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STABILIZING TRANSIENT VOLTAGE AND FREQUENCY USING BATTERY ENERGY STORAGE SYSTEM

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***Abstract**:* Power system stability has become a great concern with the increased power flows across the transmission system. Battery energy storage system (BESS) has widely been used and long been acknowledged that it can significantly contribute in stable power system operation and control. This paper investigates a large-scale power system transient stability improvement by incorporating a large size BESS. Faults have been applied to find the maximum active power transfer limit across the transmission line. The control of BESS is so designed that battery charging/discharging is based on the nominal system frequency as a reference. In addition, faults on the DC side of BESS are also studied to determine their impact on the connected AC system stability. A PI-lead and lead-lag controlled BESS is proposed for multi machine power system to provide simultaneous voltage and frequency regulation within the defined battery state-of-charge ranges and an equivalent Finnish transmission grid is used to evaluate the system performance. According to Australian National Electricity Market grid requirements, the performances of the proposed control schemes are compared with conventional PI controlled BESS and STATCOM under multiple temporary and permanent fault conditions. In addition, two adjacent disturbance events are also applied to evaluate system performance with BESS and STATCOM. Through simulation results, it is shown that when there is a 44% increase in power export and the STATCOM fails, incorporating BESS improves the performance and justifies the novelty of this study. Moreover, the proposed leadlag controlled BESS manifests better transient performance than BESS with PI-lead and traditional PI controller, in the event of divergent temporary and permanent faults.

Index Terms **– Battery energy storage system, frequency stability, PI lead controller, Lead-lag controller, maximum and adaptive SOC, voltage control.**

I. INTRODUCTION

The most relevant issue in operation of isolated power systems is frequency stability [1]. Frequency stability is concerned with the ability of the generators to supply the loads within acceptable frequency ranges in case of generator tripping. Frequency stability is governed by the kinetic energy stored in the generator-prime mover rotating masses and the prime mover frequency primary regulation. If frequency excursions are not within +/-2.5 Hz range (see [2]), cascade tripping of the remaining generators can occur because of generator over/under frequency protections tripping. High penetration of renewals may significantly affect frequency stability of isolated power systems since renewable energy sources connected to the grid through power electronic interfaces (wind and solar photovoltaic generation) provide neither inertia nor primary frequency regulation ([4]-[6]). The lack of inertia results in higher rate of change of frequency which requires faster and larger primary frequency regulation reserves to prevent frequency being outside +/-2.5 Hz range.

This leads to our third point, which is that of power swings. Simple MW flow is easy to understand from DNOs heat maps, but the ability of the DNO network to cope with large power swings is much less clear and usually needs some analysis.

For power swing, we are referring to the speed at which the BESS needs to change from import to export and vice versa. For power arbitrage this is very slow and doesn't cause a significant power swing, but for fast response services like DC, the power swing can be significant with a 50MW BESS, potentially going from full export to full import in 1s, giving a 100MW/s power swing – which would challenge the most robust of power systems. This is why the G99 forms ask for the ramp rate of the BESS. This is bit of a tricky area, and often a major constraint, which we will go through in another post. Our third point is that a BESS can provide reactive power as well as providing active power, and importantly it can provide reactive power at the same time, which is useful for regulating voltage on the DNO network. Provided the BESS is correctly sized, it could easily provide 20MW of active power and 20MVAr of reactive power.

So, when preparing a grid application for a BESS it is important to understand what services we are hoping to provide to the system and what the local limitations are. The DNO or National Grid, typically want to know the MW capacity of the site, and the worst-case power swing as well as any reactive power flow capability, as these are what will affect their system behaviour and responses, but are not usually that interested in the MWh rating of the system.

The present power transmission system is experiencing numerous control and stability challenges with growing energy demand and penetration of renewable energy resources (RES). Structural reform of vertically integrated traditional power system is very complex and challenging. The ever-increasing size and complexity of electric grid infrastructure has drawn much attention in power system operation, stability and performance as it is often susceptible to diverse small or large dynamic and transient disturbances that inevitably occur in power system. Deregulated electricity market and electricity pricing schemes cause unplanned exchange of power within the network. This may result in overloading certain lines of transmission network and may lead to system instability in the event of network faults. In addition, compelled by sustainable energy initiatives, large-scale PV and wind farms are often located far away from load center. Therefore, transmission system stability and reliability needs to be ensured to satisfy power system reliability requirement of (N-1) criterion in order to maximize the utilization of accessible transmission resources. In the electric grid, every disturbance events, regardless of temporary or permanent in nature, generates low or high frequency oscillations. Flexible AC Transmission System (FACTS) devices have been contributing significantly in enhancing power system transient stability (low/high order oscillation) by regulating power flows and enhancing power transfer capacity of transmission system.

Under numerous phenomena, such as vertically integrated electricity structural reforms in a complex manner, the increased size of power system network, the aging transmission and distribution networks, the reduction in conventional electricity resources, and the deregulated electricity market have resulted increased power transfer across the grid which impacted adversely on the stability and reliability of the power system. Nowadays, maintaining a stable power system operation is facing difficulties while satisfying the power system reliability requirement of N-1 criterion when diverse ranges of unavoidable disturbances occur in power system. Moreover, increased uncertainty from variable nature of the large-scale renewable energy resources make stability tasks more difficult to maintain due to the impact of the dissimilar dynamic behavior of conventional and non-conventional generators on the system stability under small or large disturbance conditions. Transmission lines are operating nearly at transmission capacity especially during the harsh period [1], which creates additional threats to the power system stability at the advent of line faults or overloading in many cases. Construction of transmission lines and generation facilities can reduce such congestions in transmission line.

The new but mature technology termed as “FACTS’’ with faster response capability facilitates the power control and enhancement of available transfer capability (ATC) of the transmission system. In practice, a STATCOM with integrated energy storage system (ESS) can ensure significant improvement over traditional STATCOM performance. Considering several types of existing energy storage system, battery storage (electro-chemical) system is becoming more desirable because of their longer period energy storage capability and downward trend of battery prices. The battery energy storage system with a STATCOM has emerged as promising near-term technologies in power applications. MW-level battery energy storage system, integrated in a traditional power system is running for decades and operational experience is rather encouraging from the existing installations, as in Chilean power grid, West Virginia, Ohio, and California. The installation of Battery Energy Storage System (BESS) in electric grid provides multiple service including frequency support, voltage support, power damping oscillations, power quality and reliability and energy management. BESS can also reduce the transmission congestion.

Insufficient capability for frequency support can raise severe issues in power system operation and control. Number of publications on frequency challenges related to PV penetration in power system are available. Stability studies by the authors in argued that reduction in inertia increases frequency oscillations of the system. In addition, authors in indicated that higher PV penetration induces dramatic frequency oscillation beyond grid operating standards that potentially threatens uninterrupted load supply. Power oscillation damper, synchronous power controller and multiple-model adaptive control strategy [9] is adopted at PV terminal to damp out power system oscillations resulted from temporary power imbalances and maintain robust damping performance. A droop-type control, synthetic inertia control and operating point lower than maximum power point (MPP) are proposed to regulate PV power output and contribute in system frequency regulation. A comparative study carried out by the authors in demonstrated that a combination of droop and inertia control performs better than the conventional MPP tracking, or discrete droop and inertia control. However, PV power output is curtailed by more than 50% to provide such over-frequency regulation. Moreover, whereas wind turbine can provide a certain level of under/over frequency regulation through the use of its stored kinetic energy, PV is incapable of providing under-frequency support as PV does not have any rotating masses i.e. stored energy. As NEM has a penalty policy for violating Frequency Control Ancillary Services constraints, hence the auxiliary energy source is needed to ensure frequency control within the regulatory constraints and avoid any penalties with the increased PV penetration. BESS has proven to have great potential in providing primary frequency reserve in emergency situation to maintain grid requirements. BESS and other auxiliary devices, namely, shunt capacitor and ultra-capacitor offers enhanced damping performance. However, the study did not bring any insight on BESS sizing and battery SOC. Moreover, a very low PV penetration level (1%) is considered for comparative analysis which does not describe the severity of increased large-scale PV penetration. The performance of BESS in controlling primary frequency is demonstrated in an islanded Microgrid and small power system. However, the study is bounded to small-scale power system also no RES is considered in the system.

II. Related Work

In this paper, comparative performance of STATCOM and BESS in enhancing power transfer capability across interconnected electric grid is explored. This paper investigates the performance of STATCOM and BESS in enhancing transient stability, making contribution in voltage and frequency regulation to support the increased amount of power export between two large-scale interconnected power systems, with the conventional synchronous generators and RES. The impact of disturbance events such as temporary and permanent short circuit faults, permanent line outage are considered for transient stability analysis following voltage and frequency operating standards published by the Australian Energy Market Operator (AEMO) according to NEM policy. The main contributions of this paper are summarized as follows:

• The evaluation and comparative performance analysis between STATCOM and BESS is to enhance transient stability and support the increased amount of power transfer between interconnected power systems, under various temporary and permanent contingencies. BESS is designed to provide simultaneous voltage and frequency regulation and operate within the defined SOC operating ranges and this research has not been reported in current literatures.

• PI-lead and lead-lag controlled BESS are proposed in this study and to the authors' best knowledge these types of controllers have not been applied to BESS to regulate both the voltage and frequency simultaneously by controlling BESS active and reactive power. The design effectiveness is compared to conventional PI controlled BESS in stabilizing voltage and frequency of a large-scale real power system and enhancing power transfer capability of the power system.

• The analysis of the impact of multiple adjacent disturbance events on the transient stability and the efficacy of state-of-the-art STATCOM technology and BESS with the proposed control strategies to avoid blackout that has been neglected in earlier studies of power system stability analysis. To evaluate the performance of BESS with the proposed control approaches and STATCOM in enhancing transient stability, multiple case studies have been carried out using an equivalent 400kV Finnish transmission grid and comparative performances are evaluated and presented.

The power arbitrage service of a BESS is technically and commercially the simplest concept for battery storage. It is based on the simple premise of absorbing energy when it power is cheap, such as at night or when there is excess power from CHP or solar array, and then discharging the battery during peak load times. The benefit of such an approach allows what is known as load demand curve shifting, where the excess power from renewables (often solar) is stored at high production times / low demand then discharged at low production times / peak demand. This has two main benefits. Firstly, and depending on the profile, high tariff electricity costs can be avoided, and a flat charging profile created. Secondly, it means that the size of the grid connection can potentially be reduced, although one needs to consider what happens if there was a shortfall in the surplus power i.e. a very cloud day, if the surplus comes from a Solar PV array. The revenue streams here are obviously limited to the cost of energy creation and storage at cheap times, compared to the cost of energy during high tariff times, and is based on the concept of peak shifting the energy demand, so that it is balanced more evenly across a 24 hour (or whatever other timeframe).

In the authors opinion, this is the 'holy grail' of most BESS units and The System Operators (TSO), an electrical system demand that is predictable, and therefore easy to plant and dispatch. In practice to achieve, this the BESS has to be cheap and robust enough to store and dispatch energy as needed, and when is most economic to do so. The power arbitrage service of a BESS is technically and commercially the simplest concept for battery storage. It is based on the simple premise of absorbing energy when it power is cheap, such as at night or when there is excess power from CHP or solar array, and then discharging the battery during peak load times. The benefit of such an approach allows what is known as load demand curve shifting, where the excess power from renewables (often solar) is stored at high production times / low demand then discharged at low production times / peak demand. This has two main benefits. Firstly, and depending on the profile, high tariff electricity costs can be avoided, and a flat charging profile created. Secondly, it means that the size of the grid connection can potentially be reduced, although one needs to consider what happens if there was a shortfall in the surplus power i.e. a very cloud day, if the surplus comes from a Solar PV array. The revenue streams here are obviously limited to the cost of energy creation and storage at cheap times, compared to the cost of energy during high tariff times, and is based on the concept of peak shifting the energy demand, so that it is balanced more evenly across a 24 hour (or whatever other timeframe). In the authors opinion, this is the 'holy grail' of most BESS units and The System Operators (TSO), an electrical system demand that is predictable, and therefore easy to plant and dispatch. In practice to achieve, this the BESS has to be cheap and robust enough to store and dispatch energy as needed, and when is most economic to do so.

III. FREQUENCY STABILITY

Power system stability is concerned with the ability of the generators to run in synchronism and to supply the loads at acceptable frequency and voltage ranges in case of normal (load variations) and abnormal disturbances (faults, generator tripping) that may occur in power systems. The power system stability problem is a very difficult one. Its study is facilitated by separating it into three sub problems: angle, frequency and voltage stability [9]. Frequency stability will be present in all isolated power systems not matter how strong the power network is. Precisely, frequency stability analyzes the capability of generators to supply load at acceptable frequency ranges in case of generator tripping. Frequency results from the generator rotor speeds. Generator rotor speeds result from the equilibrium between the power supplied by their primer movers (either turbines or engines) and the power consumed by the loads. Frequency stability is governed by the inertia of the rotating masses of primer movers and generators and the gain and time constant of the primary frequency regulation of prime movers in such a way that:

• After a generator trips, frequency decays with a rate of change that depends of the inertia of prime mover generator rotating masses and the magnitude of the generation lost.

• Prime mover primary frequency regulation reacts to the frequency decay increasing the output of the power supplied by the prime movers.

• Frequency stabilizes if two conditions are fulfilled: the remaining on line generators have enough reserve to supply the generation lost and they are also able to increase the power output fast enough to avoid that frequency is below the settings of generator under frequency protections to avoid generator cascade tripping.

Frequency stability is at risk in isolated power systems because of the fact that the frequency rate of change in case of generator tripping is bigger than in an interconnected power system. The inertia or the kinetic energy of the rotating masses of an interconnected system is much bigger than the inertia of the rotating masses of an isolated system. In addition of, the magnitude of the generation that can be tripped compared to the total rotating generation is much bigger in an isolated system than in an interconnected one. Frequency stability can only be preserved by appropriate load-shedding schemes that disconnect fractions of the load to prevent the system collapse either in case of lack of reserve or in case of extreme disturbances. Load shedding schemes are commanded by under frequency and rate of change of frequency protections.

IV. ENERGY STORAGE SYSTEMS

Storage of electric energy has been sought since the beginning of the development of electric power systems to overcome the technical problems and over-costs that result from the non-storageable nature of electric energy and the time variation of the load. Pumped storage power plants have been the only practical solutions for massive (long term) storage. Pumped storage power plants have been incorporated to power systems for many years due to two main reasons:

• To optimize the operation of thermal based generation systems taking into account the constraints of nuclear and thermal power stations.

• To avoid spillage in hydro systems. Pumped storage power plants can also provide system ancilliary services such as:

- Active power-frequency control.
- Reactive power-voltage control.
- Black-start.

The development of pumped storage power plants stopped due to the lack of affordable sites and gains in flexibility of power generation and the opportunities of demand side management actions. The increasing penetration of intermittent energy sources is motivating again the development of energy storage systems. Long-, medium- and short-term energy storage systems are being explored: The long-term energy storage systems under investigation are:

- compressed air
- power to gas

Medium-term energy storage systems under investigation are batteries of different technologies (Li-ion, NaS). The short-term energy storage systems under investigation are:

- Ultra-capacitors
- Flywheels IEC White Paper on Electrical Energy Storage provides an excellent overview of the state of the art and the applications. Figure 1, borrowed from, maps the energy storage technologies in a plane power-stored energy.

Batteries and supercapacitors have made tremendous progress in performance over the past two decades, while sustainability, environmental effect, as well as a life cycle and safety issue have been relatively neglected. As explosive demand for energy systems in electric vehicles is expected to produce a large volume of wastes that contain toxic components, reformulation of device structures and associated technologies with environmentally benign materials and chemistries is essential for a green or sustainable energy future.[42-46] In this section, we discuss emerging biodegradable battery and supercapacitor systems, including approaches such as injectable, rechargeable batteries, 3D-printed disposable supercapacitors, and their sustainable chemistries, materials, and degradation manners.

4.1 Batteries

Batteries shows materials and device configurations to fabricate a sodium-ion secondary battery consisting of sodium- and iron-based polyanion compounds and pyroprotein-based carbon with cellulose-derived binders as composite electrodes, a porous cellulose acetate mesh as a separator, sodium perchlorate in a propylene carbonate solution as an electrolyte, and carboxymethyl cellulose/polyester/silicon-based materials as a biodegradable encapsulation pouch.[47] The assembled battery exhibited comparable electrochemical performances as those of conventional non-degradable ones, with a charge–discharge capacity of 110 mAh g^{-1} and cycle retention of 93%. The natural biodegradation of battery begins when the pouch was contacted with water/moisture/fungi in the soil and it dissociated into silicic acid, glucose, terephthalate, adipate, and 1,4-butanediol via natural microbial degradation and hydrolysis reactions. The cathode was hydrolyzed into sodium, iron, phosphate, and pyrophosphate; the binder and cellulose separator were transformed into glucose via fungal degradation; and the electrolyte was degraded into ethanol, methanol, carbon dioxide, propylene glycol, sodium, and chloride via natural hydrolysis and microbial degradation. Cytotoxicity tests revealed that all the components of the battery were naturally biodegraded without any toxic end products. It presents a highly flexible, rechargeable aqueous fiber battery that could be directly injected into the body with minimal invasion.[48] A particular design strategy of the conductive fiber of polyglycolic acid (PGA) yarn was to utilize incorporation with polydopamine/polypyrrole as an anode, MnO_2 as cathode, chitosan as a separator, and body fluids for an electrolyte. The anode and cathode were twisted together to accomplish a fiber battery, which exhibited high flexibility by maintaining 89% of capacity even after 1000 cyclic tests at a bending angle of 180°. In vivo injection of fiber batteries into the abdominal subcutis of a mouse model demonstrated a specific capacity of 25.6 mAh g^{-1} at a current density of 1000 mA g^{-1} with a retention of 69% after 200 charge discharge^{-1} cycles. The implanted battery system gradually dissolved upon hydrolysis, enzymolysis, and completely disappeared after 10 weeks without the need of surgical interventions. Potential alternative, metal-free, all-polypeptide organic-based redox-active amino acid materials were developed to fabricate a sustainable, rechargeable, and on-demand degradable battery, as illustrated in Figure **2c**.[49] Redox-active polypeptides and small-molecule peptide repeated units were synthesized to verify redox potentials and identify degradation products. A composite of metal-free, polypeptide-based cells incorporated with viologen-chloride polypeptide was used as an anode, biTEMPO (2,2,6,6-tetramethyl-4-piperidine-1-oxyl) polypeptide composite was used as a cathode, and electrolyte-soaked filter paper served as a separator, for a polypeptide-based battery. The resulting performance indicated a fair electrochemical performance and stable operation with a maximum charge capacity of 37.8 mAh g^{-1} and cycling stability of 250 cycles at 1 C (the current required to reach full charge in 1 h).

The viologen and biTEMPO polypeptides are constructed such that it comprises amide links in the backbone and easter links in the side chains, that are prone to degradation in enzymatic, basic, and acidic environments; therefore, on successive on-demand degradation in acidic conditions (1 and 6 M hydrochloric acid (HCL) at 80, and110 °C), both polypeptides generated L-glutamic acid and n-hexylamine. Cell viability study revealed that the degradation products showed lower toxicity effects on mouse fibroblast cells and bovine coronary venular endothelial (CVE) cells. Primary batteries with completely dissolvable materials could play an essential role in powering temporary electronic implants for the prevention, treatment, and management of illness. It presents materials and device configuration of a fully biodegradable magnesium–molybdenum trioxide ($Mg–MoO_3$) primary battery, wherein Mg and MoO_3/Mo served as anode and cathode materials, respectively; sodium alginate with phosphates was used as an electrolyte.[50] A single-cell $Mg–MoO_3$ battery showed high electrochemical performance with a stable output voltage of 1.6 V, capacity of 6.5 mWh cm^{-2}, and output current of 12.5–150 µA cm^{-2}, for an extended lifetime of up to 13 days, and demonstrated operational functionality by powering a light-emitting diode (LED), calculator, and amplifier of an electrocardiogram (ECG) signal detector. As Mg serves with excellent biocompatibility/biodegradability (daily allowance: ≈300 mg d^{-1}) and with high solubility of MoO_3 in aqueous solutions (≈1 g L^{-1}), the fabricated battery completely dissolved within 9 d in PBS (pH 7.4) at 85 °C. Implanted batteries into the subdermal region of rats completely disappeared after 4 weeks without overt cell reactions and thus validated the possibility for potential on-board advanced power sources. Hydrogel-reinforced cellulose paper-based Zn paper batteries were developed by simple screen printing of Zn microparticles-composed anode ink and Ni- or Mn-composed cathode ink on the front and back of the paper, respectively. The flexible battery showed an areal capacity of 1.1 mAh cm^{-2}, an output voltage of 1.7 V for a single unit, 500 charge $discharge^{-1}$ cycles, and it powered a mini electric fan for 45 min continuously. The hydrogel-reinforced cellulose paper became fractured after 2 weeks of burial in natural soil and completely degraded in 4 weeks.

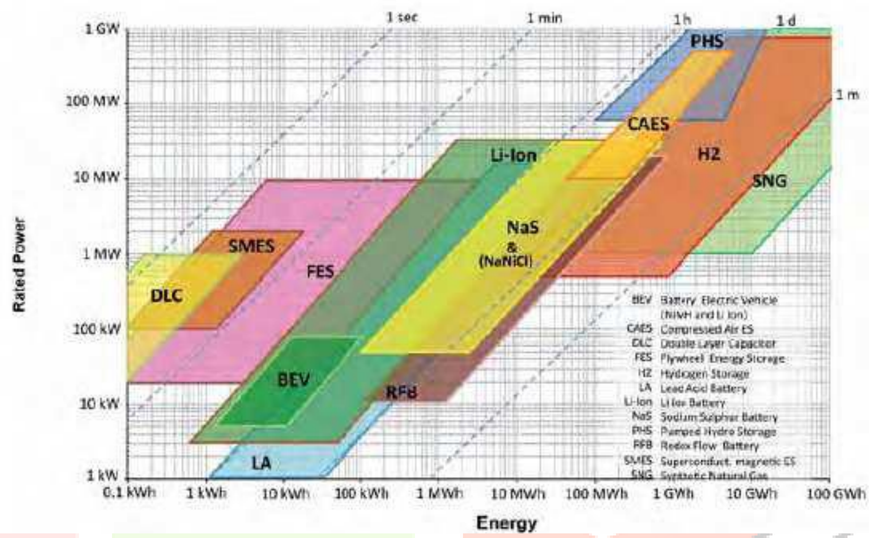


Figure 1: Overview of energy storage systems.

The main application of medium-term energy storage is peak-shaving for congestion management in subtransmission and distribution grids. Thanks to the power electronic interface with the grid, medium- and short-term energy storage systems can provide fast response active power-frequency and reactive power-voltage control.

V. CASE STUDIES

A corresponding electric transmission grid model termed as Siirtoverkkomalli i.e. Finnish transmission network is designed in MATLAB/SIMULINK environment to carry out a comprehensive power exports scenarios within areas. It comprises maximum power transfers from the South end nodes to the north end node Bus_Nordic_N at which the transmission network becomes weak and the impact that Battery Energy Storage System would have in restoring healthiness to the grid. In this study, two anomalous operating conditions are considered to point out instability in the system:

- Three-phase-to-ground fault at Central North (CN)
- Loss of line; North - Bus_Nordic_N

A. Case 1: 500MW power export case

To identify the stable operation threshold of the grid, a large amount of active power has been exported from the SouthWest, South and SouthEast nodes to the Bus_Nordic_N node. The maximum active power export limit from the south end of the network to the north end is found to be at 500MW. In fact, the system is usually stable under the steady-state operation. However, with a three-phase-ground fault at 32s at node CN, fault clearing at 32.1s and loss of one of the heavily loaded line between North to Bus_Nordic_N, the system instability occurs as shown in Fig.4.

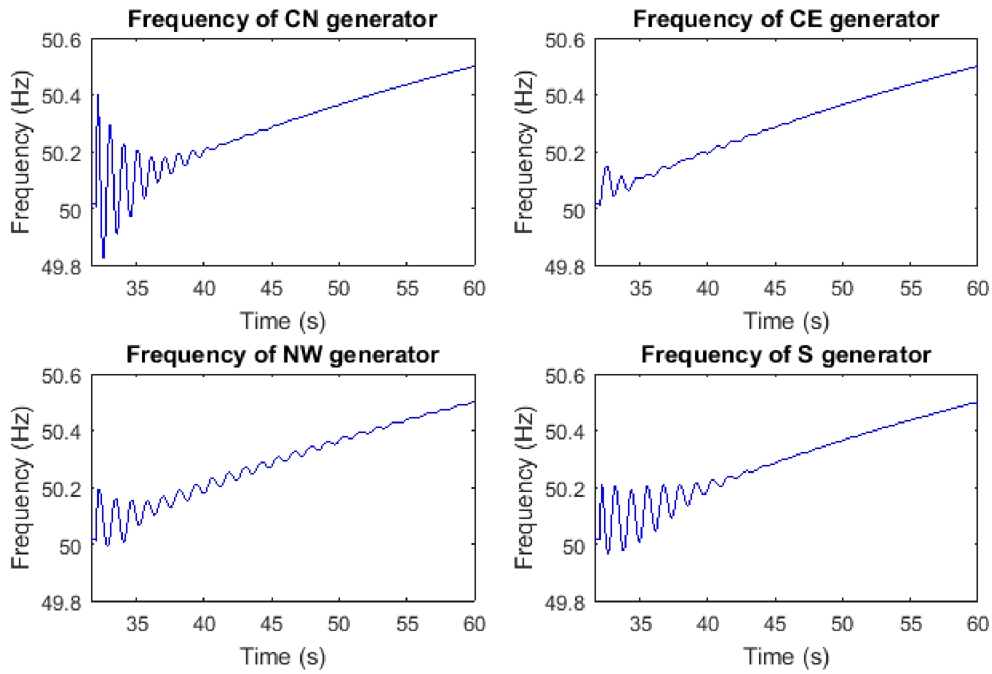
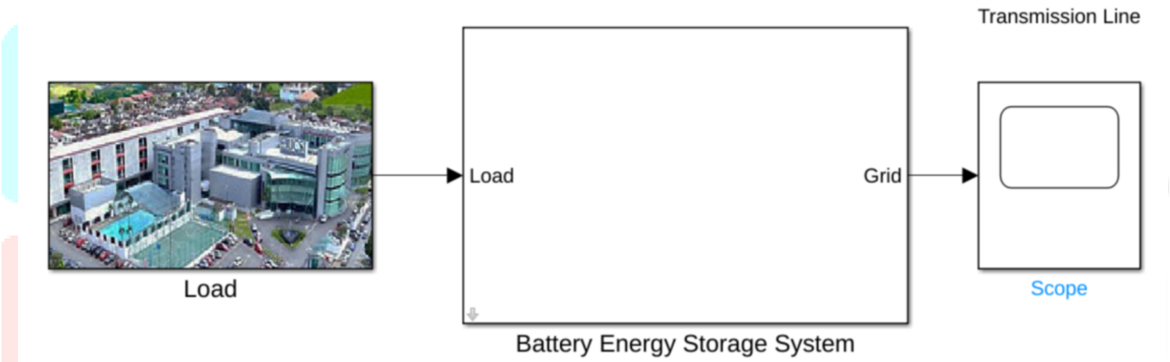


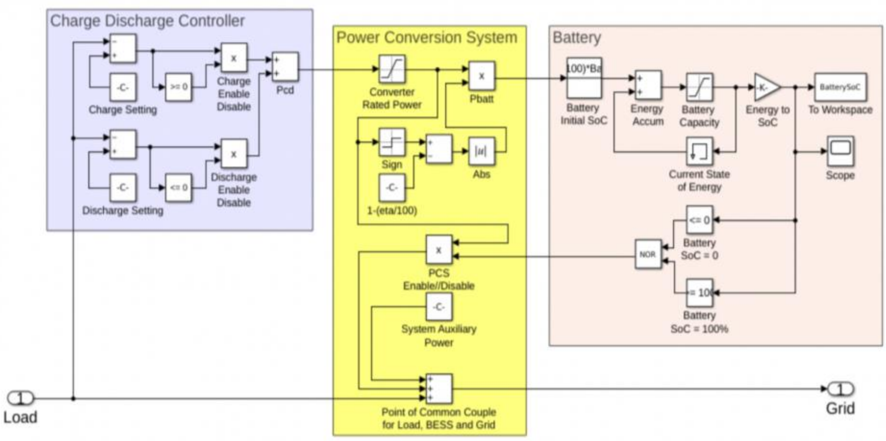
Figure 4. Frequency of generators undergoing a 3-phase-to-ground fault

1) Project Model



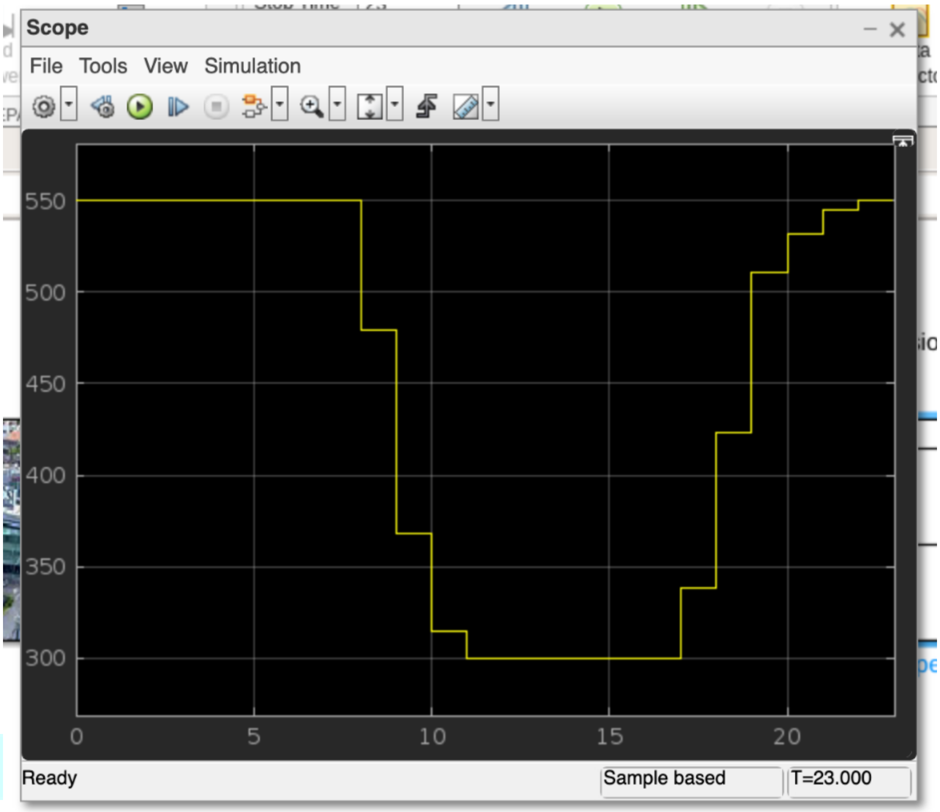
In the final Model of simulink software. Three Model will be connected in series that is Load, BESS, Scope for getting the graphical representation of output.

2) BEES



The BEES model with based on the three major block one is Charge Discharge controller which will monitor the discharge rate of battery and another one will the power conversion system which will couple the load with Battery and GRID. At the last battery

3) Simulation Graph



While running the system from 36 secs. Generation of power will managed by Battery System with fault condition occur in the model . In the model if all the condition will NON FAULTY then system will provide Battery a power of 550Voltage with 90% of efficiency.
Project Model

VI. CONCLUSION

BESS model will help to analyze the transit occurs during the conversion of AC into DC for transmission lines on battery management system. This project proposes a BESS PCS considering the REP constraint on the premise of system frequency stability. At the beginning, the dynamic models of Thermal Gen, Hydro Gen, and BESSs are established. The REP-constrained PCS can dynamically determine the BESS power configuration by comparing the target REP levels and the REP boundaries of each control area in different load scenarios. A model of the Australian five-area interconnected power grid is established in MATLAB/Simulink to verify the effectiveness of the PCS, and the suggested BESS power for each control area is obtained. Therefore, high REP level can be achieved in the future, as the BESS mitigates the system frequency fluctuations effectively, and the proposed PCS indicates the optimal BESS power. In addition, the implementation of the BESS is not only for frequency regulation but also for the way to configure BESS power in multiple purposes, which will be discussed in further work.

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