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Battery Energy Storage for Renewable Energy Integrated Power System Stability Enhancement

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Abstract- With growing environmental concerns and sustainability movements, renewable energy source (RES) penetration is increasing and expected to have a steady growth in the coming years. Power systems have encountered several inherent technical challenges, resulting from either low inertia contribution by the increased RES or the displacement of fossil fuel generation systems within the network. The decreased system inertia and the decline in power reserve capacity are affecting the dynamic and transient stability performance of the power system adversely and this adverse impact will continue to increase due to further RES penetration in electric power systems. In this context, this thesis contributes new knowledge to the modeling of droop-controlled BESS for enhancing damping capability and transient stability of large- scale power networks with different level of RES penetration. The BESS with conventional Proportional Integral (PI), and two new PI-lead and lead-lag controlled BESS with coordinated charge control are given wider attention. In the initial stage, a wind farm is designed to perform frequency control in a micro grid. A sectional droop gain method is adopted for regulating doubly fed induction generation (DFIG) power output. It is observed that the proposed multi-gain droop control method demonstrates superior performance than the conventional approach. However, DFIG has a certain limit of providing under-frequency support as a result of inherent incapability of regulating incoming wind speed.

Keywords- Renewable Energy Source, Conventional, doubly fed induction generation, micro grid.

I. INTRODUCTION

Continual growth in energy demand and intensified sustainability concern of fossil fuel-based electricity generation has thrust the escalation of renewable energy sources (RES), mainly photovoltaic (PV) and wind energy penetration, into the existing power system. The government policy, social movement, advancement in renewable energy technologies, present-day installation scenarios, academic and industry research portfolios are indicating the focus on an emission free future electricity industry. Due to such resolutions, a similar momentum of RES penetration is expected to be maintained in the years to come. Regarding the realm of this work, incorporating the large-scale RES of alternating nature has brought an additional dynamic and transient stability challenges in the existing electric grid.

Scientific Contribution

The key objective of this paper is to design and develop a BESS model with independent active and reactive power control features that are suitable for multiple power system applications.

The competency and performance of BESS are investigated in the context of the capability for dynamic and transient stability enhancement of large-scale power system integrated with different level of RES penetration. To utilize the fast regulation capability of BESS, this project has explored dynamic and transient stability benefits offered by the incorporated BESS in power system under various contingencies for improving power system damping performance and thus enhancing system stability. In this project work, BESS controls are coordinated to regulate system frequency using active power and voltage using reactive power. However, the preferences of active and reactive power are planned depending on their particular application in the power system. In contrast, to design an individual BESS model for separate application with major modification in control techniques, this model reduces adjustment complexity and provides the flexibility to be used in different environment with minimum amendments in it.

In this paper, BESS contributions are addressed in minimizing the adverse impact of RES, improving power system damping and transient stability and thereby facilitating cleaner energy penetration that will benefit industry and community. Furthermore, simultaneous transient voltage and frequency stability support from BESS is considered and this can provide added value over Static Synchronous Compensator (STATCOM) in relation to the voltage and frequency stability.

A sectional droop control method associated with fuzzy logic regulated pitch angle adjustment for real-time frequency regulation in an isolated microgrid (MG) using doubly-fed induction generator (DFIG) type wind turbine. The remarkable outcome is visible for both the conventional PI and fuzzy logic controller regulated pitch angle controls. A comprehensive analysis of the application of BESS in reducing distresses related to the penetration of low/zero inertial wind and PV energy system and supporting better frequency oscillation damping and increasing renewable energy penetration. The new models originating from this research encapsulate the dynamic characteristics of the network.

Considering various application scenarios, BESS modeling ranges from voltage and or frequency feedback control to the active/reactive power controllers. This has led to the selection of feedback signals and the adoption of different control loops to regulate BESS responses to the changes in system dynamics according to BESS capacity and design constraints. An adaptive battery state-of-charge (SOC) recovery strategy for flexible BESS operation according to the network planning without compromising the total battery capacity for network events.

II. LITERATURE REVIEW

Liu et al reviewed the battery energy storage system for grid applications. Renewable and Sustainable Energy Reviews, provides an overview of Battery Energy Storage Systems (BESS) and their grid applications, including power system stability enhancement. The authors reviews the different types of batteries used in BESS, the state-of-the-art BESS technologies, and the challenges and opportunities for integrating BESS into the grid.

Hossain et al focused on the role of BESS in power system stability enhancement. The author provides a comprehensive overview of the different types of power system stability problems and the ways in which BESS can mitigate them. They also review the different control strategies used for BESS integration and the challenges and limitations of BESS.

Palizban et al reviewed the various applications of BESS in power systems, including power system stability enhancement. The authors discuss the benefits and limitations of BESS for different applications, such as peak shaving, frequency regulation and voltage support.

Su et al focused on the role of BESS in renewable energy integration and power system stability control. The authors review the different types of renewable energy sources and their intermittency issues, as well as the ways in which BESS can address these issues. They also review the different control strategies used for BESS integration and the challenges and opportunities for future research. Overall, the literature suggests that BESS can play a critical role in enhancing power system stability in renewable energy integrated systems. However, there are still challenges and limitations that need to be addressed, such as cost, reliability, and safety issues. Further research is needed to optimize the design, sizing and control strategies of BESS for different applications and operating conditions.

Huang et al proposed an optimization method for determining the optimal capacity of BESS for power system stability enhancement. The authors use a stability index based on the Lyapunov exponent to evaluate the power system stability, and then use a genetic algorithm to optimize the BESS capacity. The proposed method is tested on a modified IEEE 39-bus system with renewable energy sources.

Li et proposed an optimal placement and capacity sizing method for BESS in power systems based on improved particle swarm optimization (PSO). The authors consider the voltage stability and transient stability indices as the objective functions, and use the improved PSO algorithm to find the optimal BESS placement and capacity. The proposed method is tested on a modified IEEE 118-bus system with renewable energy sources. Raza et al discussed the role of energy storage systems, including BESS, in improving the grid stability during renewable energy integration. The authors review the different types of energy storage systems, the benefits and challenges of energy storage integration, and the different control strategies for energy storage systems. They also discuss the future prospects and research directions for energy storage systems.

Singh et al provides a comparative analysis of different types of battery energy storage systems for grid applications, including power system stability enhancement. The authors compare the performance, cost and environmental impact of different types of batteries, such as lead-acid, lithium-ion, and flow batteries, and discuss their suitability for different grid applications.

Yang et al proposed a coordinated control strategy for BESS and flexible AC transmission system (FACTS) devices for power system stability enhancement. The authors use a fuzzy logic control approach to coordinate the control actions of BESS and FACTS devices to improve the power system stability under various operating conditions. Wu et al proposed a coordinated control strategy for BESS and wind farm based on cascaded predictive control.

III. CONVENTIONAL FIXED DROOP AND EMULATED INERTIA CONTROL METHOD

Large synchronous generators (SGs) usually take care of the temporary power imbalances and maintain the grid frequency. With the existence of physical inertia of the machine. SGs is able to provide inertia response and followed by primary, secondary and tertiary frequency control as shown in Figure 3.1 depending on their droop settings and available capacity.

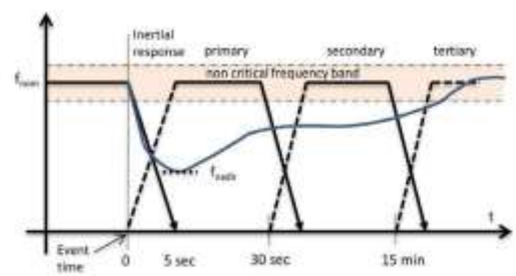


Figure.1. Transmission System Operators for Electricity

(TSO-E) defined Frequency Stages

The advancement in power electronics interface of wind turbine with the grid lets to the modification of the DFIG controller to integrate droop-inertial control loop and regulate DFIG power output accordingly. This provides DFIG to emulate the characteristics of a SG and contribute in frequency regulation. In order to regulate grid frequency, DFIG power needs to be adjusted and this is known as reloading.

IV. THE PROPOSED MULTI-GAIN DROOP CONTROL METHOD

A large droop gain will result in higher contribution from DFIG output in frequency regulation but this can cause higher oscillation, especially near the edge of dead band regions i.e., low-frequency oscillations. Therefore, this chapter provides a new control method that addresses this problem. The proposed sectional droop intended to regulate DFIG power output in accordance with the changes in frequency while adjusting the droop gain into two different levels associated with two separate frequency ranges i.e., low and high frequency boundary as illustrated. The sectional droop gain is adjusted according to the intensity of df rather than the wind speed.

The controller is inactive when the value of grid frequency is within the NOFB i.e., the active power reference of DFIG for frequency control ΔPPFC is zero i.e., Ps = 0. The dead band boundaries for both the conventional and the proposed droop control is the same. The low and high frequency boundary is designated as high and low sensitive region. The purpose of selecting sensitivity region is to adjust active power participation in frequency control.

The boundary between medium low ΔfMl and dead band low limit and medium high ΔfMh and dead band high limit indicate smaller frequency alteration and it is defined as highly sensitive region. The droop gain is small in this region which reduces considerably the participation of DFIG power output in frequency regulation. If wind farm contributes in frequency control, the net power of wind farm may be decreased based on the total volume of energy exchanged for providing under/over- frequency control. The reduction in net power transfer to the grid will incur financial losses and this can affect wind farm owner to decide whether they are interested in providing such services or not.

Nevertheless, considering stability concern and the mandatory grid requirements will push wind farms to participate in frequency control and they must oblige regardless of the economic performance. As such, techno-economic analysis also needs to be considered and further study can be carried out in this area to evaluate the benefit of the grid and wind farm owner while providing frequency control services.

V. WIND PENETRATION AND PRIMARY FREQUENCY CONTROL

The primary concern of wind integration is its low or zero inertia which predominantly influences system’s capability in responding to any temporary power imbalances in the grid. This section discusses the impact of wind penetration and the primary frequency control capability of the grid

VI. THE IMPACT OF WIND PENETRATION

The BESS model typically includes a battery bank, a three-phase bi directional DC/AC converter and a three-phase step up transformer connecting BESS into the system. However, the regulation of BESS differs significantly depending on their particular application. In research works, several BESS operation control techniques have been adopted depending on their function The main difference in BESS control technique is whether BESS is planned to support active or reactive power or both. A very common approach in BESS control is to regulate BESS active power in response to frequency deviation. However, the facility to interchange reactive power with the grid is not accessible in such circumstance. In certain case, both the active and reactive power exchange is considered to regulate frequency and voltage, never the less active power is typically given priority over reactive power.

With increasing PV penetration, BESS can reduce the voltage rise/drop by regulating active and reactive power without any priority given in providing BESS active and reactive power or regulating active power only. Another control approach is in PV/wind output power smoothing dispatch strategy where the sole purpose of BESS is to regulate active power only. considering the variation in active power output of PV/wind energy system. Hence, it can be summarized that BESS controlling is mainly depends on their particular purpose in power system. In this thesis, the modeling and application of BESS for both the active power priority over reactive power case and equal priority of active and reactive power cases are presented. Associated simulation studies will be carried out to demonstrate the performance of an individual BESS control techniques.

On the contrary, the volume of reactive power is defined by the BESS converter size. BESS can participate in voltage and frequency control as long as the total power demand remains within the converter capacity. However, this chapter discusses only the active power control of BESS.

VII. TEMPORARY OUTAGE OF THE HEAVILY LOADED LINE

Out of the many networks event, line outage is often experienced by the power system mainly due to various weather dependent and natural conditions such as collapsed electric poles, broken conductors, etc. In order to analyze the substantial impact, the heavily loaded line is selected for the event of temporary outage. The applied duration of line outage is 0-0.24s and the line is restored after 240ms. The frequency output of generators G2 and G1 are shown in Figure 4.1 and Figure 4.2. Simulation results exhibit that in the case of generator G2, the grid limit allows (12.7%) of wind penetration. In order to analyze the impact of BESS, the penetration of wind power is increased to 106MW. The increased wind penetration results in the frequency of generator G2 to violate the grid allowed operational requirements. On the contrary, the integrated BESS reduces the frequency rise within the acceptable limit which justifies the influence of BESS with the increased penetration of wind power in the grid. However, the impact of the same level of wind penetration is still minimal in the case of generator G1 because generator G1 has more headroom available than G2.

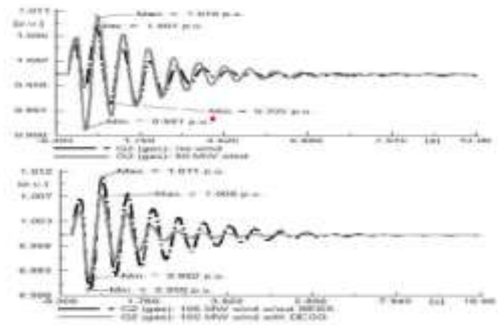


Figure.2. The Frequency response of generator G2 for line event

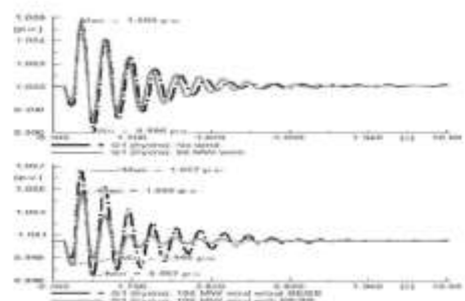


Figure.3. The Frequency Response of Generation G1 for line event Load Growth Event Load B

An abrupt load changing event is studied for further investigating BESS performance in enhancing the stability of the grid. The load event is applied for the case of wind penetration. A temporary load growth of 50% at load A is triggered during t=1- 1.5s and the frequency performance is monitored for different operating conditions.

The simulation results as portrays that when there is no wind penetration, the grid can successfully maintain the lower frequency boundary within the grid code requirements following the applied temporary load growth. However, with the wind penetration and same load increase event, the frequency drops to 0.989pu i.e., the grid fails to satisfy grid requirements. This phenomenon clearly indicates the negative impact of low inertial wind power in the grid. The frequency of generators G1 and G2 with temporary load

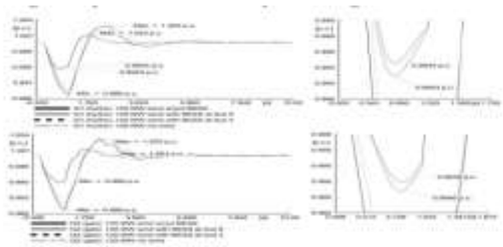


Figure.4. The Frequency of generators G1 and G2 with Temporary Load Growth

VIII. FREQUENCY CONTROL WITH PV AND NEM GRID CONDITIONS FOR FREQUENCY

Stability following any contingency event. The energy reserve can be arranged through the accessible generator's output or any other forms of energy storages. The steady-state frequency should be maintained within the NOFB. The generator should provide any temporary imbalances between the load demand and the generation to maintain the nominal frequency or compensate any under/over-frequency action. Hence, the governor response to the changes in frequency with n numbers of generation systems where, the change of power demand is defined by ΔPd which is the error between the generated power PGen and the load power demand PL. The total system inertia constant is Hn and the nominal frequency is fref. As the growth of PV penetration increases, the system inertia will be reduced regardless of fossil- fueled power plants are connected or dismantled permanently from the existing network. In addition, with the reduced inertia and varying PV output/network operating conditions, the grid may fail to compensate for any power imbalances. A BESS can be an alternative energy storage device to provide frequency control and minimize the negative impact of PV as illustrated.

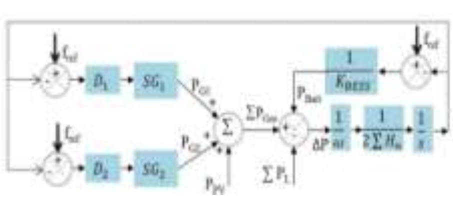


Figure.5. Primary frequency control of PV integrated system with BESS

Attributes of the Test System

The PV penetration, operating strategies and the proposed BESS charging technique are studied on IEEE 9-bus system (50Hz). The PV output is considered as an aggregated output and the PV farm is connected to the grid via a 0.6/230kV transformer at bus 9.

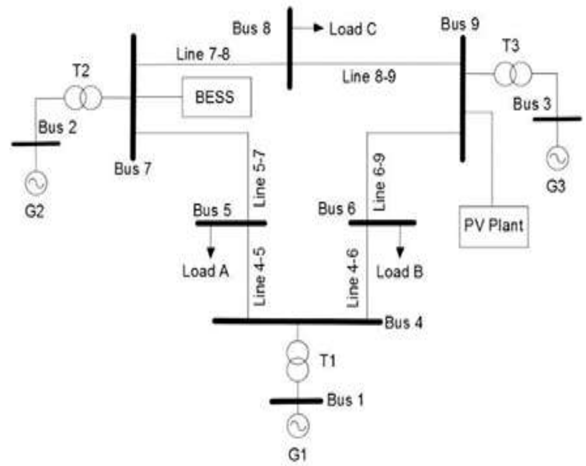


Figure.6. The IEEE 9-bus system with PV and BESS location

Bess Layout

BESS control which comprises voltage and frequency regulator that generates the reactive and active power reference for BESS regulation. The detailed discussion of voltage and frequency controllers. Once the reference for d and q axis are directed to PQ controller, it regulates the updated current reference based on the charge controller error and power output at BESS AC side. Active/Reactive (PQ) Controller In this project, three different categories of controllers PI, PI-lead and Lead-lag controllers are employed for regulating BESS active and reactive power. The PQ controller with the conventional PI controller is displayed.

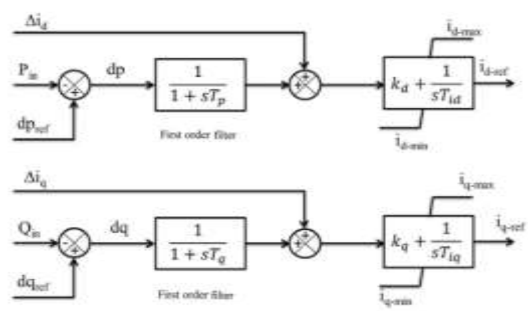
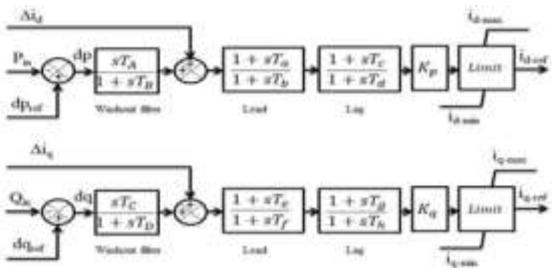


Figure.7. Conventional PI regulated PQ controller

PI-lead Controller

The proposed PI-lead controller is constructed by combining PI and lead controller in series. The purpose of cascading a lead controller with a PI controller is to achieve an improved transient outcome reduce the maximum percentage overshoot and settling time with the compensation of a positive phase angle by varying the location of closed-loop poles in the s plane controller.



Fiure.8. Lead-lag regulated PQ controller

System Description

In order to analyze BESS contribution in enhancing system stability as compared to STATCOM, an equivalent network of the transmission grid is selected in this work. The simplified diagram of the testing grid is illustrated. The grid consists of the equivalent model of 15 SGs, 11 loads and 7 series capacitors. The associated parameters of capacitors, the active and reactive power output of loads and SGs are outlined in Appendix B2. The parameters of the network components such as SGs, transformers at generator and load terminal and transmission lines can be found.

The voltage at the generator connected terminal and hence connected via a transformer to the high voltage grid. The generators in the transmission grid are an equivalent depiction of the entire generation network. The SW generator is selected as the reference machine and the rest of the generators are designed as PV. No PSS is considered at the generator's terminal. The transmission lines 32 joint consists of two parallel lines and the rest of the lines are of a single line. The voltage at load connected point and loads are modeled as balanced load.

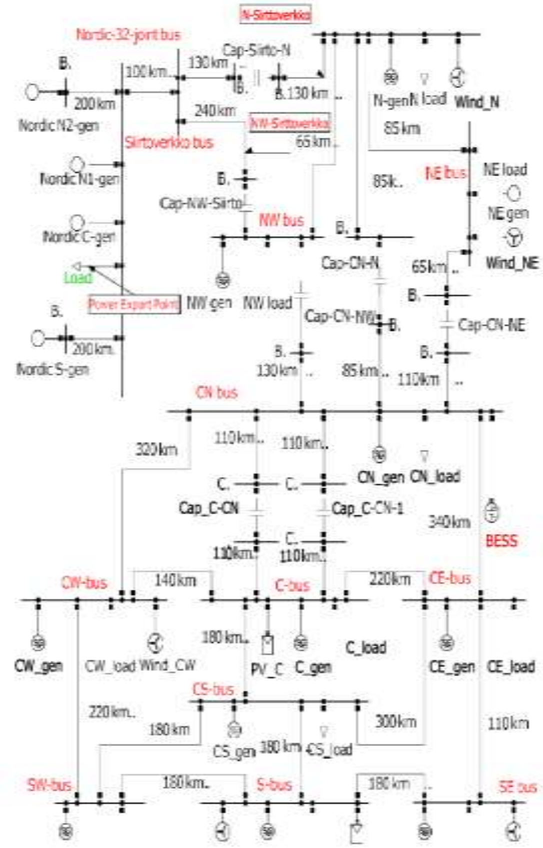


Figure.9. The studied customized equivalent transmission grid

Statcom and Wind Model

The STATCOM model comprises a DC source that supplies stable voltage to the VSC. The VSC converts the DC voltage into AC which is connected to the grid connecting transformer. This transformer operates as an interface to the grid. The voltage at STATCOM connection point is selected as the reference for regulating STATCOM output. The wind turbine models are DFIG type. The wind farms are equipped with FRT and hence remain connected to the grid during contingencies.

Stability Criterion

In order to satisfy the grid defined standards, the oscillatory responses of the grid should be constrained within limits following a single/multiple contingencies. The frequency standards define that for a network event, the frequency must be restricted within ±1% of the nominal frequency (0.99 1.01pu) within 1 minute of the post-fault condition and should be restored within the NOFB of 0.997-1.003pu in a period of 5 minutes as illustrated. This image is sent to the Arduino for processing. A module like the OV7670 is commonly used in Arduino projects to provide clear and detailed images, which are crucial for accurate facial recognition. In the event of numerous contingencies, the frequency must be retained between 0.991.01pu. Within 2 minutes and restored to the NOFB within 10 minutes.

The AEMO defined transient voltage standard varies between ± 10% of the nominal voltage value which must be retained within 20 minutes at post-fault condition. At any time of operation, the grid voltage and frequency must not violate the above-mentioned conditions. If the voltage and frequency are retained within the defined limit at post-fault condition, the system is considered as stable and secure.

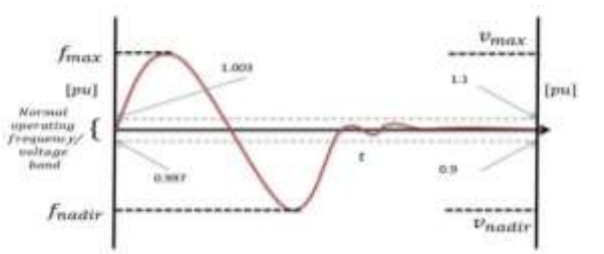


Figure.10. Voltage and frequency standards by NEM

EV Charging Station

The layout of the presented EVCS is illustrated with corresponding arrows defining power flow. The connection comprises several EVs which are connected to the AC bus via an aggregator, a 22kW PV module, a 200kW and a 167kW BESS and a grid connecting the transformer. PV and BESS are integrated to the AC bus via DC/AC converter. EVCS is connected to the grid via transformer. In order to determine the corresponding rated power of BESS, charging demand at two spots, food center and residential area are considered. However, load demand which is more than 90kW are considered in this study and thus the capacity of the grid connecting transformer is selected as 90kW for demonstration purposes.

It is observed that the highest load demand for a particular period of time is 290kW in a day. This indicates the reality of overloading of a small-sized transformer or selecting a large size transformer to avoid overloading for a shorter length of time. EVs load demands are considered as an aggregated load instead of as an individual load demand and therefore, a detailed model for EV is not considered in the simulation study.

Furthermore, it is assumed that EV operates only in charging mode and thus EV arrival, state-of-charge of individual EV is not taken into consideration. PV Output varies in real time, but in this study, PV is designed to generate 20kW during all the studied contingency events.

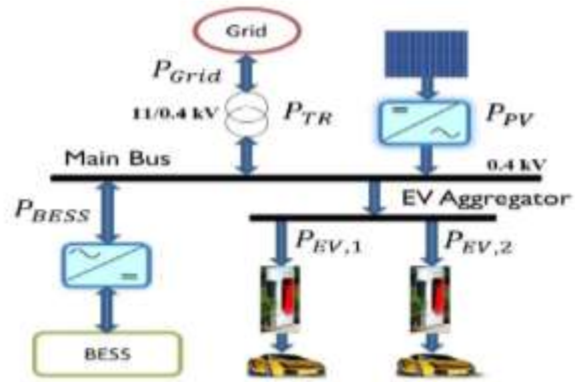


Figure.11. Studied EVCS with EVs, PV and BESS

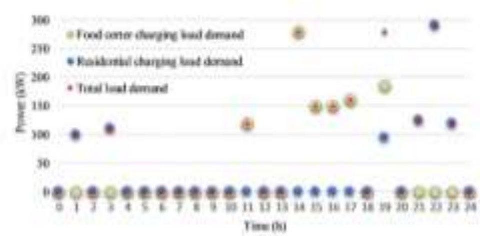


Fig No. 12. Load profile of EVCS in food center (PEV,1) and residential area (PEV,2)

BESS Modeling at EVCS

The presented BESS model encompasses battery bank, BESS controller and bi-directional DC/AC converter. The rated capacity of BESS converter defines the amount of active and reactive power available to participate in providing response to the control action. However, in this study, active power of BESS is the main focus and hence the reactive power control is disabled which can be extended if needed.

Reference Power Generator

The reference power generator PBESS−ref generates active power reference for regulating BESS power output in response to the measured power (Pmeas(s)). The (Pmeas(s)) is taken at the point of transformer connection and according to the defined control logic as illustrated in where BESS output power at AC terminal is defined by Pin. The nature of application delineates the amount and direction of BESS power flow. During transformer overloading reduction, BESS injects the amount of power deficit above the rated capacity of transformer.

Active Power (P) Regulator

The calculated power resulting from the error between reference power generator Pref as presented in passes through a first order filter. The filter output is passed through a PI controller which generates active power reference. The time constants T1 and T2 in the first order filter shapes the dynamic response and thus a large value of time constant results slower transient response. In order to avoid integrator windup, an anti-windup limiter is incorporated in the PI controller.

IX. CONTROL OF BESS SCALING DOWN OF TRANSFORMER OVERLOADING

The main purpose of installing BESS is to reduce the amount of imported power in EVCS if EV power demand surpasses the transformer’s nominal capacity and thus avoids transformer overloading. where the total power output at the transformer end and EV charging demand are defined by PTR and PEV respectively. The addition of PEV,1 and PEV,2 results PEV that must be equal or less than the nominal capacity of transformer for avoiding overloading. The power output of BESS PBESS continues to support as long as SOC constraints are maintained. The reference power output of BESS PBESS−ref regulation can be written as follows:

PBESS−ref = PEV − PTR−nom

The nominal capacity of transformer is defined by PTR−nom. The overall process of reducing transformer overloading with BESS is illustrated. According to BESS output response PBESS−ref is available. If power output for EV charging demand is greater than PTR−nom i.e., a positive value or else PBESS−ref is zero. The value of Pref is then passed through a PI controller to generate d-axis current reference as illustrated.

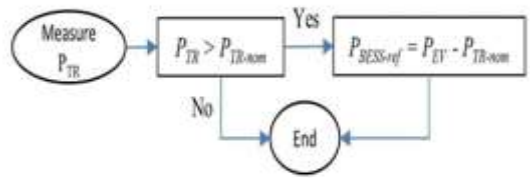


Figure.13. Flow diagram for transformer overloading reduction with BESS

If PV panels are installed in the EVCS ceiling, this can lessen the amount of grid power consumption and thus transformer overloading can be reduced partially. However, due to the intermittent nature of PV, grid power is subjected to frequent oscillation. In order to support this phenomenon, BESS is designed to provide PV output smoothing when PV output drops below a certain predefined.

X. RESULT AND DISCUSSIONS

Battery energy storage systems (BESSs) are increasingly used in renewable energy integrated power systems to improve system stability and performance. In this paper, the use of BESS for power system stability enhancement in renewable energy systems.The integration of a BESS with a renewable energy system can improve the system's power stability by controlling power fluctuations and improving power quality. The BESS can also help to regulate voltage and frequency, which are essential for the stability of power systems. The simulation results demonstrate that the use of a BESS significantly reduces the voltage and frequency fluctuations in the system. This reduction in fluctuations results in improved power quality, reduced system losses, and a more stable power supply. Furthermore, the BESS also helps to mitigate the effects of intermittent renewable energy sources such as wind and solar, which can cause fluctuations in power supply. By storing excess energy during times of high supply and releasing it during times of low supply, the BESS helps to ensure a more constant and reliable power supply.

Overall, the results of this project demonstrate the significant potential of BESSs for enhancing power system stability in renewable energy integrated power systems. The use of BESSs can help to improve power quality, reduce system losses, and provide a more stable and reliable power supply. This project provides valuable insights into the design and implementation of BESSs in renewable energy systems and highlights the importance of BESSs for the future of renewable energy.

XI. HARDWARE IMPLEMENTATION

Figure.14. Solar Panel

Figure.15. Hardware Implementation

XII. CONCLUSION

This research paper focuses on improving voltage and frequency stability with the growing penetration of renewable energy in the power system. The study presented in this thesis contributes to new knowledge in the modeling of BESS for regulating voltage and frequency in dynamic simulation studies of power system. In addition, the design of sectional droop control in wind turbine for frequency control in a MG and BESS in reducing transformer overloading in a charging station also contributes to the current knowledge. The detailed modeling of BESS, for the regulation of frequency is the initial stage of developing BESS model which is further modified according to the applications and design requirements in later stages to carry out dynamic simulation studies of power system. The pivotal control technique differs, depending on the particular application of BESS i.e., if frequency/voltage or both the voltage and frequency regulation is needed. A BESS in EVCS can significantly lower grid power consumption and thus reduce overloading of the grid connecting transformer. It is demonstrated that a BESS can lessen an overloading of 138% than that of without a BESS scenario.

BESS demonstrates simultaneous capability in regulating its output to reduce transformer loading and PV smoothing coherently as required by the EVCS. BESS engages in B2G when the energy selling price (battery discharging) is above the purchasing price of recharging the battery to ensure profit. During battery recharging, BESS only participates in recharging, if there is a spare capacity of transformer after feeding the EVCS load demand.

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