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Retired electric vehicle battery to reduce the load frequency control oscillation in the micro grid system

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ABSTRACT

The potential of a retired electric vehicle battery (REVB) is its capacity to provide backup power supply to the power system grid. This paper proposed energy storage system (ESS) based on REVB called retired battery energy storage system (retired BESS) to tackle the intermittent of renewable energy source such as wind turbine and dynamic load change. To examine the efficacy of the proposed technique, the load frequency control (LFC) of microgrid (MG) system is utilized in this study and the proposed technique is compared to conventional LFC controller, PI controllers, superconducting magnetic energy storage (SMES), and a new electric vehicle battery. The kind of retired BESS cell used in this study is Li-ion nickel manganese cobalt oxide (NMC) type with a state of charge as of 70%. The capacity of each cell for retired BESS is 38 Ah. From the simulation result, the use of retired BESS can reduce frequency oscillation, compress the settling time to reach steady state, and maintain the robustness of the MG system. A retired BESS has a minimum error performance index value compared to conventional LFC, proportional integral (PI) controller, and SMES.

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1. INTRODUCTION

The reduced production of fossil energy, especially oil and the global commitment to reduce greenhouse gas emissions, has encouraged the government to continuously increase the role of new and renewable energy as part of maintaining energy security and independence [1], [2]. According to PP no. 79 of 2014 concerning National Energy Policy, utilization of new renewable energy (NRE) for power plants in 2018 was 8.8 GW or 14% of the total power generation capacity (fossil and non-fossil) which was 64.5 GW [3]. However, some inverter-based NREs such as wind power plants (WPP) cannot provide a mechanical inertial power response [4]. As a result, the electric power system will be more susceptible to frequency stability disturbances in the event of a power imbalance between the load and the generator. The power balance between load power requirements and generator generating capacity is one of the important factors in the stability of the operation of electric power systems such as micro grids (MG). The MG system consists of an inverter that can convert direct current (DC) energy sources from new and renewable energy such as solar, wind, water, or biogas to use alternating current (AC) electricity [5], [6]. However, in the operation of the electric power system there will always be changes in the load so that the generator needs to adjust its output power through the governor or excitation setting. The speed of the governor on the generating unit as a control function is a quantity that continuously changes according to changes in load, so a frequency regulation system is needed, known as load frequency control (LFC) [7].

LFC is a system that is used to maintain fluctuations caused by changes in load [8]. The use of the LFC functions in regulating the frequency of the electric power system by increasing and decreasing the generator load based on the difference between the system frequency and the nominal frequency. To determine the performance of the LFC system, it is necessary to know the components associated with the system. These components include: governor, turbine, energy storage system (SPE) and load system [9]. SPE functions in storing excess power and providing additional power to the electric power system. It aims to optimize frequency stability in the electric power system. The application of one type of SPE called capacitor energy storage is reported in [10]. Singh and Zaheeruddin [10], capacitor energy storage is used to enhance the frequency stability of tidal turbine power plant. It was observed that by adding capacitor energy storage, the overshoot of the frequency can be reduced. In addition, the settling time of the frequency can be accelerated by adding capacitor energy storage. Research effort in [11], proposed a novel load frequency control using redox flow battery. Setiadi [9], two area power system is used as the test system to observe the efficacy of the redox flow battery. In addition, wind turbine generation is also added in the system. From the simulation results it was found that redox flow battery can enhance the frequency performance of the system. Monila and Mercado [12], shows the application of superconducting magnetic energy storage to stabilize and control the power flow of microgrid. In addition, wind farm is added to the microgrid to simulate the uncertainty effect. It was found that the power flow of microgrid is enhance when superconducting magnetic energy storage is added to the system. The application of battery energy storage system for enhancing the dynamic performance of renewable rich power system is reported in [13]. It was reported that by adding battery energy storage the dynamic performance of power system can be enhance significantly. However, all the SPE above have handicap in term of cost. Hence, retired battery energy storage system (retired BESS) which utilizes leftover batteries in electric vehicles can be solution.

An electric vehicle (EV) is a vehicle that is driven by an electric motor that is sourced from electrical energy. The electrical energy is stored in the battery in electric vehicles. However, a battery contained in an EV must be replaced when the battery capacity has reached 80% of the initial capacity of the battery used [14]. The capacity of the battery will decrease after reaching 1,400 cycles (charge and discharge cycles) [14]. After reaching that time, the used EV battery must be replaced with a new battery. As a result, unused batteries will cause a large amount of battery waste. A battery that is not used is called a retired battery. The main concept of utilizing retired batteries is to reuse batteries that no longer have the required specifications in electric vehicles, but these batteries can still be used in other applications such as energy storage system applications in electric power systems. The potential for retired batteries is their capacity to strengthen intermittent sources such as wind or wind power sources. One of them has been applied to increase the penetration of renewable energy sources [15]. The retired battery application has advantages such as being able to recharge the battery by renewable energy sources such as wind power sources [16]. In addition, the battery also has the potential to replace the use of fossil power plants where the battery has the potential to reduce gas emissions by around 7 MtCO2 eq. per year or 1.5% of total gas emissions as in reference [17].

This paper investigated the application of retired BESS for enhancing the frequency stability of power system. In addition, wind farms are added to the system to shows the efficacy of retired battery EV system for handling variability and uncertainty of wind farm. The rest of the paper is organized as follows: Section 2 present the fundamental theory of this research. Design concept, results and discussion are presented in section 3 and 4. In addition, section 5 highlight the contribution and the conclusion of the paper.

2. FUNDAMENTAL THEORY

2.1. Wind power plant

Renewable energy generation was a power plant utilizing renewable energy as a source of generation [18]. One example was a wind power plant (WPP) which utilizes kinetic energy from wind as its main energy source. However, WPP has intermittent properties which can cause instability in the electric power system. Therefore, many WPPs used inverters.

To evaluate the value of WPP power fluctuations in the MG system, as shown in (1) and (2) were used. Where ΔP_W, C_p, V_W, ρ, N, A are power generated by WPP, efficiency on the rotor, wind speed, density of air, propeller efficiency, vane sweep area.

$$\Delta P_w = \frac{1}{2} C_p V_w^3 \rho \, N \, A \tag{1}$$

$$A = \pi R^2 \tag{2}$$

2.2. Load frequency control

Load frequency control (LFC) was a system that is used to maintain fluctuations caused by changes in load [19]. Regarding the LFC primary regulation, load changes on the system will produce a steady-state frequency deviation that depends on the governor speed regulation. The frequency was controlled through the generator system contained in the power plant. The mathematical model of the generator system can be seen in (3).

$$\frac{d\omega}{dt} = \frac{(P_m - P_e)}{2Hs} \tag{3}$$

Where H was the inertia of the system, Pm was the change in the mechanical power of the system, was the change in the electrical power and was the change in the angular speed of the motor which varies with the load. While the load on the electric power system can be modeled in the form of (4).

$$\Delta P_e = \Delta P_L + D\Delta\omega \tag{4}$$

D was the damping coefficient of the system and PL was the change in load on the system. Then for the prime mover model in the LFC system used in the form of a turbine that can be modeled as in (5).

$$G_T(s) = \frac{\Delta P_m(s)}{\Delta P_v(s)} = \frac{1}{1+\tau_T} \tag{5}$$

P_V was the change in power resulting from the governor valve. Furthermore, the governor model used in the LFC system can be represented in (6).

$$\Delta P_g = \Delta P_{ref} - \frac{1}{R}\Delta\omega \tag{6}$$

To reduce the frequency deviation to zero or return the frequency value to its nominal value, it was necessary to add a reset function. The reset function was performed by adding an integral block to the load reference setting to change the speed reference point.

3. DESIGN CONCEPT

3.1. Technical analysis

The MG system consisted of a WPP generator, a BESS system, a conventional turbine, and an installed load. The wind energy source used was dependent on intermittent natural conditions so that the power generated fluctuates, thus the power generated by the wind generator will fluctuate with time. While on the load side, it was hoped that the stability of the voltage and frequency was guaranteed. To overcome the uncertainty of the wind energy source, a controller was needed that functions to regulate the frequency difference in the MG both on the generator and load side.

The power requirements for the main load were supplied by thermal and wind generators. When the generator fails to supply the required load because the power produced was not optimal, it will result in a fall in the frequency of the electric power system. This was very dangerous for the load installed on the power system. Therefore, the active power from the WPP was used as an additional power supply to improve the quality of the frequency produced hence its value remains at its nominal value. Besides that, BESS was used as a backup supply for a short time as a dynamic stabilizer of the system used. The excess energy generated from the wind generator will be reused by the battery to be charged into the battery. In addition, an energy storage system in the form of SMES was used as a comparison against retired BESS.

The PI value was the value obtained through the auto-tuning method on the MATLAB R201a software so that the optimal control parameter value is obtained [20]. In conventional thermal generators there is a speed regulation that functions as a comparator for the power reference set point and changes in speed on the conventional turbine thus the output power of the governor system is generated. The power will be transmitted to the position valve which will regulate the amount of steam used to drive the turbine. To determine the speed regulation used routh-hourwitz for control stability. The first step was to reconstruct the first loop in the previous block diagram as shown in (7) [21].

$$KG(s)H(s) = \frac{K}{(Hs+D)(1+\tau_g)(1+\tau_t)} \tag{7}$$

$$KG(s)H(s) = \frac{K}{(10s+0.7)(1+0.2s)(1+0.5s)} \quad (8)$$

$$KG(s)H(s) = \frac{K}{s^3+7.07s^2+10.49s+0.7} \quad (9)$$

Where, $K = \frac{1}{R}$ (10)

The characteristic equation was given as (11) and (12).

$$1 + KG(s)H(s) = 0 \quad (11)$$

$$1 + \frac{K}{s^3+7.07s^2+10.49s+0.7} = 0 \quad (12)$$

The results in the characteristics of the polynomial equation were as (13).

$$s^3 + 7.07s^2 + 10.49s + 0.7 + K = 0 \quad (13)$$

Then use the routh-hurwitz array for the polynomial

$$\begin{array}{c|cc} s^3 & 1 & 10.49 \\ s^2 & 7.07 & 0.7+K \\ s^1 & \frac{73.46-K}{7.07} & 0 \\ s^0 & 0.7+K & 0 \end{array}$$

From row s^1 it can be seen that for control stability, the value of K must be less than 73.46, besides, from row s^0 K must be greater than -0.7. then with a positive K value the value is as follows $K < 73.46$. Because of that $K = \frac{1}{R}$, for the stability of system control, the governor regulation speed must be $R > \frac{1}{73.46}$ or $R > 0.0136$. The speed regulation value used in LFC experiments usually has a value of 3%–6% from rest to full load. Therefore, the value of R = 0.05 was used in this LFC experiment.

3.2. Retired battery energy storage system model

In order to see the dynamic effect of EV batteries on the LFC system, an appropriate BESS model is needed. The BESS block diagram can be made as shown in Figure 1 [22]. In this model the BESS is presented as third order dynamic model. Look up table is used to represent the state of charge (SOC) of the battery.

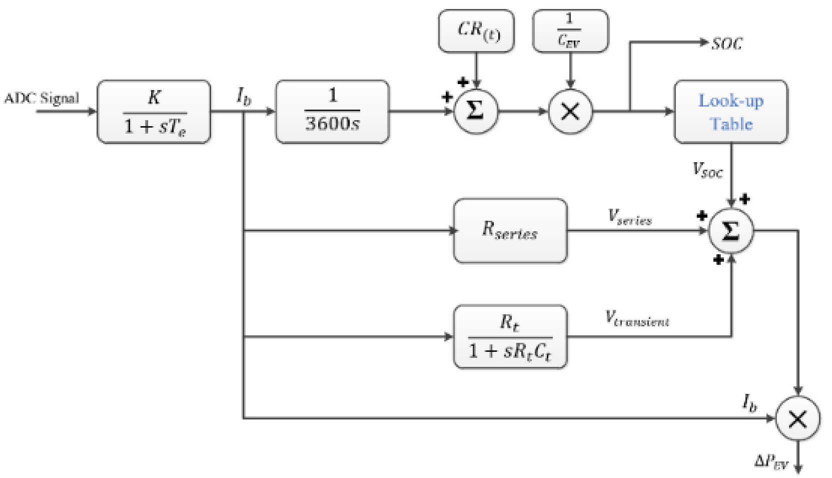

Figure 1. Battery model for LFC

The type of battery used in this design was a LiNiMnCo (Li-ion NMC) cell. To create an equivalent model parameter that represents an electric vehicle battery, a battery test was carried out which was used to show electrochemical impedance spectroscopy (EIS) and a hybrid pulse power characterization (HPPC) test. The results of the battery tests in the Table 1 show the parameters on new aged batteries and batteries that have been used in electric vehicles [23].

The old Li-NMC battery was a battery cell that has been used at 1900 full cycle at a temperature of 10°C. The battery has an efficiency (η) of 95% [24]. This battery aging characteristic was a realistic aging characteristic of electric vehicle batteries that have been in use for many years. The battery capacity between the new and old conditions was shown in Table 2 [25].

Table 1. Characteristics of cells in NMC batteries

Temperature and *State of Charge*	Parameter	New cell	Old cell
10 °C	*Rs*	0.7 mΩ	2 mΩ
70% SOC	*Rt*	1.5 mΩ	6 mΩ
	Ct	0.05 F	0.55 F

Table 2. Differences in battery capacity after and before use

Battery Cell Name	Initial capacity in Ah/Wh	Capacity After Use in Ah/Wh
Sel NMC	42.4/144.16	38/129.2

The required battery capacity needs to be measured in order to meet the power load demand. Measuring battery capacity is determined based on the following equation [24]. Where P_L, Ts, DoD and η are load required power (MW), duration of frequency regulation by BESS (h), depth of discharge (%), battery efficiency (%).

$$BESS\ Capacity\ [MWh] = \frac{(P_L * Ts)}{DoD * \eta} \quad (14)$$

4. RESULTS AND ANALYSIS

4.1. Scenario 1: comparison of 100% BESS and 70% state of charge (SOC)

The initial scenario carried out aims to evaluate the performance of a battery-based energy storage system that has different SOC and transmission capacities. Batteries with an SOC of 100% are hereinafter referred to as new batteries, while batteries with an SOC of 70% are hereinafter referred to as retired BESS. The SOC affects the open circuit voltage (OCV) of BESS that was generated to be supplied to a single area micro grid system. The BESS output power functions in dynamically stabilizing the frequency in the system. An increase in load power change was given as in Table 3 to the electric power system without any integration by the wind power plant (WPP). Retired and new battery types are made with the same gain value. Other parameter values contained in new batteries and retired batteries with a transmission capacity of 140 MW can be seen in Tables 1 and 2. Meanwhile, new batteries with a transmission capacity of 100 MW can be seen in Table 4 [26].

Table 3. Load integration in the first scenario

Integration type	Operation time (s)	Power (MW)
Load	30-300	200

Table 4. Battery specification with 100 MW transmission capacity

Battery type	State of charge	Battery capacity MWh/MW	Parameter	Parameter Value	Unit
			Rs	13	mΩ
Tesla roadster	100% SOC	40/100	*Rt*	1	mΩ
			Ct	1	F

The simulation results in the form of output power at the three BESSs are shown in Figure 2. The power is the output power supplied to the micro grid system. The output power at BESS affects the LFC micro grid system in balancing power due to power load demand. The power balance in the system affects the frequency generated by the generator. The frequency deviation caused by the integration of BESS and power load can be seen in Figure 3. It is noticeable that the new 140 MW BESS shows that the frequency deviation on the micro grid is -0.01416 p.u or -0.835 Hz. Then the new BESS of 100 MW has a frequency deviation of -0.01416 or -0.849. While on the retired battery there is a frequency deviation of -0.01395 p.u or -0.837 hz. From this value, it can be seen that the new battery has a smaller overshoot value compared to a battery with a retired battery at the same transmission capacity. The new 140 MW battery can reduce the overshoot value by ± 97.102% compared to the 140 MW retired battery. Meanwhile, the new battery with a smaller transmission capacity (100 MW) has a larger overshoot of 1.694% compared to BESS which has a transmission capacity of 140 MW.

Settling time is the amount of time (in seconds) required for the damped oscillation of the transient response to persist at ±2% to ±5% of its steady-state value. Settling time has an important role in providing information related to the speed and quality of the response generated on a single area micro grid. The new type of BESS can reduce the value of settling time faster than retired BESS with the same transmission capacity (140 MW) of about ± 20 seconds. The new 140 MW BESS can return the frequency deviation value to its nominal value after experiencing a disturbance 73.950% faster than the 140 MW retired BESS. Then the BESS with a transmission capacity of 100 MW has a settling time value of 250 seconds. The BESS tends to affect the value of settling time on the system by 28% and 20% which is longer than the new BESS of 140 MW and retired BESS of 140 MW. It shows that the capacity and aging of the battery have an influence on the quality and response speed of the electric power system. However, both the new BESS and the retired BESS are still able to dampen the frequency oscillations caused by power disturbances and can return the frequency value to its nominal value.

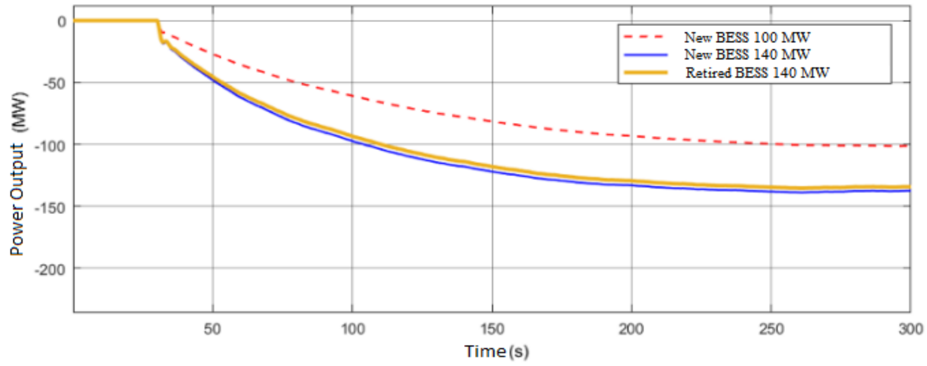

Figure 2. Output power at each BESS with different capacity and SOC

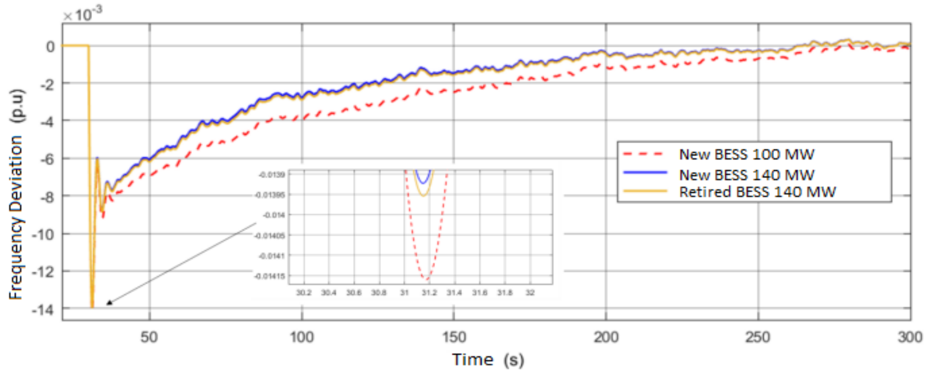

Figure 3. Graph of system response with different SOC BESS

The frequency overshoot of the simulation results in experiment one is compared with the frequency overshoot that is allowed according to the North American Electric Reliability Corporation (NERC) standard is shown in Table 5. While the cumulative number of errors in each type of BESS as shown in Table 6 uses a comparison of ITAE values. From the result, retired BESS still giving a good frequency support to the system indicated by the small value of frequency system ITAE value.

Table 5. Comparison of simulation result values with ISO 8528-5 frequency standard

Controller	*Overshoot* (Hz)	Error (%)	Standard ISO 8528-5
New BESS 100 MW	-0.849	43.4	± 1.5 Hz
New BESS 140 MW	-0.835	44.3	
BESS *retired* 140 MW	-0.837	44.2	

Table 6. Integral time absolut error (ITAE) value scenario one

No.	**Controller**	ITAE Value
1.	New BESS 100 MW	58.66
2.	New BESS 140 MW	21.32
3.	BESS *retired* 140 MW	22.62

4.2. Scenario 2: impact of fluctuation by WPP

In this scenario, one area is connected to a power load disturbance. In addition, a fluctuating pattern of wind speed is added to the LFC system. The graph of load power and WPP integration can be seen in Figure 4. While in Table 7, the operating time and parameter values in the simulation are given.

From Figure 5 it can be seen that in the 120 th second there is an integration by WPP of 80 Watt or 0.8 p.u. This integration resulted in a change in the frequency increase in the one area microgrid system. Meanwhile, if the system is disturbed in the form of a change in load increase of 200 MW or 0.2 p.u, it will cause a decrease in the frequency deviation in that area. The frequency change has different values depending on the type of controller provided. The biggest change in frequency decrease occurred in the conventional LFC type controller of -0.01433 p.u or -0.859 Hz. Meanwhile, other controllers such as PI controller, SMES and retired BESS tend to have a relatively smaller overshoot value compared to conventional LFC. The PI controller was able to reduce the overshoot value 2.16% smaller than conventional LFC, while for SMES and retired BESS controllers it was able to reduce the overshoot value by 56.468% and 95.10% smaller than conventional LFC, respectively. When the frequency deviation is steady, the SPE system is able to provide a relatively small steady-state error compared to the controller that is not integrated with the SPE. In conventional controllers the LFC does not show steady state at a value of zero to 1000 seconds. While the SMES and retired BESS systems have a steady value of zero (0). This shows that LFC with added SPE tends to have better robustness than conventional LFC and PI controllers.

Energy storage systems such as SMES and BESS are proven to be able to reduce the amplitude of frequency oscillations more optimally than conventional LFC or PI type controllers. When the microgrid system is overloaded, the SPE will supply the stored active power as a dynamic stabilizer so that power stability can be achieved as indicated by the frequency deviation close to zero. Meanwhile, when the WPP integration is connected to the system, the power contained in the system increases so that the SPE reduces its power output in stabilizing the power of the micro grid system. At this time the SPE acts as a smoothing power. Then the output power of the SPE is shown in Figure 6.

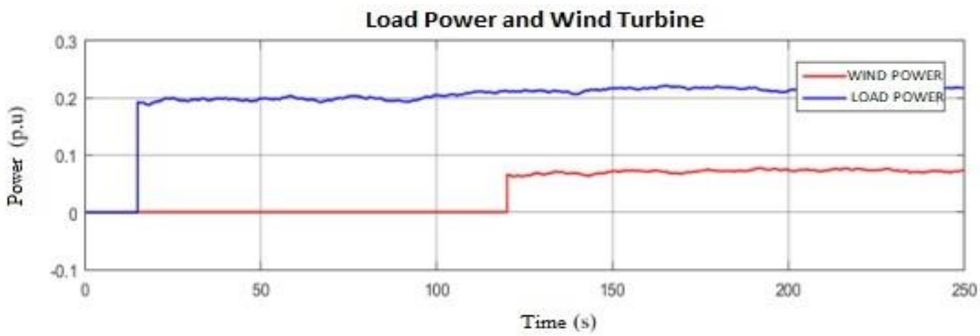

Figure 4. Wavefrom on generating and load sides

Table 7. Parameter value and WPP operating time and load

Integration type	Operation time (second)	Power (MW)
Load	15-1000	200
WPP	120-1000	80

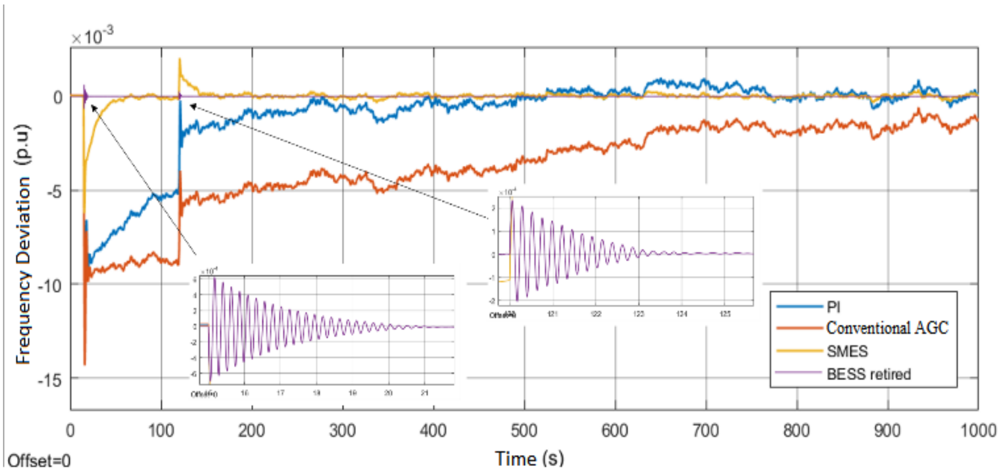

Figure 5. System response in scenario three

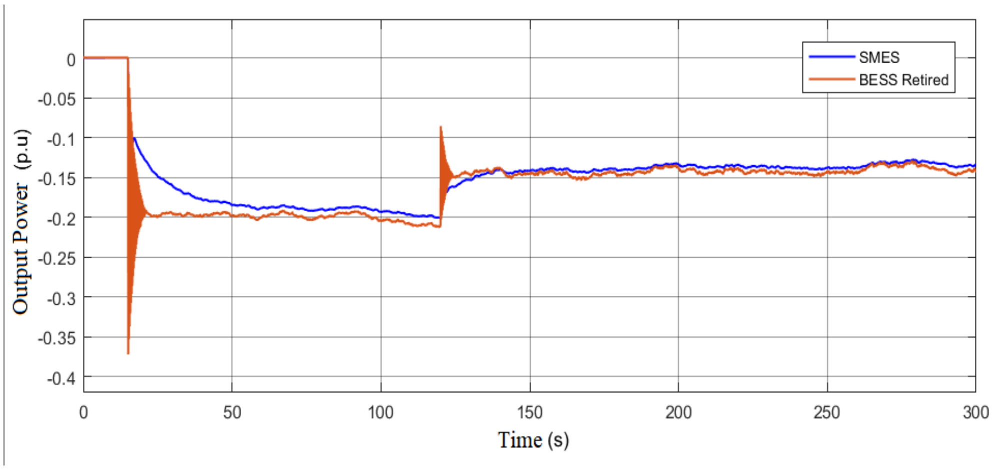

Figure 6. Comparison of output power on SPE

The controller with SPE is proven to be able to reduce frequency deviation effectively to maintain system stability. This can be proven from the cumulative number of errors in each system as can be seen in Table 8. The frequency deviation overshoot generated by the simulation in this third experiment is compared with the permissible frequency deviation standard in the electric power system according to ISO 8528-5 as shown in Table 9.

Table 8. Scenario three ITAE value

No.	Control system	ITAE value
1.	Conventional LFC	1273
2.	Controller PI	229.2
3.	SMES	40.19
4.	*Retired* BESS	0.4913

Table 9. Comparison of overshoot with ISO 8528-5 frequency standard in experimental three

Controller	-Overshoot (Hz)	Value error (%)	Standard ISO 8528-5
Conventional LFC	0.882	41.2	± 1.5 Hz
PI	0.864	42.4	
SMES	0.38334	74.444	
Retired BESS	0.042954	97.1364	

5. CONCLUSION

This paper investigated the influence of adding retired electric vehicles battery as the battery energy storage system on frequency stability analysis. Microgrid system is used as the test system to investigate the efficacy of the retired EV. From the simulation results it is noticeable that can reduce frequency deviation and maintain the robustness of the system as a comparison with other controllers, retired battery has a minimum error performance index value of ± 5,157% larger than the new type battery and respectively ± 99.96%, ± 99.83%, ± 98.90% smaller than conventional controller load frequency control, controller proportional-integrator type, energy storage system based on magnetic superconducting. Further research can be conducted by adding virtual inertia controller for retired EV. In addition, designing the controller using artificial intelligence can also considered as further research.

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