Battery Energy Storage System to Improve Power Export Capability and Stabilize Transient Voltage and Frequency

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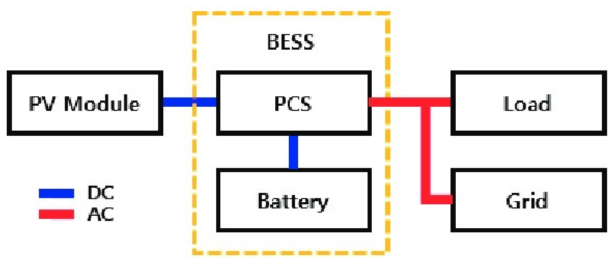
Abstract- **Over the last decade, there has been a substantial increase in the integration of renewable energy sources like wind and solar power into the electricity grid. However, the intermittent nature of these sources presents challenges for grid stability, especially in handling transient voltage and frequency fluctuations. This paper suggests a solution for tackling these challenges by leveraging Battery Energy Storage Systems (BESS). The primary objective is to enhance power export capability from renewable sources while simultaneously stabilizing transient voltage and frequency. The proposed BESS control strategy involves real-time monitoring of grid conditions, predictive analysis of renewable energy generation, and dynamic adjustment of battery charge/discharge rates. The efficiency of the suggested strategy in enhancing grid stability and power export capability has been shown through simulation studies and field tests. Results indicate significant reductions in voltage and frequency deviations during transient events, leading to enhanced grid reliability and efficiency. Better utilization of renewable energy resources and easier integration into the current grid infrastructure are also made possible by the integration of BESS. This study advances efforts to modernize the grid by offering a workable solution to handle the difficulties involved in integrating renewable energy sources and guaranteeing a reliable and sustainable power source. The simulation results, especially when there is a 44% increase in power export and the STATCOM fails, show that the addition of BESS enhances system performance and validates the novelty of this study. Furthermore, in the event of diverging temporary and permanent defects, the suggested lead-lag controlled BESS exhibits better transient performance than BESS with PI-lead and conventional PI controller.**

***Key Words*: STATCOM, PI lead controller, Battery energy storage system, lead-lag controller, power export, frequency stability and voltage stability.**

I. INTRODUCTION

Due to rising energy consumption and the growing use of renewable energy resources (RES), the current power transmission system is experiencing a number of control and stability problems. Traditional power system, which are vertically integrated, present a difficult and complex structural transformation task. Power systems are inherently sensitive to various dynamic and transient disturbances, both small and large scale. Power system performance, stability, and operation have attracted a lot of attention due to the expanding scale and complexity of the infrastructure supporting the electric grid. Unexpected power exchanges within the network have the potential to overload certain transmission network lines.



This could lead to system instability in the event of a network failure, especially with deregulated electrical markets and electricity price structures. The power grid may experience disruptions that cause low or high-frequency oscillations, whether they are temporary or permanent. Devices known as Flexible AC Transmission System (FACTS) have been developed to increase the transient stability of the system. Among these are devices that control power flows and boost transmission system capacity; of special note is the static synchronous compensator, or STATCOM. Through reactive power compensation, better inter-area oscillation, voltage regulation, and faster and smoother voltage recovery, STATCOM improves power transfer capabilities and transient stability. Furthermore, STATCOM outperforms conventional FACTS devices in many situations when it comes to reducing power system oscillations and boosting power transmission capacity. When it comes to electrical grids, all kinds of disturbance events—whether transient or ongoing—produce oscillations at different frequencies. By regulating power flows and increasing the transmission system's power transfer capacity, devices referred to as Flexible AC Transmission Systems (FACTS) have played a significant role in enhancing the transient stability of power systems (including both low- and high-order oscillations). Static synchronous compensators (STATCOM), a particular kind of FACTS device, are the subject of this study. By controlling voltage, reducing inter-area oscillation, and providing quicker and more seamless voltage recovery through reactive power compensation, STATCOMs improve power transfer capabilities and transient stability. Furthermore, STATCOMs have been proven to outperform alternative FACTS devices in many cases when it comes to reducing power system oscillations and boosting power transmission capacity.

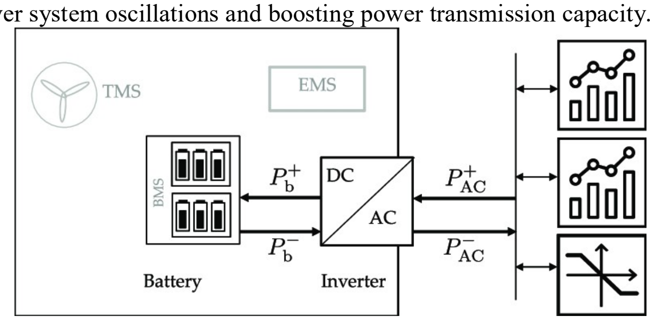


Fig1.Single Phase Full Bridge Inverter

The Battery Energy Storage System (BESS) performs distinct functions in the power system from STATCOM. These include controlling frequency, reducing oscillations in electromechanical power, improving transient stability, balancing the active power output in Renewable Energy Source (RES) farms, and providing assistance with voltage and power quality. Many times, a super-capacitor or battery-equipped STATCOM performs better than a stand-alone STATCOM, particularly in systems that are integrated with renewable energy sources (RES). In particular, the impact of the Battery Energy Storage System (BESS) in improving transient stability and reducing power oscillations has been thoroughly investigated.

Many research works have been done on controlling voltage and frequency to improve the damping capacity of the power system. Prior studies have demonstrated that the combination of a BESS with a STATCOM can improve power, frequency, or voltage damping. Nevertheless, the state of charge (SOC) of the battery was either ignored in these studies or was taken to be a constant value, which is not the case in a real power system. Furthermore, the BESS is solely controlled by the conventional Proportional-Integral (PI) controller, and because deadband is not included in the design, the suggested BESS control is vulnerable to rapid charging and discharging. Studies have been done on a BESS for controlling voltage or frequency, but not both at the same time, in an isolated power system that is prioritized by active or reactive power. In order to lessen inter-area oscillations, a STATCOM with a BESS has been proposed for a large-scale power system. The BESS would be utilized as an active or reactive power stabilizer.

(A. Chakraborty, S. K. Musunuri, A. K. Srivastava, and A. K. Kondabathini). The literature analysis pointed up a number of advantages of including BESS for transient voltage and frequency stabilization as well as enhancing power export capabilities. Enhanced grid resilience, decreased curtailment, greater grid stability, and better utilization of renewable energy are some of these advantages. For BESS integration to be successful, a number of obstacles must be overcome, including high upfront expenditures, a small amount of energy storage capacity, and technical problems with battery degradation and system control. Benefits from integrating BESS include better usage of renewable energy, lower curtailment, more grid resilience, and greater grid stability. For implementation to be successful, though, obstacles including high upfront prices, a small amount of energy storage capacity, and technical problems with battery deterioration and system control must be resolved.

(K. Karthikeyan and P. Dhal). The literature found a number of control measures for enhancing BESS power export capabilities. They consist of power factor control, reactive power control, and active power control. To maximize the utilization of BESS for power export, more sophisticated control strategies such fuzzy logic control and model predictive control were investigated. Three control strategies—active power control, reactive power control, and power factor control—are used to increase power export capabilities utilizing BESS. To maximize BESS use, cutting-edge methods like fuzzy logic control and model predictive control are also investigated.

(M. Beza and M. Bongiorno). The review of the literature emphasized various control techniques for employing BESS to stabilize transient voltage and frequency. These solutions include voltage regulation, frequency control, and active power modulation. In order to improve the stability of the system during transient occurrences, coordinated control techniques such as virtual inertia control and droop control were researched. Active power modulation, frequency control, and voltage regulation are the three control mechanisms used by BESS for transient voltage and frequency stability. Coordinated strategies to improve system stability during transient occurrences are being researched, such as droop control and virtual inertia control.

II. PROPOSED CONTROLLERS

In order to improve transient stability and facilitate enhanced power transfer between interconnected power systems under various temporary and permanent situations, the analysis compares and evaluates the performance of STATCOM and BESS. BESS is intended to function within the specified SOC working ranges while concurrently regulating voltage and frequency. There are currently no reports of this research in the literature. Additionally, it suggests lead-lag and PI-lead controlled BESS. To the best of the authors' knowledge, BESS's active and reactive power have not yet been controlled by these kinds of controllers to concurrently regulate voltage and frequency. The efficiency of the design in boosting the power system's capacity for power transfer and stabilizing the voltage and frequency of a large-scale real power system is contrasted with that of traditional PI-controlled BESS.

In order to prevent blackouts, the study examines the effects of several nearby disturbance events on the transient stability as well as the effectiveness of modern STATCOM and BESS technologies. Previous power system stability analysis studies have overlooked this factor. Several case studies have been carried out utilizing a comparable 400kV Finnish transmission grid in order to evaluate the efficacy of BESS with the recommended control methods and STATCOM in enhancing transient stability. The outcomes of these comparative performance evaluations are reported.

A battery bank, a bi-directional three-phase DC/AC converter, and a three-phase step-up transformer that

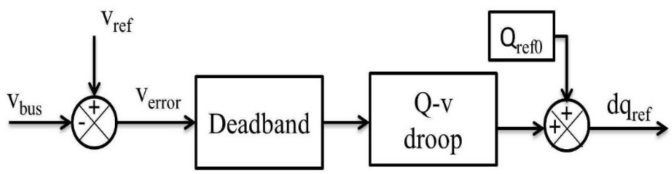


Fig2. Schematic diagram of integrated controllers

incorporates the battery energy storage system (BESS) are the components of the BESS. We explore the BESS's extensive control methods and modelling in this part. Notably, the battery capacity limits active power support for frequency control, while the PWM converter capacity constrains reactive power support. Through the manipulation of two distinct current parameters along the d and q axes within the converter capacity, BESS demonstrates the ability to independently regulate both voltage and frequency. The six main portions of the fundamental BESS controller design are voltage controller, frequency controller, PQ power controller, d and q axis current controller and charge controller.

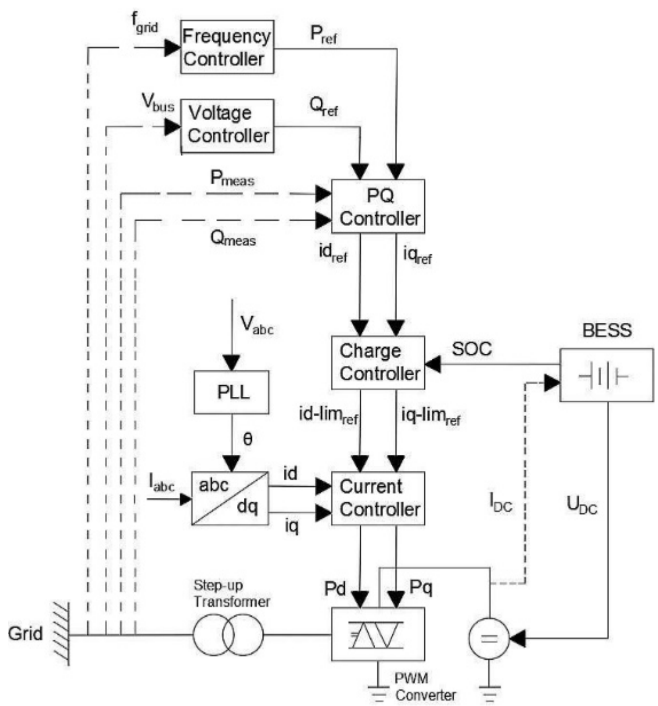


Fig3. Voltage controller with deadband

Voltage controller:

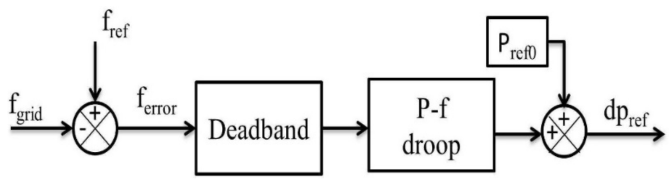
The Voltage Controller Figure 3 generates a reference signal for reactive power control by measuring the difference between the nominal reference voltage and the actual bus voltage. The reactive current direction is modified in relation to both positive and negative values of V_{error} by this control mechanism, which functions in accordance with the droop value. Local voltage and frequency measurements are used as input signals at the BESS connection point (central-north bus) to generate and regulate BESS active and reactive power.

Frequency controller:

When the frequency error between the grid and the nominal frequency is more than the deadband limit according to the droop setting, the frequency controller, as shown in Figure 3.2, creates a reference for active power control. When the droop setting is exceeded, the frequency controller, as shown in Figure 3.3, uses the frequency error between the grid and the nominal frequency to produce a reference for active power control. As long as there is sufficient battery capacity available, positive and negative error values (ferror) control the active power supply (when discharging) and consumption (while charging).

III. FUNCTION or OPERATION

The *PQ controller* produces the control signal when it is triggered by the voltage and frequency controller. The voltage and Q controller manage the start of the reactive power signal, while the frequency and P controller are in charge of producing the active power control signal. The charge controller's "Δi_d" signal is integrated and utilized as an input by the PI/PI-lead/lead-lag controller to produce the active power reference



signal.

Fig4. Anti windup PI controller

Similar to this, the reactive power reference signal is created for reactive power control by adding the "Δi_q" signal to the PI/PI-lead/lead-lag controller's input.

Anti-Windup PI Controller is used in conjunction with a traditional PI controller to prevent integrator windup, as shown in Figure 5. The following is an expression for the PI controller equation with anti-windup:

$$y_0 = \left[K_p \times y_{error} + \frac{K_i}{T_i} \int_{y_{min}}^{y_{max}} y_{error} \; dt \right]_{y_{min}}^{y_{max}}$$

where,

$y_o = i_{d-ref} = i_{q-ref}$ at PQ controller output,

$y_{max} = i_{d-max} = i_{q-max}$ and $y_{min} = i_{d-min} = i_{q-min}$ for d and q axis.

The non-stationary characteristics of the power supply can cause PI controllers to fail in their attempt to improve stability. In order to decrease steady-state error and improve system stability while ac

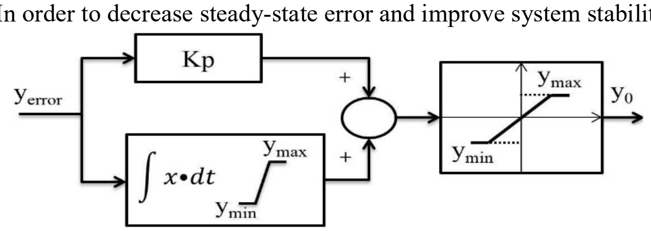


Fig5. Anti windup PI limiter

celerating the transient response, this controller combines the features of lead and lag controllers. This significantly lessens each controller's unique limitations. for a thorough comprehension of the working principles of the lead-lag controller. To keep the output power reference within a predetermined range, a limiter is used. Appendix A has a full description of the lead-lag controller's unique parameters.

Through trial and error, the locations of poles and zeros are determined. The proposed lead-lag controller's d-axis transfer function is shown as follows:

$$K_1(s) = \frac{T_{z1}(s + 1/T_{z1})}{T_{p1}(s + 1/T_{p1})} \frac{T_{z2}(s + 1/T_{z2})}{T_{p2}(s + 1/T_{p2})}$$

where DC gain = 1. Tz1 > Tp1 (lead) and Tp2 > Tz2 (lag).

The transfer function of the proposed lead-lag controller for the q-axis is outlined as:

$$K_2(s) = \frac{T_{z3}(s + 1/T_{z3})}{T_{p3}(s + 1/T_{p3})} \frac{T_{z4}(s + 1/T_{z4})}{T_{p4}(s + 1/T_{p4})}$$

The configurations for the poles and zeros of the lead-lag controller, tailored for both the d-axis and q-axis, are specified below:

$$K_1(s) = K_1(s) = \frac{8\,(s + 1)(s + 0.25)}{(s + 2)(s + 0.067)}$$

with Tz3>Tp3 (lead) and Tp4>Tz4 (lag).

Charge controller: The State of Charge (SOC) levels control the active power input from the Battery Energy Storage System (BESS). As a result, the following predetermined criteria are used to determine the current reference for the d-axis:

$$\mathrm{i}_{d-in} = \begin{cases} \mathrm{i}_{d-ref} & SOC_{min} \le SOC \le SOC_{max} \\ 0 & \text{otherwise} \end{cases}$$

The peak absolute current, which is dependent upon the reference currents for the d and q axis, is shown in the second section Figure 6. The difference between "$\mathrm{i}_{d\text{-}ref}$" and "$\mathrm{i}_{d\text{-}ref\text{-}out}$" from the charge controller, denoted as "$\Delta \mathrm{i}_d$," is integrated into the PQ controller's active power reference, as illustrated in the charge controller schematic in Figure 3.6. Similarly, the PQ controller's reactive power reference incorporates the "$\Delta \mathrm{i}_q$" variance—that is, the difference between "$\mathrm{i}_{q\text{-}ref}$" and "$\mathrm{i}_{q\text{-}ref\text{-}out}$"—from the charge controller.

Fig6. Charge controller

The converter's capacity limits the Battery Energy Storage System's (BESS) perceived power. To avoid overloading, the total current over the d- and q-axes must therefore equal the nominal value of the converter. As such, the total current needs to match the unit's maximum absolute value (max Value) of 1. The following describes how to coordinate the current between the d- and q-axes:

$$\mathrm{i}_{d-ref-out} = \int_{-|max\ Value|}^{|max\ Value|} \mathrm{i}_{d-in}\, dt$$

$$\mathrm{i}_{d-ref-out} = \int_{-y_{value}}^{y_{value}} \mathrm{i}_{d-in}\, dt$$

where,

$$y_{value} = \sqrt{\left| \int_{0}^{|max\ Value|^2} |max\ Value|^2 - (\mathrm{i}_{d-in})^2 \right|}$$

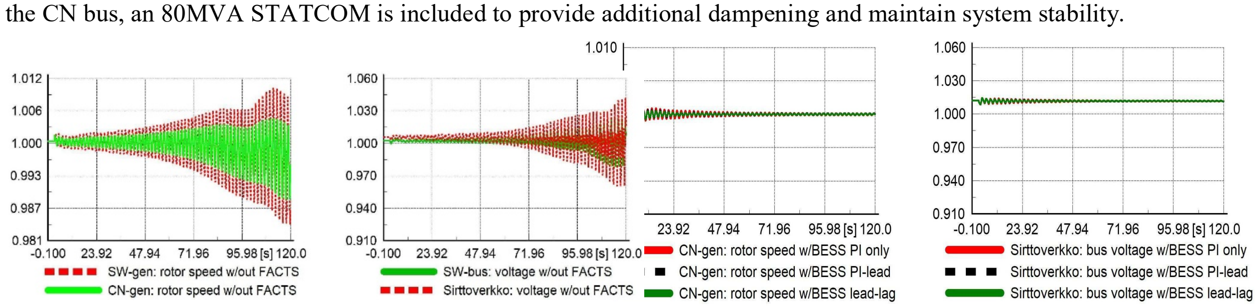
Battery used in this study is represented by an electrical equivalent circuit model, which will be covered in more detail in the next appendix. According to this paradigm, the battery functions as both an internal resistance and a direct current (DC) voltage source, with the battery's current determining its State of Charge (SOC).

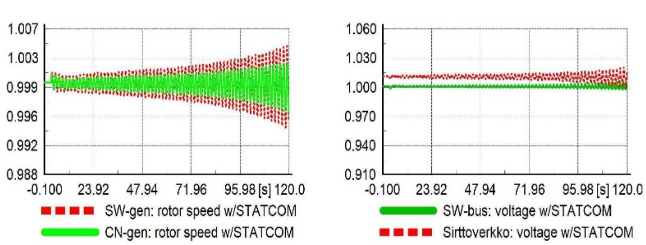
SIMULATION AND RESULTS:

In order to provide the system additional damping and reduce instability phenomena that arise during higher order power exchange and unintentional disturbance events, the STATCOM and BESS are integrated at the CN bus. Through an iterative process, the placement of STATCOM/BESS is chosen based on overall satisfactory performance for each and every case study.

The frequency of generators [p.u.] and voltages [p.u.] at bus and PCC without STATCOM/BESS support.

The capacity of STATCOM to improve power transfer in power systems has been demonstrated. At the CN bus, an 80MVA STATCOM is included to provide additional dampening and maintain system stability.





The relative PCC voltage and generator frequency with integrated STATCOM is shown. It is noted that STATCOM falls short in stabilizing system reactions and offering adequate dampening to the system. As noted in NEM rules, the system's post-failure output responses are oscillatory and never settle inside the designated stability recovery band. A sizable STATCOM is selected comparatively to offer system dampening. It has been noted, nonetheless, that STATCOM's massive scale is still unable to stabilize the post-failure system responses.

STATCOM provides 80MVAR of reactive power and zero active power. Consequently, it is clear that the failure of STATCOM during system stabilization is caused by the lack of active power. Therefore, when there is a disturbance affecting voltage and frequency, a STATCOM cannot improve network power export capabilities. To provide enough systems damping and stabilize system voltage and frequency, active and reactive power provision is therefore necessary.

System voltage stability is greatly increased via series correction. Two connecting lines between the two systems are compensated using series compensation, per the network's fundamental design. A permanent line outage on the N-Sirtoverkko line is implemented at t = 3.1s in order to assess BESS capability without series compensation between these two lines. The system responses displayed in Fig. 25 demonstrate how BESS efficiently reduces accelerating oscillations and stabilizes the system voltage and frequency in accordance with NEM stability criteria even in the absence of series compensations installed between the two interconnected systems.

The suggested PI-lead and lead-lag controlled BESS has a smaller SSE value than the traditional PI controlled BESS, indicating higher performance of the proposed controllers, according to the SSE calculation of voltage and frequency for Cases I, II, and V in Table I. Other case studies show that the suggested controller performs similarly. Furthermore, BESS with lead-lag control performs better than BESS with any other controller.

IV. CONCLUSION

In conclusion, the implementation of a battery energy storage system (BESS) using ETAP to stabilize transient voltage and frequency and improve power export capability offers numerous benefits. It enhances voltage and frequency stability, improves power export capability, increases grid resilience, facilitates renewable energy integration, provides cost savings, and allows for future scalability. These outcomes contribute to a more reliable, efficient, and sustainable power system operation. Stabilizing transient voltage and frequency is crucial for improving power export capability. Transient voltage and frequency fluctuations can negatively impact the stability and reliability of power systems, especially in situations where power is being exported. By addressing these issues, power exporting capabilities can be enhanced, leading to more efficient and reliable electricity transmission.

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