Load Frequency Control of Two-Area Network using Renewable Energy Resources and Battery Energy Storage System

In an interconnected system, the frequency and tie-line power interchange are very susceptible with the diversification of power load demand. Literally, in a multi-area power system, the load frequency control (LFC) is substantially aimed to minimise the deviations of these parameters relatively. Knowingly, the power production from renewable energy resources could offer promising solutions despite their intermittency (i.e. photovoltaic/wind generation), hence in this context, a battery energy storage system (BESS) is proposed to delineate dynamic response along with grid-connection. This study has proposed LFC with BESS control method to suppress frequency deviations for a power system and being compared with photovoltaic (PV) approach. The effectiveness was verified using newly developed AGC30 model of Japanese Power System and was modelled using MATLAB Simulink. Furthermore, an analysis of the tie-line power oscillations also are carried out and comparison analysis demonstrates further the reliability of the proposed model and control methods.

Keywords: Battery Energy Storage, Load Frequency Control, Photovoltaic

1. Introduction

Load Frequency Control (LFC) is a prime important in an interconnected power system which mainly used to control frequency deviations of supply and demand imbalance. LFC is employed to allow an area to first meet its own load demand with initiating allowable primary and secondary control mechanism in retrieving a steady-state system frequency, (e.g. \( \Delta f = 0 \)). In conjunction with the increasing rate of renewable energy resources, it is presumed that it can help to regulate the frequency control either for small scale or big scale power system.

According to Renewable Energy Institute of Japan, a cumulative solar and wind power generating capacity has reached about 37 GW by the end of 2015 out of 300 GW total generation capacity. This percentage deterministically will be increased since the Japanese government had a promising plan to increase the dependency on renewable energy (RE) overwhelmingly.

Ultimately the aim of integrating high penetration of renewable energy (RE) into an integrated grid system is mainly to reduce the reliance on conventional thermal power generation. However, invariably from past decades, thermal generating units play an important role in frequency regulation of power systems due to its capability to deploy primary and secondary control effectively [1]. Generally, the kWh output of generating units can also significantly minimised if photovoltaic (PV) and wind turbine (WT) successfully be controlled [2]. In [3], PV generating units is determined to suppress frequency deviation and control the tie-line power flow control. Apparently, the output of Photovoltaic and WT

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generations greatly fluctuates due to their nature, and this could possibly affect system frequency at high risk. So, a countermeasure must be taken into consideration to cope with frequency deviations for instance battery energy storage system (BESS).

Batteries and other power storage devices are discussed for supply and demand adjustment especially during off-peak periods [4]. Battery Energy Storage System (BESS) was used as a reserve capacity for supplying off-peak loads event [5]. Moreover, it has been reported in [6]-[7] batteries have a faster response than conventional power generations and give better performance regarding frequency regulations during any event of transient instability. In [8], BESS is utilised to support load frequency for both during main grid mode and islanded mode. In addition, BESS must, use corrective measures and control algorithms, to keep their state of charge within limits [9]. It is also reported that BESS could also partially or fully helps micro grids to compensate power absorption by local loads along with voltage support.

In today’s current expanding power system, more integration of electric vehicles (EV) are deployed. It has been determined that the EV equipped with Vehicle to grid (V2G) control strategy can help in damping system frequency fluctuations [10]. V2G control strategy is performed to maintain the battery energy around the residual SOC along with adaptive frequency droop control [11], [12], [13]. EVs help to re-heat thermal turbine units quickly to provide more stability. In [14] it was discussed that more complex control of EV application with recent power electronic devices i.e. Thyristor controlled phase shifters being utilised for LFC mechanism with a new distribution functional observers are introduced to cope with accidental failures. In [15] the EV is used together with multiple time delays in the control inputs and output feedback control for smart grids application.

A delay commonly introduced for LFC purposely to match generator response with system control signal which is quite fast [16]-[17]. In [18], a latest computer-based communication network was established with the intention to minimise the delay signal for LFC with dynamic supplementary adaptive programming and only tested in one area, but not for multiple areas. In [19], it has addressed and introduced the use of a combination of typical high-end communication elements for controlling the load frequency.

So, in this study, an investigation of the newly developed model of AGC30 system is determined for frequency regulation. Moderate penetration of PV was introduced to cope with frequency changed by imposing delta control approach. Next, a battery energy storage system (BESS) is proposed using dead band control and both of these control mechanisms were being compared deliberately. In this simulation, the off-peak load was utilised to further investigate on supply and demand variation and all the related results have been discussed thoroughly.

2. Notation

The notation used throughout the paper is stated below.

**Constants:**
- \( \Delta f_i \) Incremental frequency deviation for the \( i_{th} \) area
- \( \Delta P_{di} \) Incremental change in load demand for the \( i_{th} \) area
- \( \Delta P_{tie} \) Incremental change in tie-line power
- \( \Delta P_{gi} \) Incremental change in governor position for the \( i_{th} \) area
- \( \Delta P_{ti} \) Incremental change in power generation level for the \( i_{th} \) area
- \( B_i \) The bias constant for the \( i \)th area
3. Problem formulation

3.1. Load Frequency Control

Basically, in automatic generation control (AGC), all generating sets could contribute in regulating frequency deviations evolved due to power imbalance scenario. In overall the efficiency, stability, and economy definitely enhanced by maintaining the power interchanges over the tie lines at the scheduled levels. There are three main parts of control demonstrated as shown in Fig. 1.

1. Governor Free (GF)
2. Load Frequency Control (LFC)
3. Economic Dispatch Control (EDC)

![Period of Load Change](image)

Fig.1: Period of Load Change and Appropriate Control

The main goal of GF control is to detect frequency deviation at the site and controlled within few cycles. Next, the LFC will be deployed within seconds up to 20 minutes. Then in the larger scale of operation, EDC is being utilised completely to minimise total operating costs in an area by determining the real output capacity of each generating unit will meet for specifically given load demand. An economic dispatch algorithm will run every few minutes to select the combination of generating units that could possibly minimise overall operating generation cost. The system investigated comprises an interconnection of two areas load frequency control. The model equations of two areas load frequency control can be written as follows [20];

\[
\Delta PG1 = \frac{-1}{T_{g1}} \Delta PG1 + \frac{-1}{R_{1}T_{g1}} \Delta f1 + \frac{1}{T_{g1}} U1 \tag{1}
\]

\[
\Delta PT1 = \frac{1}{T_{T1}} \Delta PG1 + \frac{1}{T_{T1}} \Delta PT1 \tag{2}
\]

\[
\Delta f1 = \frac{K_{p1}}{T_{p1}} \Delta PT1 + \frac{-1}{T_{p1}} \Delta f1 - \frac{K_{p1}}{T_{p1}} \Delta P_{tie} - \frac{K_{p1}}{T_{p1}} \Delta P_{d1} \tag{3}
\]
\[ \Delta P_{tie} = T_{t2} \Delta f_1 - T_{t3} \Delta f_2 \]  \hspace{1cm} (4)

\[ \Delta P_G = \frac{-1}{T_{G2}} \Delta P_G + \frac{-1}{T_{R2,G2}} \Delta f_2 + \frac{1}{T_{G2}} U_2 \]  \hspace{1cm} (5)

\[ \Delta P_{T2} = \frac{1}{T_{T2}} \Delta P_G + \frac{-1}{T_{T1}} \Delta P_{T2} \]  \hspace{1cm} (6)

\[ \Delta f_2 = \frac{K_{p2}}{T_{p2}} \Delta P_{T2} + \frac{-1}{T_{p2}} \Delta f_2 - \frac{a_{12,Kp2}}{T_{p2}} \Delta P_{tie} - \frac{K_{p2}}{T_{p2}} \Delta P_{d2} \]  \hspace{1cm} (7)

From Fig. 2 it shows the generic frequency analysis model for an interconnected power system.

From Fig. 3 and 4, the PV control block diagram is shown. In this study, a delta control method is introduced to act as a reserve capacity through which LFC signal can trigger PV control to adjust its output and maintain frequency deviations.

Generally, it is known that the fluctuations of short cycles are mainly large for photovoltaic power generation, as a result of sudden changes in weather, but these outputs are synthesized on an area basis. In the case of a smoothing effect, the fluctuation of a short period is suppressed. In this study, 50 MW of control margin is applied to offer resilience through which the system can adjust its dynamic response in terms of AR, \( \Delta f \) and \( \Delta P_{tie} \).
3.3. Battery Energy Storage System

In the scenario where the uncontrollable energy resources of solar or wind energy massively deployed and being connected to the network, explicitly it would imply more frequency deviation during intermittency period of time. It is also known that battery dynamic response is superior to PV or WT which if by combining and deploying a battery into the network certainly could minimise the abrupt change of system frequency. So here, it is manifestly presumed a battery energy storage system (BESS) must be embedded along with renewable energy resources or works independently to give accessible necessary support towards grid stability.

a) **BESS Modelling**

Unlike renewable energy generations, BESS output does not fluctuate under weather conditions so it can be designated for suppressing frequency regulation with suffix amount of capacity. In the investigation for AGC30 model, in the initial model, the proposed battery was set at the largest scale with 50 MW and 300 MWh at Toyohama substation in the Kyushu area.

It is also reported that in the area with limited generation capacity such as isolated islands, likely the introduction of renewable energy will be penetrated and expanded hence selection of battery types to suit the ratio of power capacity (kW) to the energy capacity (kWh) must be determined and under this consideration, basically a bulk energy storage systems are introduced as shown in Table 1.

Next, it is decided to make the storage capacity as realistic as possible in obtaining greater control effect. Under low demand period which is about 10,000 MW, the load frequency control (LFC) must be secured to 2% of the entire system capacity in the area e.g. 200 MW. It is carefully pre-determined here for battery storage system to have a substantial control effect with having at least 1/4 or 1/5 of the LFC capacity ($P_{\text{Battery}} = 50\text{MW}$).
Table 1: Large Scale Battery Storage System

<table>
<thead>
<tr>
<th>Plant Area</th>
<th>Power Generation Substation</th>
<th>Battery Type</th>
<th>Rated Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hokkaido</td>
<td>South</td>
<td>Redox Flow</td>
<td>15 MW</td>
</tr>
<tr>
<td>North East</td>
<td>West</td>
<td>Lithium-ion</td>
<td>20 MW (short-period)</td>
</tr>
<tr>
<td></td>
<td>South</td>
<td>Lithium-ion</td>
<td>40 MW</td>
</tr>
<tr>
<td>Kyushu</td>
<td>Toyohama</td>
<td>Sodium Sulphur</td>
<td>20 MW</td>
</tr>
</tbody>
</table>

Moreover, to suppress a short cycle fluctuation of area requirement (AR) and system frequency it is assumed that Lithium ion battery is capable of the task due to its rapid charge and discharge capability. The default model of existing energy storage system was generically modelled (not following the standard model) because previous details information of the battery is considered extremely small.

In Fig. 5 and Table 2 show the block diagram of initial battery storage model used in AGC30 with its initial setting values.

Table 2: Battery Parameter Initial Setting

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOC Target Value</td>
<td>50%</td>
</tr>
<tr>
<td>SOC Initial Value</td>
<td>50%</td>
</tr>
<tr>
<td>SOC Proportional gain, (Kp)</td>
<td>1.0</td>
</tr>
<tr>
<td>LPF Time constant</td>
<td>50 seconds</td>
</tr>
<tr>
<td>SOC Limiter</td>
<td>±10%</td>
</tr>
<tr>
<td>Charge and Discharge Efficiency (ef)</td>
<td>95%</td>
</tr>
<tr>
<td>Rated Charge and Discharge Time (ct)</td>
<td>60 minutes</td>
</tr>
</tbody>
</table>

Basically, the SOC is designed to return to its targeted value in the time domain depending on the cycle of fluctuation of the battery storage control. Moreover, the LPF (1st order system) is used to control the SOC for no longer than five minutes and then the LFC control will take further action.
b) Battery Control Method

Similarly, as in governor-free control mechanism, the battery storage control aim is to measure the system frequency and control its output accordingly in conjunction with the rate of adjustment. Basically, this kind of control is essential for an isolated area with having large frequency fluctuation and almost no control delay is available thus the dynamic response of battery splendidly offers significant improvement. However, due to the great responsiveness of the battery, the rate of sharing capacity is increased resultant in deficiency and shortage of power undisputedly. Therefore, in most cases, HPF will extract the power and only components which having a short cycle and rapid fluctuation will be shared of the battery storage power.

Another method for area requirement (AR) distribution to battery storage system is by keeping the AR fluctuation within its specified value with regard to load fluctuation in the local area or intermittency of the power supply. Generally, economic load dispatch (EDC) control will keep on energising due to the load frequency control (LFC) insufficiency. Thus, to overcome this deficiency of LFC capacity, the AR is allocated relatively for shorter fluctuation period from the battery energy storage hence it is possible to make sure both speed of output change and LFC capacity would follow the AR fluctuation appropriately. The next alternative is to measure the output variation of natural energy resources and cancel it out by using BESS but it is exclusive for larger area network compared to small or remote islands area due to the limitation of the smoothing effect. The smoothing effect works well with the larger system.

So, in this investigation, the main aim is to improve the influence of the renewable energy resources fluctuation by implementing or integrating battery storage control and further
yields explicit resiliency. Literally, the battery gain is set at 0.7 but there is no problem to set it up to 1.0 since few generators can still follow the fluctuation of 15-minutes cycle and consequently the battery output will stay longer at the upper limit of the limiter.

c) Proposed BESS Controlled

The default model of energy storage given in the AGC30 was modelled generically so here an alternative for improvement is proposed for a battery energy storage system (BESS) control which also includes the control effect of area requirement (AR) and LFC signal as shown in Fig 6 and 7 correspondingly.

A visual concept of AGC30 model as in Fig. 8 shows that the proposed BESS Control can be added together with predefined of PV and WT actual data while the load characteristic will be taken into an investigation for mere off-peak load scenario. A dead band control is applied for any frequencies which deviate within ±0.1Hz. The battery output capacity will response whenever the limitation of the dead band is violated and will then accommodate the system frequency eventually.
4. Results

In this investigation, as mentioned earlier we implemented the latest developed model of so-called AGC30 for detail analysis on frequency regulation. This model intentionally been constructed by the institution of IEEJ to conceptualise deliberately frequency regulation control for interconnected two area power system with the deployment of alternative renewable energy resources and battery respectively in actual Japanese power system. The overall configuration of the AGC30 test model system is shown in Fig. 10. Basically, there are 30 generators being connected and are controllable and include another 7 uncontrollable generators i.e. nuclear and hydro with having a total of 10 GW of demand.
The reason for choosing only off-peak load mainly because of rate-of-change of frequency certainly increased and become severe to the reduction of end load demand. In this matter, all related control must be incorporated to take action to minimise the prominent deviations. A simulation is carried out for peak and off-peak load scenarios and can be fully apprehended as in Fig. 11.
a) **PV Controlled Approach**

In this section, only PV deployment will be investigated without WT presence for simplicity purposes. Thus, in Fig. 12 it shows the PV output at off-peak load which represent the worst case as the imbalance between supply and demand would be at highest values. By referring to the initially developed model of PV stochastic data, a total of 1.2 GW of active power has been integrated as a static input at the summation of power imbalance block without any other compensation elements such as battery and WT. Therefore, with adjusting the PV output with delta control it can be sufficient for taking the control effect substantially. As previously mentioned, AGC30 system is designated so that under low demand period, LFC signal is predetermined with 2% of the entire PV capacity. For that reason, the control margin is being set with 50 MW to cover LFC signal control capacity.

![Fig. 12: PV Output Power at Off-Peak Load](image)

From Table 3, it can be illustrated that, by integrating PV in AGC30 system, AR, $\Delta f$ and $\Delta P_{tie-line}$ seem to be decreasing compared to the original system without PV in terms of Max, Min and average deviation index. Nevertheless, the max margin does not show promising results in terms of suppressing frequency deviations (4.5% reduction only).

<table>
<thead>
<tr>
<th>Control Action</th>
<th>Value</th>
<th>AR [MW]</th>
<th>$\Delta f$ [Hz]</th>
<th>$\Delta P_{tie-line}$ [MW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without PV Control</td>
<td>Max</td>
<td>257.93</td>
<td>0.1363</td>
<td>174.41</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>-252.58</td>
<td>-0.169</td>
<td>-155.53</td>
</tr>
<tr>
<td>With PV Control</td>
<td>Max</td>
<td>201.998</td>
<td>0.1302</td>
<td>166.79</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>-226.32</td>
<td>-0.138</td>
<td>-138.31</td>
</tr>
</tbody>
</table>
Fig. 13: Index Control (AR, Frequency Deviation, and Tie-line Flow Deviation) at Off-Peak Load

Fig. 13 (a)-(c) conforms to Table III statistics. It is shown that at some points PV integration has an influence on suppressing deviations. However, at some other points, the proposed control doesn’t show an efficient response. From the simulation, it is noticed that, by increasing control margin, the average deviation in frequency, Tie-line flow deviation and AR is reduced. However, average deviation index increases, for that 50 MW control margin is considered and to reduce PV curtailment.

Consequently, we proposed that BESS should suppress the deviations, regulate AR, $\Delta f$ and $\Delta P_{\text{tie-line}}$ and superiorly take control of short-period fluctuations. For that, A BESS is integrated with the AGC30 system to improve its dynamic response.

b) BESS Controlled Approach

In this section, similarly as mentioned previously only single loading scenario will be further investigated which is the off-peak load. Knowingly, the frequency will tend to oscillate more when the load demand is low due to imbalance supply and demand criterion whereby the conventional thermal generator must response briskly and control efficiently in deploying governor free and load frequency control in time.
From Fig. 14, the BESS output limit is still within the targeted allocation as stated in Table 1 (e.g. $P_{\text{MAX,BESS}} = 50\text{MW}$). By total, there are 100MW from peak-to-peak of battery capacity available in this investigation. Therefore, the proposed model successfully suppresses the rate-of-change of frequency and tie-line power flow within its specified ranges of allowable capacity.

Unlike the previous section of PV approach, in this BESS section, there is no PV integration at all being added at the summation of power imbalance block so the outputs pattern for without BESS control will be slightly different from the outputs for without PV control. However, this will be verified later to seek for comparison performances in the next section. Thus, from Table 4 and Figure 15 (a)-(c) the simulation results for off-peak load condition are shown. The index control (i.e. AR, $\Delta f$ and $\Delta P_{\text{tie-line}}$) seem to decrease from the one without BESS.

All the parameters for minimum and maximum values indicate the enhancement of deploying BESS except for the improvement of the maximum value of $\Delta P_{\text{tie-line}}$. For this reason, it can be classified and notified that in LFC control there are two major functions, load following and frequency regulation.

Consequently, we proposed that BESS should regulate for frequency problems and as for load following part it is presumed for conventional generators to take responsibility namely for large long-period fluctuations. Hence, it implies in overall that BESS dynamic response is superior to correspond in sustaining not only AR and system frequency but in average for tie-line power flow in the respective area as well.
Fig. 15: Index Control (AR, Frequency Deviation, and Tie-line Flow Deviation) at Off-Peak Load with BESS Proposed Method
Table 4: Control Result Analysis with BESS Method

<table>
<thead>
<tr>
<th>Control Action</th>
<th>Value</th>
<th>AR [MW]</th>
<th>∆f [Hz]</th>
<th>∆P_tie-line [MW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without BESS</td>
<td>Max</td>
<td>211.0</td>
<td>0.1339</td>
<td>160.7</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>-185.4</td>
<td>-0.1448</td>
<td>-128.5</td>
</tr>
<tr>
<td>With BESS</td>
<td>Max</td>
<td>203.7</td>
<td>0.1272</td>
<td>166.3</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>-174.6</td>
<td>-0.1411</td>
<td>-124.7</td>
</tr>
</tbody>
</table>

c) **BESS versus PV Controlled**

The drawbacks of using PV is more detrimental especially if being integrated into the main grid with uncertainty power or fluctuation, so the stability and operational safety can then be improved with using BESS. Ideally, the battery can compensate fluctuations produced by PV and the generation rate constraints from conventional generators. In Fig. 16 it can be seen clearly that BESS control is much better than PV control for suppressing frequency. In addition, in Table 5, the deviation percentage between both control is tabulated and as for the average, undisputedly BESS control method is superior to PV control method by 14.37 %.

![Fig. 16: Comparison of PV and BESS Control for Frequency Deviation](image)

Table 5: PV versus BESS Control Analysis

<table>
<thead>
<tr>
<th>Control Action</th>
<th>Max</th>
<th>Min</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>With PV Control</td>
<td>0.1302</td>
<td>-0.1377</td>
<td>0.04023</td>
</tr>
<tr>
<td>With BESS</td>
<td>0.1272</td>
<td>-0.1411</td>
<td>0.03445</td>
</tr>
</tbody>
</table>

Deviation 2.304 % -2.396 % 14.37 %
The area average of PV control and BESS control towards frequency deviation can be computed using the following formula below;

\[ \Delta f_{\text{Average}} = \frac{1}{T} \int_{t=0}^{T} \Delta f \ dt \]  

(8)

An improvement of 12.17% is realized through the Eq. 8 compared to 14.37% with graphical simulation results. The result taken from the equation is rationally more accurate compared to the result taken from Fig. 16 but both are presumably reliable with mere 2.2 % of differentiation only.

Furthermore, it has been realized by using the same capacity of 50 MW for both PV control and BESS control approaches, the dynamic response of BESS control for LFC signal is proven better in terms of frequency deviation suppression than that of PV control.

5. Conclusion

This paper has presented a novel LFC mechanism using both PV and BESS to regulate and suppress the system frequency caused by load demands fluctuation e.g. off-peak load. First, a framework of the test system of AGC30 for investigation has been developed and given beforehand. Based on this particular model, a further simulation of two area network with the provision of proposed PV and BESS approach are deployed. Extensive simulations and comparisons were carried out in every section of this paper to show and prove the effectiveness of the proposed control alternatives. It is expected that with both control approaches, the frequency stability of the test system can be well-maintained. In a nutshell, the BESS control approach shows significant impact towards minimising the deviation of indices control (i.e. AR, frequency, and tie-line power flow) and successfully implemented and fitted with new developed model of AGC30. By giving with this idea, V2G (vehicle-to-grid) concept can be soon realised and integrated with the same test system in future.

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References


