.6 Hz because of the industrial load being disconnected. With noticeable oscillations and lengthy stabilization times, these values indicate a more vulnerable system reaction. However, the BESS settings (cases 2 and 4) demonstrated more consistent performance. The frequency only decreased to 59.85 Hz in scenario 2, while it significantly increased to 60.12 Hz in scenario 4, suggesting a notable improvement in frequency regulation when compared to prior disruptions. Additionally, it was confirmed that BESS may serve as a flexible resource that can adapt to different system operating conditions without necessitating the reduction of other network components. Its integration not only promotes primary frequency management but also lessens the labor needed for generating plants, improving the system's overall efficiency. From one angle, it was demonstrated that the simulation, which was based on a nine-node system modelled in Power Factory, was suitable for demonstrating how BESS affects contingency events. The findings corroborate the purpose of the research: to demonstrate that the implementation of energy storage systems enhances the stability of the electrical system. As a result, BESS offers substantial advantages in frequency regulation, oscillation reduction, and overall enhancement of the operational reliability of electrical networks, making it a practical and efficient technical solution for handling generator loss or load disconnection occurrences.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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