Novel PID Controller on Battery Energy Storage Systems for Frequency Dynamics Enhancement

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Abstract—Frequency dynamics is one of the important aspects of power systems' stability. From the frequency dynamics, the operator could plan how is the reliability of the electricity. The frequency can be maintained by controlling the balance between load demand and generation. To maintain the balance of the generation, the governor is playing an important role to increase the speed of the turbine and enhance the generating capacity of the generator (ramp-up). However, as the speed of the governor is slower than the increasing load demand, in the sub-transient area, the frequency may experience higher overshoot. Hence, it is important to add additional devices such as battery energy storage systems to enhance the frequency dynamics response in the sub-transient area. One of the important parts of storage is the controller. The controller must make sure the storage charges and discharge energy are in the sub-transient area. Hence PID controller can be the solution to make the storage operate optimally. This paper proposed a novel PID controller on battery energy storage systems (BESS) to enhance the dynamics performance of frequencies. The five-area power system is used as the test system to investigate the efficacy of the proposed novel idea. Time domain simulation is investigated to see the improvement of the frequency dynamics response. From the simulation results, it is found that adding a PID controller on BESS could enhance the BESS response and result in frequency dynamics response improvement.

Keywords—Battery Energy Storage System; Clean Energy Technology; Energy Governance; Multi-area Automatic Generation Control; Proportional Integral Derivative.

I. INTRODUCTION

In these modern times, the demand deviates from its normal state by an unpredictable small amount [1]. Therefore, the system may suffer from nominal frequency deviations, which can produce undesired effects [2]. Thermal Generating Unit (TGU) needs to continuously supply electricity with increasing demand [3]. Automatic Generation Control (AGC) has the role to maintain oscillation frequency and tie-line power in unpredictable load changes [4]. The AGC controller parameter has a significant influence on the control performance of Area Control Error (ACE), which measures the balance of generation with electricity demand, and contract compliance between control areas [5]. It is called secondary control and requires each control area to fulfill its demand [6]. As a result, it can maintain the nominal frequency in the system [7]. The main aim of this paper is to help to solve the frequency problem on multi-area and five-area AGC interconnects TGU non-reheat systems [8].

The power system is tasked with maintaining a balance between power demand and power generation so that high-quality and reliable electricity is available to users [9]. To do that integral controller, PI control, and PID controller are used in the AGC. The application of integral control for AGC is reported in [10]. In [10], renewable energy integration is considered. In addition, the integral controller is optimized using the auction-based algorithm. The research effort in [11], proposed a PID controller as the AGC controller. It is reported that the PID controller is giving satisfactory control for balancing the demand and production. The application of fuzzy-PID to maintaining the balance between demand and production is reported in [6]. In [6], the hydro-thermal-power system is considered as the source. In addition, high voltage direct current (HVDC) lines are also considered in the system. From the simulation results, it is observed that the fuzzy-PID can be used to control the hydro-thermal power plant governor for maintaining the balance between the power and the demand. The application of the 3DOF-PID controller for frequency enhancements is reported in [12]. The renewable energy power plant is considered in the system. From the simulation results, it is noticeable that the proposed method can help the system to maintain the frequency response. However, if the interconnected system is more than two areas, controlling only the governor to enhance the frequency dynamics response is out of date. Hence, it is important to add additional devices that can store and release electricity power in a short time [13], [14].

Battery energy storage systems (BESS) can be used as additional devices that can use to enhance the frequency dynamic performance [15]. BESS can use to store and releasing energy in a short period [16]. The application of BESS to help AGC for enhancing the frequency response of the power system is reported in [17]. From the simulation results, it is noticeable that BESS can help AGC to enhance the frequency performance by storing and releasing energy in a short period. The application of BESS for frequency regulation in islanded power systems is reported in [18]. From the simulation results, it is noticeable that BESS can be used to regulate the frequency. It is found that the frequency has less overshoot and faster settling time compared with the
system that only uses AGC. Asian Development Bank (ADB) publishes a handbook regarding the application of BESS [19]. From the book, it is reported that BESS can solve numerous problems associated with the integration of energy in large-scale grids. However, very scant attention has been made to developing the controller of BESS for enhancing the frequency dynamic response of power systems [20]. Hence, it is important to contribute to this area.

PID controller is one of the most practical controllers in engineering applications [21]. The application of PID controller for DC-DC converter controller is reported in [22]. From the results, it is noticeable that PID could provide a signal controller to the DC-DC converter. The research effort in [23], tries to utilize the PID controller as the DC motor controller. It is found that the DC motor speed has less overshoot and faster settling time when using the PID controller as the controller. The application of the PID controller as the controller of the flywheel energy storage system (FESS) is reported in [24]. From the simulation, it is proven that FESS with PID could provide better active power to the grid. In addition, many industries use PID controllers due to their simplicity and easy-to-understand structure [25]. Hence it is important to add a PID controller as an additional controller of BESS.

This paper proposed a novel method of adding a PID controller as an additional controller of BESS. Five areas of the interconnected power system are used as the test system of the paper. The rest of the paper is organized as follows: Section 2 describes the fundamental theory of the paper. Results and Discussion are described in Section 3. Section 4 highlighted the contribution and conclusion of the paper.

II. FUNDAMENTAL THEORY

In the electric power system, the frequency is a variable that is constantly changing because it is influenced by the generator and load. To stabilize the power system operation, the frequency is always maintained according to the limit permitted. The standard operation of different frequencies under normal and abnormal conditions has been carried out by different system operators are shown in Table I.

| Table I. Frequency Quality Parameters in the Synchronous Area of ENTSO-E |
|---------------------------------|-----|-----|-----|-----|
| Nominal Frequency               | CE  | GB  | IRE | NE  |
| Standard Frequency Range        | ±50 | ±200| ±200| ±100|
| Maximum Instantaneous Frequency Deviation | ±800| ±800| ±1000| ±1000|
| Maximum Steady State Frequency Deviation | ±200| ±500| ±500| ±500|
| Time to Recover Frequency       | 15 min | 1 min | 1 min | 15 min |

The operating frequency standards set by the European Network of Transmission System Operators for Electricity (ENTSO-E) are shown in Table I. There are four synchronous regions in Europe. The territory of Great Britain (GB) is forming its synchronous area. In the Continental Europe (CE) region are the areas of Austria, Belgium, Bosnia, Bulgaria, Croatia, Czech Republic, France, Germany, Greece, Herzegovina, Hungary, Luxembourg, Italy, Macedonia, Netherlands, Montenegro, Poland, Portugal, Romania, Serbia,
Slovakia, Slovenia, Spain, Switzerland, and western Denmark. The Inter-Nordic System (NE) is a transmission network in eastern Denmark, Finland, Norway, and Sweden. The All-Island Irish System (IRE) is the area of the Republic of Ireland and does not include Northern Ireland.

A. Automatic Generation Control

The power output generated by the generator in a multi-area power generation system interconnected via a power exchange (tie-line) must be of high quality [26]. These characteristics include a stable frequency and output voltage. A power generation system must be able to respond to load changes by releasing the necessary power [27]. A controller system is required to maintain the stability of the system output, which is commonly referred to as AGC, to have a stable output of power, frequency, and voltage. AGC works by adjusting the valve opening on the turbine to compensate for changes in power so that the power, frequency, and voltage remain stable [28].

In an electric power system, the generator will release two types of power: active power and reactive power. The active power on the generator causes the frequency to rise and fall in response to changes in the active power released. To stabilize the frequency oscillation, a controller system that can adjust the generator's output frequency is required [29]. This control system is commonly referred to as Load Frequency Control (LFC) [30]. Changes in the active power removed from the generator are influenced by the rotor angle (δ) and the frequency value (f), while changes in the reactive power in the generator are influenced by the voltage magnitude [31].

A change in the rotor angle ∆δ will cause a change in the value of the tie-line power and the output frequency. To correct this, the rotor angle error signal must be corrected [32]. The generator's output frequency and tie-line power will be used as input signals to the governor's valve controller [33]. The output signal at the valve will be an input to the prime mover to increase or decrease torque depending on the magnitude value of the input signal. Changes in the output value of the generator (∆Pc) are affected by the prime mover and this condition will change the value of frequency ∆f and tie-line power ∆Ptie [34].

LFC is designed based on the rotor angle setting on the generator. Changes in the rotor angle will be corrected so that the system frequency will be stable. The frequency deviation signal ∆f and ∆Ptie is amplified and converted into an active signal which will be sent to the prime mover to increase torque [35].

B. Inertia Representation

To control the system frequency in a synchronous generator, the active power, and the resulting kinetic energy function must be controlled [36]. The rotor's rotating mass generates inertia power measured in joules-seconds (Js) or watt-seconds squared (W·s²) [37]. This inertia power is used to compensate for a disturbance during the first 1-5 seconds of operation or when the primary and secondary controls are not activated [38]. Based on the swing equation, the inertial response of a synchronous machine can be written as follows, as described in (1) [31].

\[
\frac{d\omega}{dt} = \frac{T_m - T_e}{J_m} = \frac{P_m - P_e}{\omega}
\]

Where \( J_s, \omega, T_m, T_e, P_m, P_e \) is the moment of inertia, rotor speed, mechanical torque, electrical torque, mechanic power, and electrical power. (2) and (3) [39] describe the mathematical representation of inertia (3). Where S is the synchronous generator's power rating output [40].

\[
H = \frac{E_{\text{kinetik}}}{S}
\]

(2)

\[
E_{\text{kinetik}} = \frac{1}{2}J_s\omega^2
\]

(3)

When the system is made up of several interconnected generators, the total inertia constant is the ratio of the kinetic energy of each generator added together [41]. Furthermore, the system output power rating influences the inertia constant. As a result, referring to the total inertia can be written using (4) [42].

\[
H = \frac{\sum(SG_i)}{S_{PS}}
\]

(4)

Where the system's minimum inertia can be used to solve two major dynamic problems. The first issue is lowering the rate of change of frequency (RoCoF) after the perturbation appears. The second issue is to dampen frequency overshoot and limit frequency nadir when there is a disturbance in the system. RoCoF is the deferential frequency used to calculate the system's inertia response. The system's RoCoF value should be limited to ±1 Hz/s. RoCoFs mathematical representation can be described using (5) [43]. Where \( f_0 \) is the nominal frequency of the system.

\[
\text{RoCoF} = \frac{d(\Delta f)}{dt} = f_0(P_{m} - P_{e})
\]

(5)

III. METHOD

A. Test System

This study uses a multi-area AGC system. The AGC scheme is useful when the system load changes continuously [44]. Therefore, the generation is customized automatically to recover the frequency [45]. The five-area system in this study is shown in Fig. 1 because most of the research in the AGC field is concerned with the same two-area thermal system, and not much attention is paid to the different multi-area AGC systems [46]. In Fig. 2, the design of the five-area AGC system is modeled from the reference [47].

The transfer function of the governor shows (6).

\[
G_g(s) = \frac{K_g}{T_g s + 1}
\]

(6)

Meanwhile, the transfer function of the non-reheat turbine in (7) in (8) is the transfer function for rotating mass & load [48].

\[
G_c(s) = \frac{K_c}{T_c s + 1}
\]

(7)

\[
G_p(s) = \frac{K_p}{T_p s + 1}
\]

(8)
The five-area system gets the frequency deviation equation at (9) to (13) [49].

\[
\Delta f_1(s) = \left[ \frac{K_p}{T_p s + 1} \right] [\Delta P_m(s) - \Delta P_L(s) - \Delta P_{TL1}(s)] 
\]

(9)

\[
\Delta f_2(s) = \left[ \frac{K_p}{T_p s + 1} \right] [\Delta P_m(s) - \Delta P_L(s) - \Delta P_{TL2}(s)] 
\]

(10)

\[
\Delta f_3(s) = \left[ \frac{K_p}{T_p s + 1} \right] [\Delta P_m(s) - \Delta P_L(s) - \Delta P_{TL3}(s)] 
\]

(11)

\[
\Delta f_4(s) = \left[ \frac{K_p}{T_p s + 1} \right] [\Delta P_m(s) - \Delta P_L(s) - \Delta P_{TL4}(s)] 
\]

(12)

\[
\Delta f_5(s) = \left[ \frac{K_p}{T_p s + 1} \right] [\Delta P_m(s) - \Delta P_L(s) - \Delta P_{TL5}(s)] 
\]

(13)

Meanwhile, the tie-line power deviation equation points (14) to (18) [50].

\[
\Delta P_{TL1}(s) = \frac{2 \pi T_s}{s} \Delta f_1(s) - \Delta f_2(s) + \frac{2 \pi T_s}{s} \Delta f_3(s) - \Delta f_4(s) + \frac{2 \pi T_s}{s} \Delta f_5(s) - \Delta f_6(s) + \frac{2 \pi T_s^2}{s} \Delta f_7(s) - \Delta f_8(s)
\]

(14)

\[
\Delta P_{TL2}(s) = \frac{2 \pi T_s}{s} \Delta f_1(s) - \Delta f_2(s) + \frac{2 \pi T_s}{s} \Delta f_3(s) - \Delta f_4(s) + \frac{2 \pi T_s}{s} \Delta f_5(s) - \Delta f_6(s) + \frac{2 \pi T_s^2}{s} \Delta f_7(s) - \Delta f_8(s)
\]

(15)

\[
\Delta P_{TL3}(s) = \frac{2 \pi T_s}{s} \Delta f_1(s) - \Delta f_2(s) + \frac{2 \pi T_s}{s} \Delta f_3(s) - \Delta f_4(s) + \frac{2 \pi T_s}{s} \Delta f_5(s) - \Delta f_6(s) + \frac{2 \pi T_s^2}{s} \Delta f_7(s) - \Delta f_8(s)
\]

(16)

\[
\Delta P_{TL4}(s) = \frac{2 \pi T_s}{s} \Delta f_1(s) - \Delta f_2(s) + \frac{2 \pi T_s}{s} \Delta f_3(s) - \Delta f_4(s) + \frac{2 \pi T_s}{s} \Delta f_5(s) - \Delta f_6(s) + \frac{2 \pi T_s^2}{s} \Delta f_7(s) - \Delta f_8(s)
\]

(17)

\[
\Delta P_{TL5}(s) = \frac{2 \pi T_s}{s} \Delta f_1(s) - \Delta f_2(s) + \frac{2 \pi T_s}{s} \Delta f_3(s) - \Delta f_4(s) + \frac{2 \pi T_s}{s} \Delta f_5(s) - \Delta f_6(s) + \frac{2 \pi T_s^2}{s} \Delta f_7(s) - \Delta f_8(s)
\]

(18)

![Fig. 2. Non-Reheat Thermal Generation System](image_url)

**B. PID-Based BESS**

The performance of energy storage devices can be determined by the energy produced and their energy density [51]. The use of energy storage can be distinguished by place and duration of use, as determined by the technology used [52]. Battery technology in energy storage devices can be distinguished based on energy density, round trip efficiency, lifetime, and environmental friendliness of the device [53].

One of the most important performance elements of energy storage devices is their service life, this has the greatest influence in terms of economic efficiency [54]. In addition, environmental friendliness is a major consideration because the device is not harmful to the environment and can be recycled [55].

Technically, BESS has proven to be able to provide frequency regulation [57]. BESS response times (in seconds) are much faster than conventional power plants (typically 3-5 seconds). Thus, the energy policy must have the technical capabilities of all types of assets including BESS to be used in frequency regulation [19]. Some examples of projects (BESS), Supercapacitor Energy Storage (SCES), Flywheel Energy Storage (FES), and Superconducting Magnetic Energy Storage (SMES) in the real world are shown in Table II. The projects mentioned are not meant for frequency setting. BESS projects in Japan and Ireland are used to reduce fluctuations in wind power generation [56].

**Table II. Real-world Energy Storage Facilities and Their Applications [56]**

<table>
<thead>
<tr>
<th>Name/Location</th>
<th>Rating</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>BES/Australia</td>
<td>30 MW/8 MWh</td>
<td>Fast frequency response</td>
</tr>
<tr>
<td>BES/USA</td>
<td>8 MW/2 MWh</td>
<td>Frequency regulation</td>
</tr>
<tr>
<td>BES/Germany</td>
<td>8.5 MW/8.5 MWh</td>
<td>Frequency control, spinning reserve</td>
</tr>
<tr>
<td>BES/Puerto Rico</td>
<td>20 MW/14 MWh</td>
<td>Frequency control, spinning reserve</td>
</tr>
<tr>
<td>BES/Japan</td>
<td>34 MW/244.8 MWh</td>
<td>Wind power fluctuation mitigation</td>
</tr>
<tr>
<td>BES/USA</td>
<td>10 MW/40 MWh</td>
<td>Spinning reserve, load leveling</td>
</tr>
<tr>
<td>BES/Ireland</td>
<td>2 MW/12 MWh</td>
<td>Wind power fluctuation mitigation</td>
</tr>
<tr>
<td>SCES/China</td>
<td>3 MW/17.2 kWh</td>
<td>Voltage sag mitigation</td>
</tr>
<tr>
<td>SCES/Spain</td>
<td>4 MW/5.6 kWh</td>
<td>Frequency stability</td>
</tr>
<tr>
<td>FES/USA</td>
<td>20 MW</td>
<td>Frequency regulation, power quality</td>
</tr>
<tr>
<td>FES/Japan</td>
<td>235 MW</td>
<td>High power supply to nuclear fusion furnace</td>
</tr>
<tr>
<td>SMES/Japan</td>
<td>10 MW</td>
<td>System stability, power quality</td>
</tr>
</tbody>
</table>

The BESS model shows in Fig. 3. The main important thing is to examine postponing measurement, command, and converter in the model [58]. The BESS equation points to (19) [59].

\[
G_{BESS}(s) = \frac{K_{BESS}}{T_{comp} s + 1}
\]

(19)

![Fig. 3. BESS Model](image_url)
Conventional PID control is appended to the designated BESS (20), used to prevent active power mismatches in energy storage systems [60].

\[
P_{\text{PID Control}} = P \left(1 + \frac{1}{s} + D \frac{N}{1 + N \frac{1}{s}}\right)
\] (20)

The determination of the PID parameter is carried out in several stages [61]. The first step is to determine the P parameter to reduce the maximum oscillation but produces continuous oscillations [62]. In the condition of the five-area AGC system with the addition of BESS, the undershoot value is greater than the overshoot value [63]. Therefore, after adding the P parameter, the undershoot value is greater than the overshoot value [64]. The second stage is to decrease the undershoot value by parameter I, causing the overshoot value to increase [65]. The addition of the PI parameter has resulted in good attenuation of fluctuations, characterized by overshoot and undershoot values that are smaller than the target operating frequency but have prolonged oscillations and exceed the target time to recover frequency [66]. Therefore, the last step is the addition of parameter D to dampen continuous oscillations [67]. If we look at the response generated by each PID parameter, parameter D gets the best response because it can dampen fluctuations without producing an impact [68]. However, because parameter D cannot stand alone, but must be paired with P [69]. This also affects parameter I, which must be paired with parameter P. Previously, the influence of the PI parameter can meet the overshoot and undershoot limits but cannot meet the time to recover frequency [70]. While the use of the PD parameter gets the opposite result, which can meet the time to recover frequency and cannot meet the target undershoot value. Therefore, the PID parameter is used to meet the target operating frequency [71].

C. Index Criterion

The objective function is determined in advance for the design of optimization techniques based on the desired specifications and constraints [72]. The objective function used to optimize the controller parameters is typically chosen based on performance criteria that are dependent on system response [73]. The desired specification in a time domain system is the value of overshoot, rise time, settling time, and steady-state error [74].

The Integral of Time multiplied Absolute Error (ITAE) is given in equation (21), the Integral of Time multiplied Squared Error (ITSE) is given in equation (22), the Integral of Absolute Error (IAE) is given in equation (23), and the Integral of Squared Error (ISE) is given in equation (24) [75].

\[
ITAE = \int t |ACE| dt
\] (21)
\[
ITSE = \int t(ACE)^2 dt
\] (22)
\[
IAE = \int |ACE| dt
\] (23)
\[
ISE = \int (ACE)^2 dt
\] (24)

Because the ISE criterion rejects major errors more than minor ones, it tends to eliminate major errors quickly while retaining minor errors for long periods of time [76]. This results in a fast response, but with a sufficiently large and low amplitude, causing unwanted oscillations [77]. Because the IAE criterion aggregates errors over time and does not weight any errors in the system response, the IAE tends to produce a slower response than the ISE criterion, but with fewer sustained oscillations [78]. The ITAE criterion incorporates errors that are multiplied by time over time, so the weight of the errors over time is much greater than the weight of the errors in the initial response [79]. The ITSE criteria provide a large controller output for abrupt changes in set-point, which are undesirable from the standpoint of controller design [80].

IV. RESULTS AND DISCUSSION

In this study, a five-area AGC system simulation is proposed to be carried out using MATLAB software. In the condition of the power plant, the thermal AGC interconnection of five areas experiences changes in the electrical load with dynamic disturbances, which increase frequency fluctuations. Therefore, the power frequency fluctuation was reduced by BESS, with the addition of a PID, which is used as the BESS control system to improve frequency stability better and faster. In other conditions, the addition of BESS requires costs for BESS purchases, installation, and so on. Therefore, to save costs on BESS installation, a study was conducted to install one BESS in a five-area AGC system, based on the location of the BESS installation area that received the best response to attenuation of frequency fluctuations. However, each region has a different frequency operating standard. Thus, to meet the frequency operating standards that have not been met by the addition of one BESS, a study was conducted on the number of BESS installations to reduce frequency fluctuations better than one BESS. Fig. 4 show the flowchart of the research procedure.

This research is carried out to improve the frequency stability of the multi-area AGC system, namely the non-reheat thermal five-area AGC system, for the result of Frequency Fluctuation Response of AGC can be seen in Fig. 5 and Fig. 6. Repairs are carried out by referring to the standard operating frequency set by ENTSO-E. There are four operating standards with two different maximum steady-state frequency deviation values, namely the GB, IRE, and NE standards working at ±500 mHz. In comparison, the CE standard has a smaller value, which has a maximum steady-state frequency deviation value of ±200 mHz. Therefore, the target for improving frequency stability is to get a maximum steady-state frequency deviation value of ±200 mHz or ±0.004 p.u.
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Fig. 4. Flowchart of the Paper

Fig. 5. Frequency Fluctuation Response of AGC Five Area System

Fig. 6. Comparison of IRON Laying Responses to the Largest Frequency Fluctuations
The five-area AGC system gets area 1, as the area that gets the largest frequency fluctuation compared to other areas, as shown in Fig. 5. Installation of BESS to improve frequency stability in the area that has the largest frequency fluctuation, namely in area 1, which refers to Fig. 5. This is proven by the decrease in the value of frequency fluctuations after using BESS and compared to before using BESS, the installation of BESS area 1 can reduce the overshoot of maximum frequency fluctuations from other areas, reduce the overshoot of maximum frequency fluctuations by 20.56% and 2.014% in the undershoot value. Meanwhile, for the installation of BESS in area 5, the worst response in improving the frequency stability of the five-area AGC system shows that the maximum frequency fluctuation has increased after the installation of BESS, an increase in overshoot fluctuation of 0.296%, and an undershoot fluctuation of 1.007%. For the response of BESS PID in five-area can be seen in Fig. 7 to Fig. 11, and shown in Table III for detailed results features.

![Fig. 7. Response of BESS PID Frequency Fluctuation in Area 1](image1)

![Fig. 8. Response of BESS PID Frequency Fluctuation in Area 2](image2)

![Fig. 9. Response of BESS PID Frequency Fluctuation in Area 3](image3)

Fig. 10. Response of BESS PID Frequency Fluctuation in Area 4

Based on the data that has been obtained, the installation of 1 BESS area causes the system to get the largest overshoot value of 2.669e-3 p.u (50.133 Hz). While the largest undershoot value is 1.070e-2 p.u or the frequency becomes 49.467 Hz. Referring to Fig. 5, the installation of 5 BESS areas got a better response than 1 area in reducing frequency fluctuations. The maximum frequency overshoot value obtained was 50.134 Hz (2.687e-3 pu), and the maximum frequency undershoot value was 49.467 Hz (1.065e-2 pu). Although the difference in the response of the installation of 1 BESS area to 5 areas is very small, it can be concluded that the more BESS used, the better response to attenuation of frequency fluctuations.

![Fig. 11. Response of BESS PID Frequency Fluctuation in Area 5](image4)

The installation of 5 BESS areas causes the system to operate in a frequency range of 49.467 Hz to 50.134 Hz, obtaining an Integral of Squared Error (ISE) performance criterion of 0.269. This shows that the reduction of the undershoot of the largest frequency fluctuations must be made better because it has not reached the expected target. The smaller the ISE performance criteria value can eliminate fluctuations with a large peak value. Hence, to get better attenuation, use the PID control to set BESS. Referring to Fig. 7 to Fig. 11, the five-area AGC system with 5 BESS PID areas received a better response than the uncontrolled BESS, indicated by the achievement of improvement targets and meeting the standard operating frequencies of GB, IRE, NE, and CE. The use of 5 BESS PID areas gets an ISE performance criterion value of 0.021, causing the system to operate in the frequency range of 50.078 Hz to 49.857 Hz.
Each region has a different standard operating frequency in areas that use the standard operating frequencies of GB, IRE, and NE, which is the maximum steady-state frequency deviation value of ±500 MHz. The installation of 2 BESS PID areas on the five-area AGC system can meet these operating standards because the system works in the frequency range of 49.531 Hz to 50.080 Hz. Fig. 10 shows the system response under 4 different criterions namely ITAE, ITSE, IAE and ISE. While Table IV shows the detailed features of Fig. 12.

![Fig. 12. Criterion Index Figure.](image)

<table>
<thead>
<tr>
<th>Index</th>
<th>Value</th>
<th>Setting Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITAE</td>
<td>11.193</td>
<td>35.538</td>
</tr>
<tr>
<td>ITSE</td>
<td>0.151</td>
<td>22.712</td>
</tr>
<tr>
<td>IAE</td>
<td>1.362</td>
<td>26.869</td>
</tr>
<tr>
<td>ISE</td>
<td>0.029</td>
<td>17.627</td>
</tr>
</tbody>
</table>

From all the results it is found that the system with BESS has a lower frequency overshoot compared to the system without BESS. This could have happened because BESS released and stored energy faster than the ramp-up of the generator. Hence, in the first swings when the load disturbance occurs, BESS provides electricity to the grid. Resulting in reducing the overshoot of the frequency. BESS could provide inertia control without getting any rotating machine when the disturbance occurs (it is called virtual inertia support). After 5 seconds, the power plant starts to ramp up the generating capacity to provide electricity as requested by the grid.

It is also found that adding additional controllers such as the PID controller at BESS could also enhance the frequency response of the generator. This could have happened because the PID controller gave more details control signals to BESS rather than the gain controller only. If the control signals are more detailed, the BESS could provide electricity faster. In addition, the BESS could also provide more detailed power to the system when the PID controller is added as the additional controller.

V. CONCLUSIONS

This study improves the frequency stability of the AGC for multi-area non-reheat thermal power, using BESS and PID control. The use of BESS in multi-area AGC can smooth and slightly dampen the frequency oscillation waves. The use of BESS with PID control can reduce frequency fluctuations better. Installation of BESS is recommended in areas that have the greatest frequency fluctuations because it can reduce frequency fluctuations in multi-area systems. The more areas BESS has installed, the better it can dampen frequency fluctuations. For further research, adding non-inertia power plants such as PV and wind power systems can be considered to investigate how the BESS could maintain the frequency of the system under low inertia grid conditions.

ABBREVIATION

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>α</td>
<td>Area synchronization parameters</td>
</tr>
<tr>
<td>B</td>
<td>Area frequency response characteristics</td>
</tr>
<tr>
<td>D</td>
<td>Derivative parameters</td>
</tr>
<tr>
<td>F</td>
<td>AGC five area system frequency</td>
</tr>
<tr>
<td>I</td>
<td>Integral Parameters</td>
</tr>
<tr>
<td>K_{BESS}</td>
<td>BESS coefficient</td>
</tr>
<tr>
<td>K_{g}</td>
<td>Steam governor coefficient</td>
</tr>
<tr>
<td>K_{f}</td>
<td>AGC five area system integral control parameter</td>
</tr>
<tr>
<td>K_{p}</td>
<td>Load coefficient</td>
</tr>
<tr>
<td>K_{t}</td>
<td>Steam turbine coefficient</td>
</tr>
<tr>
<td>L</td>
<td>Load on area</td>
</tr>
<tr>
<td>N</td>
<td>Filter coefficient</td>
</tr>
<tr>
<td>P</td>
<td>Proportional Parameters</td>
</tr>
<tr>
<td>R</td>
<td>Governor speed regulation</td>
</tr>
<tr>
<td>T</td>
<td>Synchronization coefficient</td>
</tr>
<tr>
<td>T_{C,De}</td>
<td>Order delay time</td>
</tr>
<tr>
<td>T_{conv}</td>
<td>Converter time</td>
</tr>
<tr>
<td>T_{g}</td>
<td>Time constant steam governor</td>
</tr>
<tr>
<td>T_{M,De}</td>
<td>Measurement delay time</td>
</tr>
<tr>
<td>T_{p}</td>
<td>Time constant load</td>
</tr>
<tr>
<td>T_{i}</td>
<td>Time constant steam turbine</td>
</tr>
</tbody>
</table>

APPENDIX

Power rating: Area 1=2000 MW, Area 2=4000 MW, Area 3=8000 MW, Area 4=10000 MW, Area 5=12000 MW; B_{3}=B_{4}=B_{5}=B_{g}=16 p.u. MW/Hz; K_{i1}=K_{i2}=K_{i3}=K_{i4}=K_{i5}=0.3; a_{12}=0.5, a_{13}=-0.25, a_{14}=-0.2, a_{15}=-0.167, a_{23}=0.5, a_{24}=-0.4, a_{25}=-0.333, a_{34}=-0.8, a_{35}=-0.667, a_{45}=-0.833; R_{g}=0.04 Hz/p.u. MW, R_{p}=0.033 Hz/p.u. MW, R_{g}=0.028 Hz/p.u. MW, R_{p}=0.025 Hz/p.u. MW, R_{g}=0.022 Hz/p.u. MW; T_{0}=0.544; T_{i}=0.3 s; T_{g}=0.8 s; T_{p}=20 s; K_{f}=1 Hz/p.u. MW; K_{g}=1 Hz/p.u. MW; K_{BESS}=1; T_{conv}=0.1 s; T_{C,De}=0.01 s; T_{M,De}=0.1 s; P=10; I=4; D=5; N=100; F=50 Hz; L=0.2 p.u.

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