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REVIEW ON STABILIZING TRANSIENT VOLTAGE AND FREQUENCY USING BATTERY ENERGY STORAGE SYSTEM

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Abstract: Along with the rapid growth in electronics technology, electrical power solutions are developed to provide high-performance, reliable, and durable energy supplies to various electronic devices. However, conventional power systems are challenging owing to serious after-use considerations, including environmental costs and biological hazards of eliminating heavy metals and other toxins. 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 (SOC) ranges and an equivalent Finnish transmission grid is used to evaluate the system performance. According to Australian National Electricity Market (NEM) 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 lead-lag 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, power export, STATCOM, voltage stability.**

I. INTRODUCTION

Battery Energy Storage Schemes are very versatile plants and can be used for a number of different services, depending on the plant design and aims; this can include services such as power arbitrage, voltage control, and the new Dynamic Containment (DC) service which replaces the old Enhanced Frequency Response (EFR) service. BESS units can also be used as a power balancing service, to meet shortfalls in power, to limit disturbances from the grid during transient switching events, where a plant has large dynamics loads, such as big motors and generators that switch in and out frequently. At SPE we have found that many developers are keen to add battery storage systems into their existing projects, but are often unsure exactly how the battery will be used. This leads to the dilemma of trying to design a system that will be flexible enough to allow future revenue streams, without pre-investing for expensive system upgrades.

The battery can be anything from old car batteries, to modern li-Ion batteries, or more advanced cryo-batteries or flow batteries. The battery type just determines how much energy can be stored and how quickly it can be converted from chemical form to electrical energy. Second, a simple concept that is often misunderstood is the difference between power (MW) and energy (MWh). A BESS rated at 1MW & 1MWh can provide 1MW for an hour, of 0.5MW for 2 hours, or 0.25MW for 4 hours etc. but it can never provide more than 1MW, because this limit is imposed by the inverter rating and system design. From the DNO perspective the amount of MW is important, as this governs the main power flows in their network.

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.

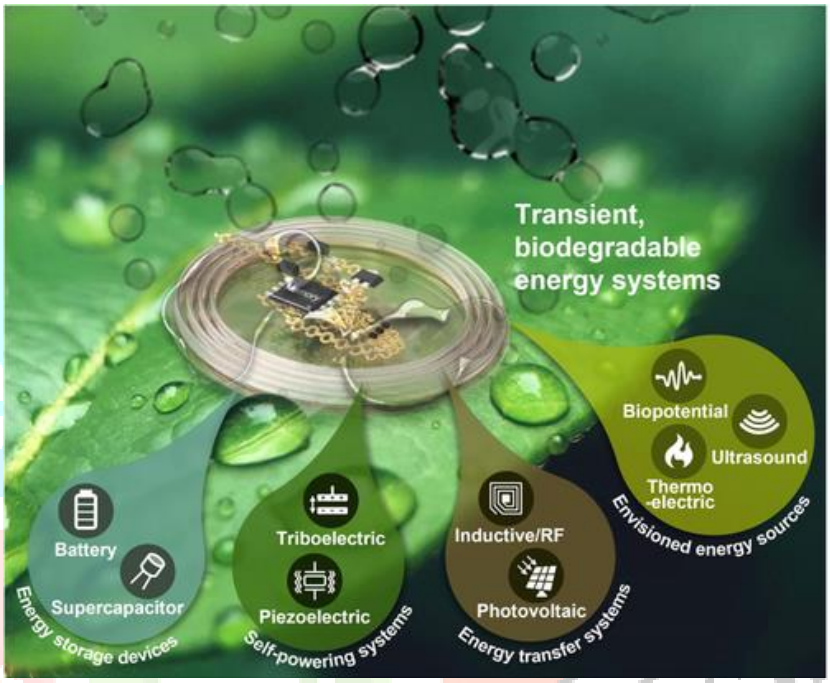

FIGURE 1: OVERVIEW OF VARIOUS TYPES OF TRANSIENT, BIODEGRADABLE ENERGY DEVICES AND SYSTEMS

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. ENERGY STORAGE SYSTEMS

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.

3.1 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.

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