B&H Electrical Engineering, Volume 20, Issue 1, 2026
ISSN:2566-3143, eISSN:2566-3151, DOI: 10.2478/bhee-2026-0013

**Original scientific paper**

*Submitted: May 5, 2025*

*Accepted: October 18, 2025*

# THE VOLTAGE REGULATION OF POWER SYSTEMS USING STATCOM AND BATTERY ENERGY STORAGE SYSTEM: A SIMULATION STUDY

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**Abstract:** Power plants must have sufficient installed power capacity to accomplish high demand and must be operated continuously with sufficient capability to meet real-time demand. Integrating an energy storage system, such as a battery energy storage system, into a Flexible Alternating Current Transmission System (FACTS) device can provide the much-needed flexibility to reduce dynamic decentralized active power capabilities and transmission-level power flow issues. This article establishes a control strategy for optimal use of STATCOM and the Battery energy storage system. The architecture of the BESS, its utility-scale applications and the benefits of its application in power systems have been studied, as well as the operation control methods of large-scale STATCOM and BESS systems have been examined. Application scenarios such as power grid frequency tuning and power flow optimization are presented. In addition, in the study where STATCOM and BESS are integrated into the power system, specific features to support voltage in power grids are demonstrated. STATCOM and BESS units have been shown to be integrated and improved with optimum power factors. To reduce energy loss and improve voltage stability, STATCOM has been validated to simultaneously improve the voltage profile in the interconnected grid by regulating the active and reactive power in the power transmission line. Finally, all the comparative results show that STATCOM and BESS devices can maintain excellent performance in controlling the voltage regulation response under various faults. The results were considered considering the current Turkish interconnection system, with a view to identifying potential avenues for enhancement.

**Keywords:** Battery Energy Storage Systems, STATCOM, Renewable Energy, Frequency Control, High Voltage, Interconnection system.

## INTRODUCTION

The implementation of Battery Energy Storage Systems (BESS) is versatile, spanning various domains of power systems. Due to its rapid active power response, it is an optimal solution for mitigating the adverse effects of wind power plants, such as reducing oscillations within the power system. BESS has been demonstrated to enhance and positively impact the reduction of rotor speed deviation at various levels of system penetration following disturbances. The impact of diverse BESS study strategies on achieving primary frequency control was the subject of investigation [1]. The objective of investigating the role of BESS in enhancing frequency stability during increased wind penetration, where some synchronous generators are substituted by multiple wind generators, is to compare the system frequency stability with and without BESS [2]. The feasibility of frequency support has been thoroughly studied and analyzed by BESS. Furthermore, the integration of BESS into power systems has been demonstrated to enhance voltage support in electrical networks. Integration of BESS units with optimal power factors has been demonstrated to reduce energy loss and enhance voltage stability [3]. The implementation of BESS is currently a key factor in sustainable energy in the United States, Japan, China, and other countries. Recent studies have demonstrated the efficacy of BESS and STATCOM in enhancing grid reliability, power quality, and facilitating renewable energy integration [4]. The power grid is undergoing constant evolution, and recent trends indicate that certain transmission system operators (TSOs) are seeking combined services capable of delivering substantial amounts of power and energy, with the advantage of rapid activation time [5]. The emergence of renewable energy sources within power systems, coupled with a decline in overall system inertia, has led to a decline in voltage and frequency support capabilities, and a general weakening of the system. In this context, flexible alternating current transmission systems (FACTS) have emerged as promising technology, capable of providing the auxiliary services essential for ensuring the stability of power system operations [6]. The rapid response time of battery systems, coupled with their multifarious functions and capabilities, renders them a highly viable solution to the challenges anticipated by future power systems [7]. To

This paper was submitted to the Conference of the South-East European Regional Council of CIGRE (SEERC 2025), held in Sarajevo, Bosnia and Herzegovina, on June 4–5, 2025.

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enhance the quality of energy by regulating voltage and reactive power, realistic system modelling was conducted with a simulation study to optimize controllable parameters in energy transmission systems. The FACTS control system is predicated on microelectronics, communication and advanced control applications, with the objective of regulating the power system to enhance its power carrying capacities within prescribed limits by adjusting the active (MW) and reactive (MVAr) power transmissions. The power transmission system is employed as a realistic power system model at 400 kV high voltage level. The load flow study of the modeled power transmission network was conducted utilizing the Dig-SILENT Power Factory program. The control of the voltage fluctuations of the modeled grid system was achieved with the aid of SVC/STATCOM devices, and the results were compared with those of the existing grid system. The employment of FACTS technology, such as STATCOM controllers, has been demonstrated to enhance the control of power systems and improve their reliability against voltage collapse [8]. Transmission providers have sought to identify local control mechanisms to address various potential issues throughout the system, including transient and dynamic disturbances, sub-synchronous oscillations, overvoltage, and overvoltage drop. A plethora of FACTS topologies have been proposed to mitigate these potential issues; however, transmission service providers often hesitate to install them due to cost and a lack of systematic control. Nevertheless, the integration of energy storage systems (ESS) and FACTS devices has the potential to result in a transmission controller that is more economical and/or flexible. Although the combination of FACTS/ESS has been proposed in theory, great emphasis has been placed on the development of control strategies for various FACTS devices, including the STATCOM static synchronous serial compensator (SSSC) and the combined power flow controller (UPFC) [9,10]. In this paper, an integrated STATCOM/BESS for dynamic and transient oscillations in energy transmission system was presented. The experimental validation of the performance of FACTS/BESS combinations was enabled. The study concluded with the presentation of some conclusions on application case studies related to load/generation output power and intermittent generation sources/contingency locations to assess their impact in power systems. The objective is to ascertain the functionality of energy storage in conjunction with the prevailing STATCOM simulation model and to determine its capacity to meet stipulated requirements.

## 1. METHODS AND MODELS

The primary challenge that must be addressed during grid operation is ensuring system stability, that is, maintaining system voltage and frequency within the permissible limits. A promising method of overcoming these challenges is to make use of BESS, which provides frequency support by injecting instantaneous power into the grid and back up traditional generation systems. The power system employed in this study, designated as the IEEE 9 bus, 3 synchronous generator (SG) system, has been realized in DigSILENT/PowerFactory. The study's generators were all equipped with a stimulator, and the G1 was adopted as a reference machine. To investigate the impact of different failure strategies, a simulation model including BESS and STATCOM was developed.

### 1.1. Battery Energy Storage System Technologies

BESS is comprised of three key components: storage batteries, a transducer, and a control system. The function of the batteries is to store and release energy. However, it should be noted that the power, capacity, and varying and discharging characteristics of different batteries can vary, meaning that the actual charging and discharging power and response speed may differ. The fundamental configuration of a BESS comprises a battery bank, a bidirectional DC/AC converter, and a grid-connected transformer (Figure 1). The BESS control comprises five distinct control sections: a voltage controller, a frequency controller, a charger controller, a PQ controller, an electric power converter model (inverter/rectifier), and a set of controllers. The overall function of this system is to store or return energy to the grid through the process of electrochemical conversion.

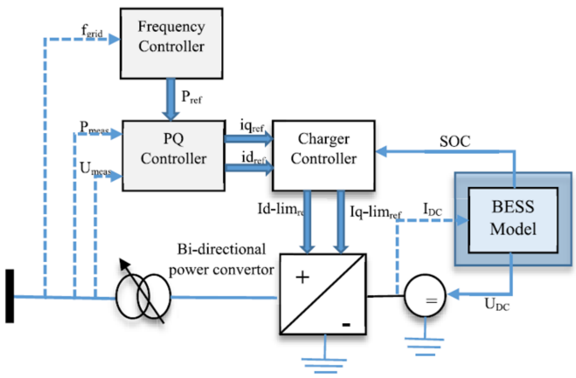


Figure 1: Block diagram of BESS structure

The overall structure of the BESS model can be seen in Figure 2. It mainly comprises a power regulating section reflecting the normal condition, a fault ride-through control and protection section reflecting abnormal conditions, and a grid-connected current computing section. The electromechanical transient model and the long-term dynamic model both follow this structure, differ only in the restrictive measures taken for power regulation.

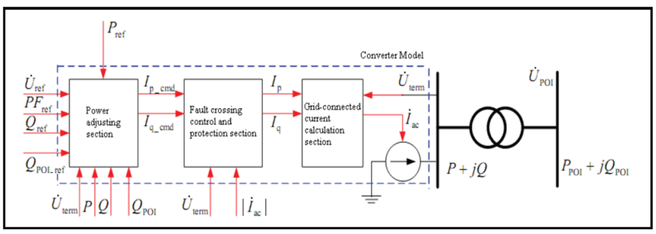


Figure 2: The BESS model structure

ISSN:2566-3143, eISSN:2566-3151, DOI: 10.2478/bhee-2026-0013

### 1.2. Voltage Controller

Reactive power can be regulated in a variety of ways, including constant voltage control, constant reactive power control, constant power factor control and constant incoming line reactive power control, which depends on the control strategy adopted by the actual system. The voltage controller is activated when the mains voltage ($d_v$) differs from the nominal value according to the expression in equation (1).

$$d_v = V_{ref} - V_{bus} \tag{1}$$

$$Q_{BESS} = \pm d_v / droop_R \tag{2}$$

BESS $d_v$ if it is negative, it absorbs the reactive power, and $d_v$ If it is positive, it provides reactive power. According $droop_R$ to the expression in Eq. (2) in response to a certain amount of voltage deviation from the rated value, the battery determines the limits of full reactive power activation.

### 1.3. STATCOM Modeling

The configuration of STATCOM comprises an energy storage device, which is connected to the power system using a VSC [11]. The VSC is a sophisticated electronic transducer, comprising isolated gate bipolar transistors (IGBTs) or integrated gate commutation thyristors (IGCTs) [12]. A salient feature of VSCs is their capacity to generate AC voltages independently of a grid system. The principle of self-commutation enables the converter switch to be activated by applying a control signal to the switch's door when the collector-emitter voltage is positive. The removal of the control signal results in the deactivation of the switch [13]. A rudimentary depiction of a grid-connected STATCOM is provided in Figure 3. In addition to VSCs, STATCOM comprises a DC-link capacitor, a smoothing reactor and a transformer. It is imperative to note that, to ensure the effective functioning of the device, the implementation of a controller is essential to regulate the VSC switches. The controller receives voltage measurement information via a power transformer (PT)

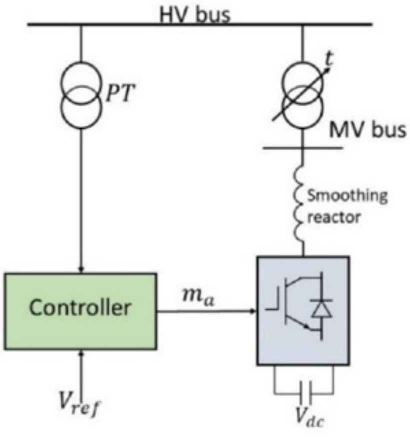


Figure 3: Basic STATCOM representation

and calculates a control error based on measurements and reference voltage ($V_{ref}$. Depending on the control error, a modulator may connect a switching pattern $m_a$ to the VSC. Banner.

Busbar voltage $V_1$ and VSC voltage $V_2$ It can be shown that the power output of VSC can be expressed as follows:

$$P = \frac{V_1 V_2}{X} \sin\delta \tag{3}$$

$$Q = \frac{V_1 (V_2 \cos\delta - V_1)}{X} \tag{4}$$

where $V_2$ is the VSC voltage, $\delta$ is the angle of the voltage and $X$ depicts the inductor reactance.

A STATCOM operation is based on the voltage difference between the compensator and the common junction. If the phase shift between the busbar voltage and the VSC voltage is zero, the VSC will act as a fully reactive element. The phase shift angle can determine the direction of the active power, while the magnitude of the voltage determines the direction of the reactive power flow. VSC, $V_2$ $V_1$> will have a capacitive character and function as a reactive power generator. $V_1$ $V_2$>, the VSC will have an inductive character and act as a reactive power absorber. Because the main purpose of STATCOM is to control reactive power, not active power. The interconnected DigSILENT frame model is shown in Figure 4. By controlling the DC voltage, we can indirectly control the active power ($P_s=V_{AC}$ $\dot{I}_{AC}=V_{DC}$ $\dot{I}_{DC}$). The voltage of the STATCOM measured from the DC bus is subtracted from the DC reference voltage. The error signal passes through the PI controller and module limiter, which outputs i(dref). Similarly, AC voltage is measured from the point at which the STATCOM is connected to the grid. Then the error between the reference and the measured AC voltage passes through the PI controller to give i($q_{ref}$). These signals are used in the internal current control loop of the transducer within the VSC model to form the PWM signals $P_{md}$ and $P_{mq}$. However, active power can also be controlled with larger energy storage. During normal operation, the angle ($\delta$) of the voltage is kept slightly larger than zero so that there is a small flow of active power to the STATCOM so that it can compensate for the losses in the VSC. The primary function of STATCOM and BESS is to ensure the consistent performance of the system in accordance with the predefined or user-defined protocol. The control target is voltage control, power flow control for oscillation damping, or temporary stability improvement. A control scheme for active and reactive power flow control has been implemented in the STATCOM and BESS system. The simplified model provides insight into the behavior of voltage and current in an ideal scenario, thereby facilitating approximate sizing and cost estimation. The simulation model utilizes a voltage source transducer to generate active and reactive power for the network. The injection or absorption of active power and the energy storage voltage are the variables upon which the model is based.

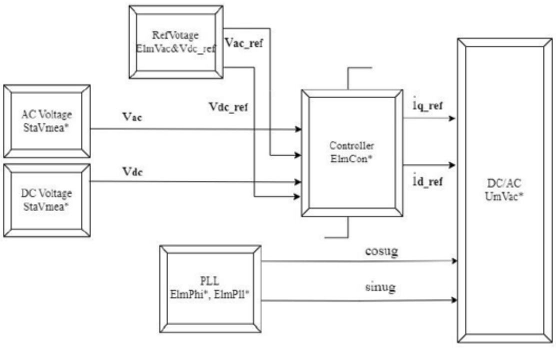


Figure 4: STATCOM frame DigSILENT model

The injection of a current into the energy storage can then be calculated, thus affecting the internal voltage of the storage. The model's control structure involves the cascading of reactive and active power, a voltage controller, and current controllers.

## 2. RESULTS AND DISCUSSION

### 2.1. System Modeling

The integration of a BESS and a STATCOM with a transmission grid network has been demonstrated to reduce voltage deviation, thereby enhancing the renewable energy integration of power system stability. However, it is important to note that integrating STATCOM and BESS units with optimal power factors may, in some cases, result in increased energy loss and voltage instability. The ability of BESS and STATCOM to regulate both active and reactive power is well-documented, and this can be achieved by improving the voltage profile of a grid. The proposed methodology is illustrated using the IEEE 9-Bus power system model. This system offers a simplified depiction of a high-voltage transmission network. The model incorporates three synchronous generators, with a total system capacity of 374.5 MW of Nominal Active Power and 368.8 MW of Load Active Power. To align with the research MW targets, some changes have been made to the generation resources in the test system, with wind farms being added to produce about 20% of the overall system production, which restates the production uncertainty (Appendix A). The study also examined energy management, operation control methods and application scenes of large-scale BESS and STATCOM equipment. The western Mediterranean region of the Türkiye interconnected grid is characterized by a significant supply of renewable energy. The selection of the IEEE 9-Bus power system model is predicated on its demonstrated similarity to the aforementioned model, in addition to its inherent ease of analysis.

Following the installation of the BESS, the bus voltage values within the system are displayed in p.u. as illustrated in Figure 5d. It is important to note that bus voltages 1, 2 and 3 remain unchanged since this bus is the generator bus. Following the connection of BESS and STATCOM to the system, alterations to other bus voltages are observed. It is evident that Bus-9 has been identified as the optimal solution for both BESS and STATCOM. The total duration of the simulation is 40 seconds. The ensuing section will present the simulation results.

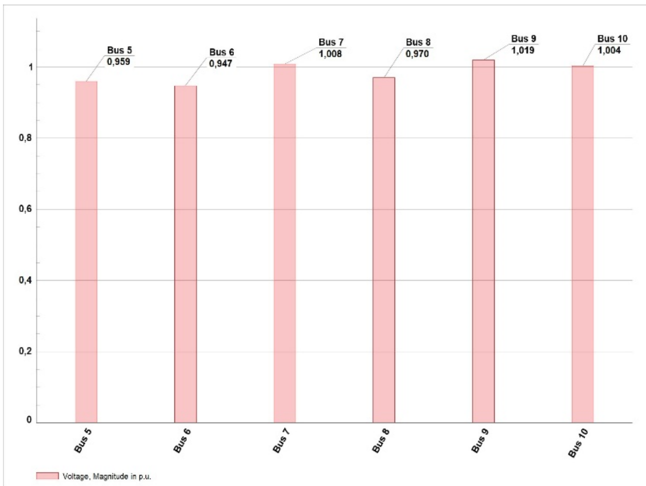


Figure 5 (a): STATCOM/BESS disconnected state bus voltage values

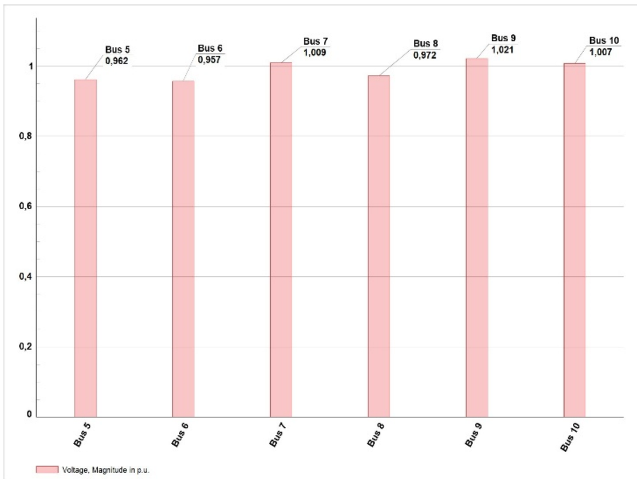


Figure 5 (b): BESS only connected state bus voltage values

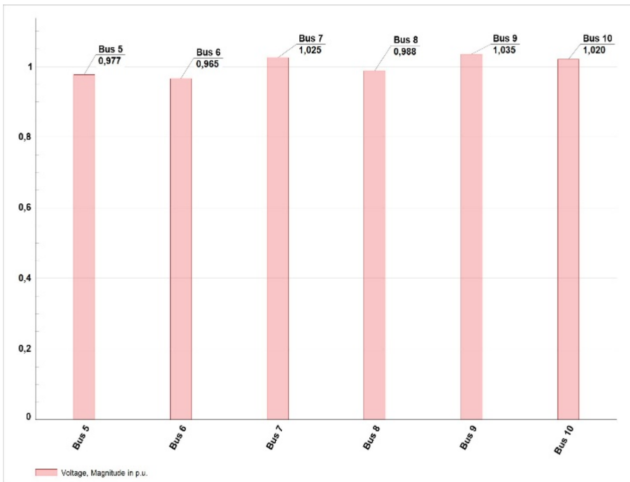


Figure 5 (c): STATCOM only connected state bus voltage values

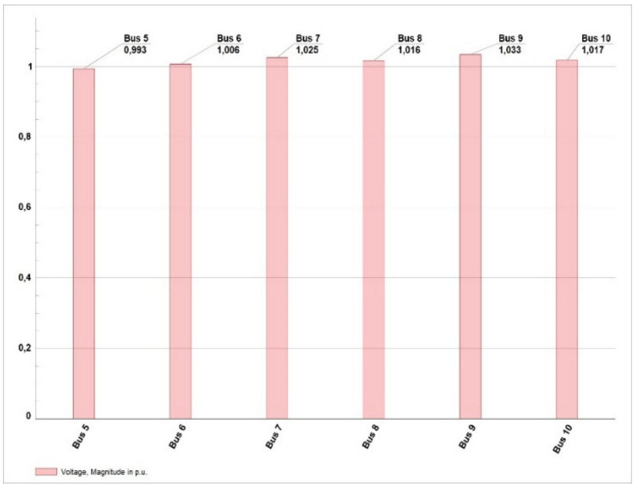


Figure 5 (d): STATCOM/BESS connected state bus voltage values

## 2.2. Case Studies

The independent control of both active and reactive power of the STATCOM/BESS system renders it an optimal candidate for numerous power system applications. The potential applications of STATCOM/BESS encompass voltage and transmission capacity control, frequency regulation, oscillation damping, and enhancement of dynamic stability. The specific requirements for such a system can vary depending on the size and placement of the STATCOM/BESS within the power system. This section will present two such applications: voltage control and oscillation damping. Power transmission line outage is a prevalent challenge in power system operations, often resulting from fallen trees or overvoltage events (lightning strikes). At the 5th second, line-5, that is, one of the parallel transmission lines between busbars 6-9, opens. This results in a system-wide reduction in voltage, leading to a low-frequency inter-field power oscillation between the two fields. The interfiled oscillation manifests as a damp mode. In the event of a system fault, voltage fluctuations are typically observed at the busbar and transmission line exhibiting the least capacity to maintain voltage stability (the reactive power support, Figure 6a-6b).

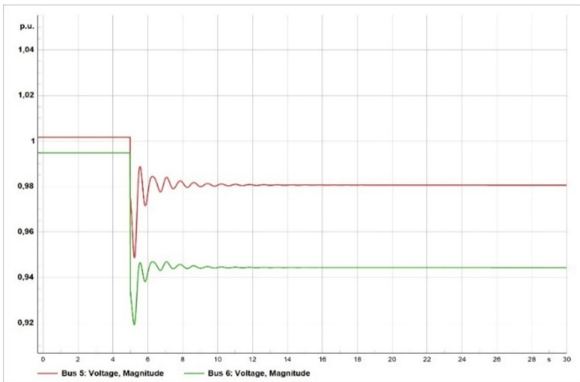


Figure 6 (a): Busbar voltage oscillations after line-5 3-phase short circuit failure to the bus that occurs while STATCOM/BESS is external to service in a steady-state operating state

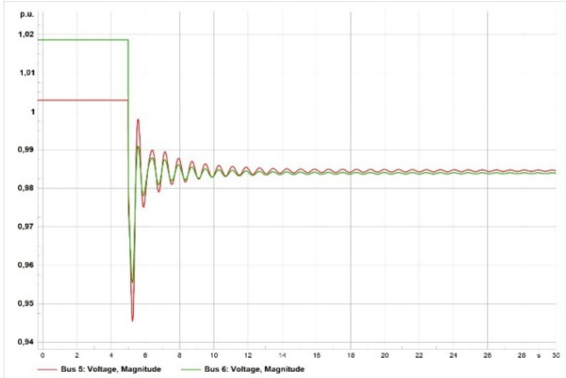


Figure 6 (b): Busbar voltage oscillations after line-5 3-phase short circuit failure to the bus that occurs while STATCOM/BESS is connected in a steady-state operating state

Voltage responses for all situations under local and remote faults are shown in figures 6a and 6b, starting at 5 seconds and lasting 30 seconds. During a local three-phase short-circuit event occurring line-5, the System underlines the voltage response improvement at busbar-5 and busbar-6. It is evident that STATCOM/BESS grid-tied states in the optimal position exhibit reduced voltage fluctuations under both local and remote faults compared to ground cases devoid of BESS installation. The necessity for STATCOM to be incorporated into most grid-connected generator units has been demonstrated. The incorporation of reactive current and voltage characteristics into most grids is intended to facilitate the injection of a specified level of reactive current during instances of severe voltage decline, such as mains failures. In this example, the STATCOM/BESS response to a three-phase grid fault was tested. The results of the simulation are shown in figures 7a-7b. The fault is applied at the 5th sec, which leads to a voltage drop to 0.96 pu. At the time of the failure initiation, the BESS was providing 30 MW of fully rated active power. Subsequent to the fault occurrence, the controller initiated the fault pass mode, prompting the STATCOM to inject the maximum allowable reactive current (1.1 pu with 10% overcurrent) into the grid. The function of the limiter is to restrict the active current, thereby ensuring that the total injected current does not exceed the maximum overcurrent capacity of the power converter.

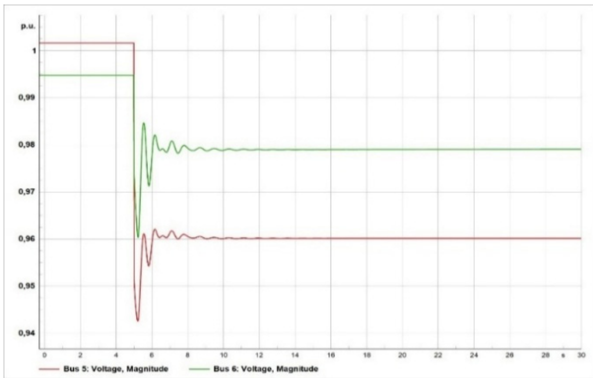


Figure 7 (a): Busbar voltage oscillations after line-2 3-phase short circuit failure to the bus that occurs while STATCOM/BESS is external to service in a steady-state operating state

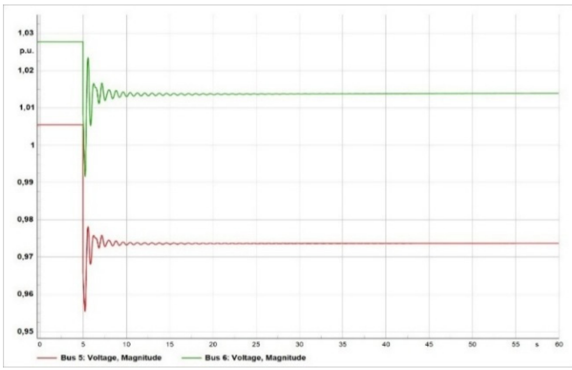


Figure 7 (b): Busbar voltage oscillations after line-2 3-phase short circuit failure to the bus that occurs while STATCOM/BESS is connected in a steady-state operating state

Optimal STATCOM/BESS allocation was observed to result in a decrease in bara-5 from 1.02 p.u. to 0.96 p.u. and busbar-6 from 0.99 p.u. to 0.92 p.u. in figure-6a, Case 1 for the power system. Similarly, for the power system, in figure-7a, Case 2, the busbar-5 decreased from 1.02 p.u. to 0.94 p.u. Furthermore, in all test cases, bus-6 exhibited a voltage response waveform with a similar, but smaller amplitude attributed to the larger system power. Moreover, as demonstrated in figures 6a to 7a, when comparing the voltage responses to remote and local faults, it is evident that the impact of a remote fault in Bus-6 on Bus-5 is less severe than a local fault of the same severity level in Bus-6. The technique proposed by the current study has been shown to provide similar voltage stability improvements with much smaller total BESS installation capacities. During a transient manufacturing fault in the system, the inertial ability to support system damping is provided by other generators. The permanent shutdown of unit G2 on Bus 2 results in an enhancement of system inertia, accompanied by the elimination of system oscillation G2. As illustrated in figure-8, the oscillations in active power during the manufacturing defect are evident. The active power output (power reference and power output) curve of the BESS is given. It is evident from the figure that, with a BESS power of 30 MW, the range of power oscillations remains within the prescribed limits, a consequence of the integration of the battery storage system. As demonstrated in figure-8, when the total output of gas energy reaches 50 MW, the active power oscillates below the nominal value. However, with the incorporation of BESS, the power release remains within the operational limit. This outcome demonstrates the efficacy of BESS in maintaining power oscillations within acceptable limits. It is noteworthy that the grid possesses sufficient capacity to manage the consequences of post-state generator failure; however, this is frequently impractical due to the diminished inertia of the system for a brief duration. This underscores the pressing need for prompt, sensitive alternatives, a need that is met by the BESS. To conduct a more profound analysis of the system voltage response to a variety of events, an additional scenario was examined, with a particular focus on changes to the reactive power stage. This is since system reactive power is of paramount importance in ensuring the maintenance of voltage stability. Specifically, the occurrence of a load incident was simulated on busbar-6, which is the weakest transmission line in the system.

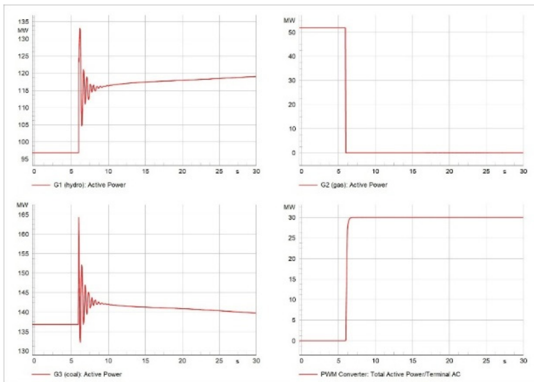


Figure 8: Generator line faults active power at the usage of STATCOM/BESS

The voltage responses at busbar-5 and busbar-6 were investigated when step changes related to reactive power output occurred (Figures 9a, 9b). The occurrence of a load event at the 6-second mark resulted in a decline in reactive power demand to 40 MVAr. This load persisted for a duration of 30 seconds. Figures 9a and 9b demonstrate the enhancement in voltage recovery subsequent to step changes, as facilitated by the proposed approach within the power system. While all situations resulted in a noticeable improvement with optimal STATCOM/BESS allocation, the voltage response in the strong transmission line was found to be more pronounced than in the weakest transmission line. The primary function of STATCOM in enhancing voltage stability was evident in both cases 1 and 2, wherein it exhibited a swift adjustment of reactive power outputs in response to critical reactive power stage changes, thereby facilitating the restoration of system voltage.

The BESS and STATCOM model were developed in DigSilent/PowerFactory, and their system performance was simulated. The model has been subjected to a range of simulations, encompassing scenarios such as single-phase-ground fault, three-phase fault, generator and load event, in addition to various transient fault interruption

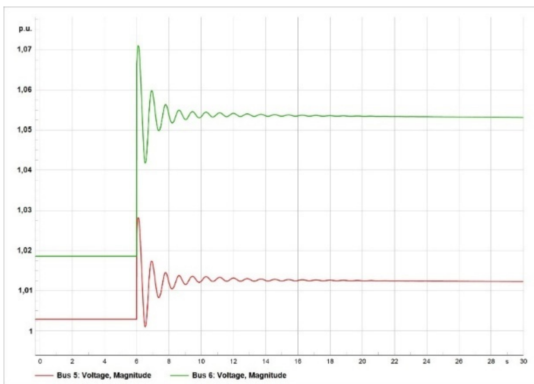


Figure 9 (a): load faults bus voltage at the external to service of STATCOM/BESS

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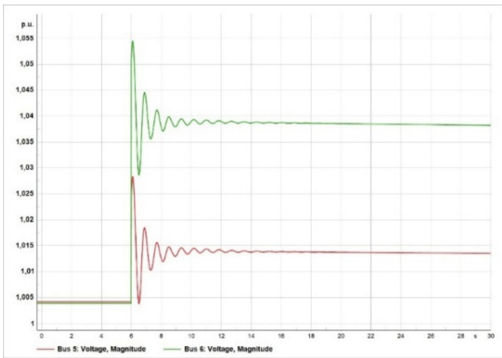


Figure 9 (b): load faults bus voltage at the usage of STATCOM/BESS

and load demand increase scenarios. The simulation results demonstrate that BESS and STATCOM possess the capability to mitigate system oscillations following disturbances and enhance stability within the existing power system. Consequently, BESS and STATCOM can be regarded as the optimal measure for enhancing stability in a sustainable future power grid. The proposed methodology has been shown to achieve superior post-failure recovery performance in comparison to systems that do not incorporate a STATCOM/BESS installation, as evidenced by a comparison of system responses to different types of events, including voltage control, oscillation damping failures, and reactive power stage changes.

## 3. CONCLUSION

Energy storage is poised to emerge as a pivotal component of a future electricity grid characterized by low carbon emissions and enhanced resilience. The present study examined the impact of progress in energy storage technology, the deployment of utility-scale storage, and the adoption of distributed storage, as well as on future power system infrastructure investment and operations. The study's findings have provided valuable insights, contributing to the formulation of a forward-looking vision for the field of energy storage. The provision of data and analysis was undertaken to accelerate the development, commercialization and utilization of next-generation energy storage technologies, with the aim of supporting the Turkish interconnected system in energy storage. The research proposes a novel and effective STATCOM/BESS allocation methodology, with the aim of increasing system reliability and enhancing transient voltage responses in weak networks with high renewable penetration. The validity of the proposed technique has been substantiated in a modified IEEE 9 bus system model constructed in the DigSilent PowerFactory software. The simulation results demonstrate that, in terms of maintaining system reliability, STATCOM/BESS exhibits a significant performance advantage over existing solutions in enhancing voltage and frequency stability under weak grid conditions. Future research will investigate the economic, ageing, and power ability of STATCOM/BESS to achieve maximum utility. The development of optimal operating techniques for BESS and STATCOM is expected to enhance system reliability and stability in poor grid conditions.

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