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Advanced virtual inertia control against wind power intermittency

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ABSTRACT

Rapid industrial development requires more energy to support their manufacturing processes. Unfortunately, conventional energy was mostly utilized as a primary energy source which is unfriendly to nature and can damage the environment. Nowadays, the transformation from the use of conventional energy to renewable energy sources is increasingly being socialized throughout the world. However, the existence of renewable energy poses new challenges in the world of electricity systems where their effect is reducing the inertia (inertialess) value of conventional energy such as thermal generators. This condition causes frequency oscillations and leads to blackout the electricity system. To overcome this problem, this paper proposed advanced virtual inertia control (VIC) based on an superconducting magnetic energy storage (SMES) employed to accommodate the effects of the integration of renewable energy into the electric power system. SMES was choosen because it has a fast response and an efficiency rate of up to 90%. A two-area power system model was utilized to examine the proposed VIC model based on SMES. From the simulation results, VIC based on has succeeded in reducing frequency oscillations by compressing the system overshoot and reducing the settling time to steady-state.

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1. INTRODUCTION

The world's energy needs currently still focus on the use of fossil energy. Fossil energy is a conventional energy source whose use is limited and not environmentally friendly. The forms of fossil energy sources are in the form of oil, gas, and coal. In Indonesia, power plants are still dominated by generators that use conventional energy sources, such as steam power plantswhich use coal as the main fuel from steam power plants [1]. However, the existence of conventional energy sources is not a solution to meet the world's energy needs. Conventional energy sources will continuously increase greenhouse gas (GHG) emissions and cause environmental problems that can disrupt ecosystem sustainability [2].

Based on environmental problems that can have an impact on survival, innovation in the energy sector is needed. Innovation in the energy sector can be implemented by utilizing new renewable energy plants (REP). The Indonesian government, through the Ministry of Energy and Mineral Resources, pays more attention to the utilization of new and renewable energy sources (RES). The government's target until 2025 is to plan the use of new renewable energy (NRE) to be realized by 23% of Indonesia's total energy needs [3]. The shift from fossil energy to NRE must be carried out in stages due to the need for capital, technology development, and human resources so that NRE can be applied optimally. The use of NRE on a large scale will bring up new problems such as frequency stability in the electrical system due to the reduction in inertia (inertialess) caused by REP [4].

The use of a small-scale electrical grid system is called a microgrid which has a function as a regulator and frequency controller in the electrical grid system. The interconnection system will connect various generators synchronously. Generators can be said to be synchronous if they have the same frequency. Determination of the amount of power between generators must consider estimates of the amount of power that will be borne by the system. Every time the power demand will change according to need. The change in power must be met by the system to be able to respond [5]. In other words, increase the power output quickly from zero to full load. The speed of the governor on the generating unit will affect the principal speed as a necessary control function in the electrical system so that the frequency is not a constant quantity. The frequency will change according to changes in the load that occurs. Therefore, a system that can regulate the frequency of the power system was created, known as automatic generation control (AGC) [6].

The electrical system has an inertia value that is able to synchronize from each generator. So that when there is an interconnection of REP into the AGC system, it will cause problems that have an impact on changes in the inertia value. Inertialess will affect the power imbalance, and a change in frequency will result in oscillations in the system [7]. A decrease in the reliability and stability of the system will occur so that the system experiences disturbance or instability. A good system is able to maintain stability when a disturbance occurs. Based on the nature of the disturbance, it is categorized into two types, namely transient disturbances (such as network breaks, and short circuits) and dynamic disturbances (such as small load changes) [8]. The disturbance will have an impact on frequency stability. Therefore, it is necessary to have a control technique that is able to maintain frequency stability when the REP interconnection occurs in the existing electrical system [9].The value of the system inertia can be set using the concept of the virtual inertia control (VIC) technique. VIC is a control technique that utilizes an inverter-based energy storage system. VIC is able to increase the system's inertia value and is able to maintain frequency stability. The VIC system is designed to connect the energy storage system with the AGC network. The system can work efficiently to meet the power requirements connected to the network system. However, the VIC system has a constant value, so that when REP penetration occurs, it will cause system instability.

The choice of energy storage system must be adjusted to the needs and reliability required with the net system. Various types of energy storage systems in general, such as superconducting magnetic energy storage (SMES) [10], capacitor energy storage (CES) [11], and battery energy storage system (BESS) [12], and others. Superconducting magnetic energy storage (SMES) is an energy storage system that is used to maintain the frequency stability of the two-area automatic generation control (AGC) power grid system caused by the penetration of new renewable energy plants (REP). The design uses SMES because it has efficiency and fast response and can be applied to electric power systems. In addition, SMES can improve frequency stability. Hence, the reliability of the overall electric power system can be maintained [13]. SMES has a continuous flow of current circulating in the superconducting windings to generate a magnetic field for energy storage. In the energy conversion process, the SMES system only converts alternating current (AC) to direct current (DC). Therefore, there are no inherent thermodynamic losses associated with converting one form of energy to another [6]. Therefore, the design will use SMES as VIC when there is penetration from REP.

2. THEORETICAL REVIEW

2.1. Virtual inertia control modeling

The derivation signal from the microgrid frequency is used proportionally to modify the active power reference of the converter [14]. Virtual inertia in the power system can be licated so that it can contribute to increasing the response of the inertial system to changes in the required power demand. The VIC concept is applied to produce damping and inertial characteristics based on conventional synchronous generators and increase system stability due to REP penetration in frequency control [15]. Virtual inertia can be emulated using a combination of SMES energy storage systems. Basically, the energy storage system is an inertial unit that can adjust the active power in the system and is able to adjust the system frequency through the inertial response by changing the adjusted power control characteristics [16]. The VIC system is based on voltage feedback from the inverter output, which generates a rated signal to supply the generator power source [17]. The VIC system uses an approach that causes the generating unit (generator) to be more responsive to frequency changes in the electric power grid system. The use of derivative control is the main key of the concept of inertial control. For example, derivative control is able to determine the rate of change of frequency (ROCOF) which modifies excess active power to nominal value after a disturbance or penetration of a new renewable energy generator (REP) [18]. Figure 1 shows the simple model of 2 area AGC, while Figure 2 shows the dynamic model of VIC.

The dynamic equation for the simplification of VIC power can be seen in (1). As long as the frequency deviation is caused by load or REP penetration, there is an active power base converter of the energy storage system controlled by rate of change of frequency (ROCOF) in order to increase system inertia, frequency performance, and stability [19].

$$\Delta P_{inersia} = \frac{J}{1+sT_{VI}}\left(\frac{d(\Delta f)}{dt}\right) \tag{1}$$

J is the virtual inertia constant, TVI is the time constant of the virtual inertia added to the form of the energy storage system, and Δf is the frequency deviation [20]. Figure 3 illustrated the dynamic mode of SMES with VIC.

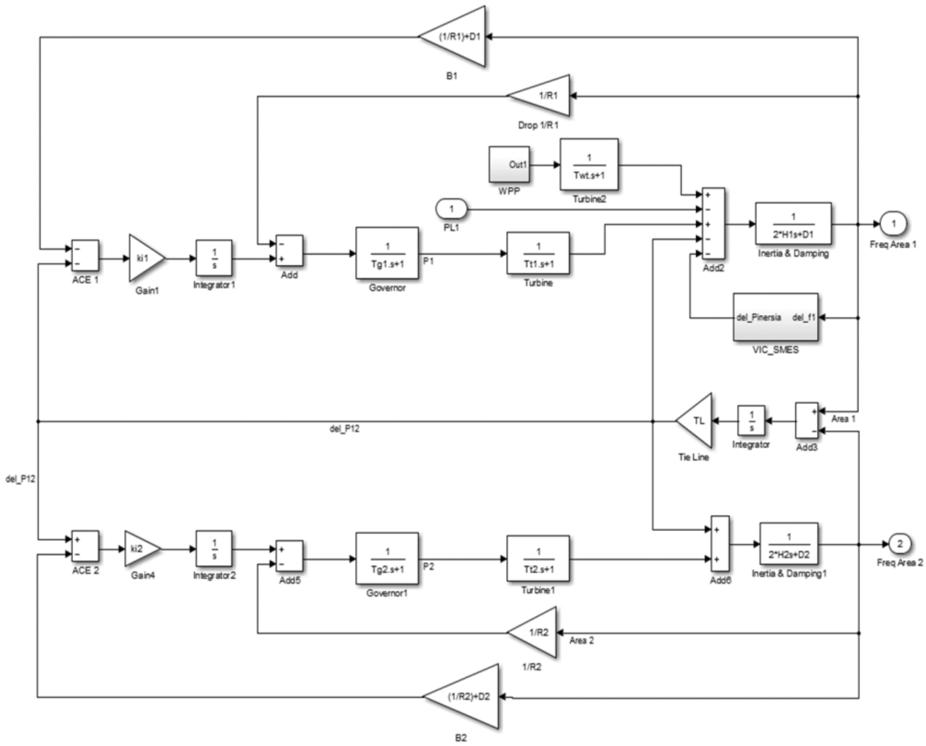

Figure 1. Simple modeling of AGC 2 area system

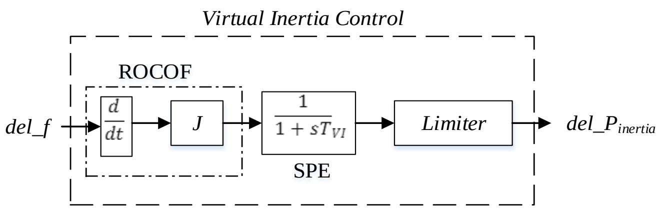

Figure 2. Dynamic model of VIC

2.2. Penetration of new renewable energy

Various load/generating properties, new and renewable energy generation (REP), and variations in system operation were identified as significant characteristics of interrelated power systems. Based on the test scenario, the interconnected power system was investigated under conditions different from the penetration level of the wind power plant (WPP) in area one. Extreme system operations demonstrate the dynamic effects of the actual operation of interconnected power systems and verify the reliability of the proposed control strategy for high-level WPPs. In other words, include penetration and changes in system inertia [21]. Therefore, the effect of REP penetration caused by changes in wind speed data will affect the overall frequency of the interconnected system indicated by a high-test contingency [22], [23].

P_w is the power from the wind power plant (WPP), which has units of watts, ρ is air density in units (kg/m3), R is the radius of the WPP (m), Vw is wind speed (m/s), and Cp is the power coefficient owned by WPP. The WPP specifications used have a rated power capacity of 2000 kW, namely G80/2000 Gamesa.

$$\Delta P_w = \frac{P_w}{P_{Base}} \quad (2)$$

The use of WPP is 26.6% of the system load. Hence, when there is penetration from the WPP, the system does not experience high-frequency deviations so that the system cannot operate stably [24].

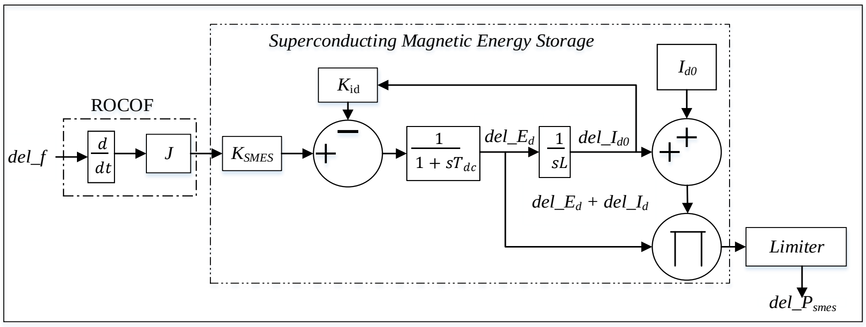

Figure 3. Dynamic model of VIC based on SMES

3. DESIGN CONCEPT

The procedures of implementing the virtual inertia control (VIC) based on superconducting magnetic energy storage (SMES) to improve frequency stability are shown in Figure 4 can be seen in *appendix*. In this study, a two-area power system model is equipped with LFC or AGC as conventional control to maintain the frequency on its nominal value. However, the integration of wind power triggers the frequency fluctuating because of weather conditions as input of wind power. Due to high-frequency fluctuation, the VIC based on SMES is utilized to damp this condition as an impact of wind power installation.

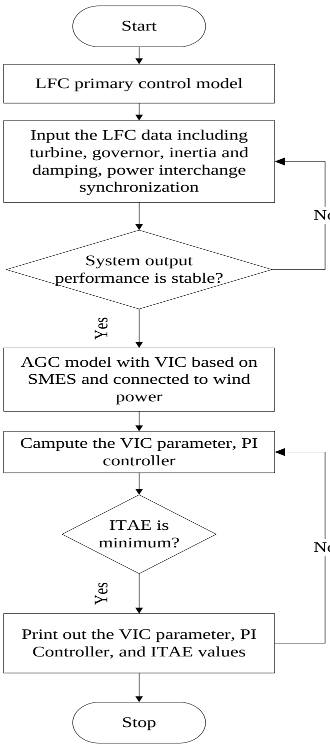

Figure 4. Flowchart

The appropriate SMES model utilized as SMES model plays key role in this study. Moreover, the VIC and AGC parameters are influencing the frequency stability due to high wind power integration. This two-area power system model is simulated by using MATLAB/Simulink by providing input in the form of predetermined parameter values. Some tests were carried out to obtain the lowest integral time square error (ITAE)-based performance index value [25]. Several scenarios have been formed, then each result from the scenario will be compared using ITAE.

4. RESULTS AND DISCUSSION

The simulation and analysis are divided into two case studies. First, a two-area load frequency control (LFC) system is utilized as test system to examine the robustness of PI controller and VIC based SMES. In this study, the proposed PI controller and VIC based SMES are compared to other controllers such as PI controller and VIC conventional, PI controller, and I controller. Second, a two-area automatic generation control (AGC) system is utilized with the integration of wind power and VIC based SMES. To examine the robustness of proposed VIC based SMES, a static load change, wind power integration level, and inertia loss are provided as disturbance to the system.

4.1. Case study 1

The system modeling is simulated using several controllers. The controllers that will be used include the addition of an integral Ki controller, a proportional-integral (PI) controller, a conventional virtual inertia control, and a virtual inertia control based on superconducting magnetic energy storage. The use of an integral controller serves to reduce the rise time value but increase the overshoot and settling time. Overshoot is the number of waves that have a peak value/point to the steady-state state or the final value at the peak time and is usually resented as a percent of the steady-state value. Settling time (Ts) is the amount of time required for transient damped oscillations to persist at ±2% of the final value.

Settling time provides information related to the speed and quality of the transient response. The magnitude of the settling time value helps the designer to achieve the desired speed without excessive oscillation or overshoot. Based on Figure 5, the frequency change in the first Δf_1 area using an integral controller has a greater settling time value than other controllers such as PI controllers, conventional PI-VIC, and PI controller and VIC based SMES. The value of the integral controller settling time is 29.0335 seconds, the PI controller is 25.8758 seconds, the conventional PI-VIC controller is 25.7704 seconds, and PI controller and VIC based SMES controller has the fastest settling time value of 22.4789. second. However, the settling time of the frequency change in the second Δf_2 area is different from the Δf_1 area. Changes in frequency in the second Δf_2 area have a greater settling time value than Δf_1 because, in area two, there is no load power that interferes with the system in area two. The change in Δf_2 as shown in Figure 6 is due to the frequency deviation from area one because the load power is only in area one. Thus, the frequency response in area two is much more time-consuming because they have to wait for a response that occurs in area one.

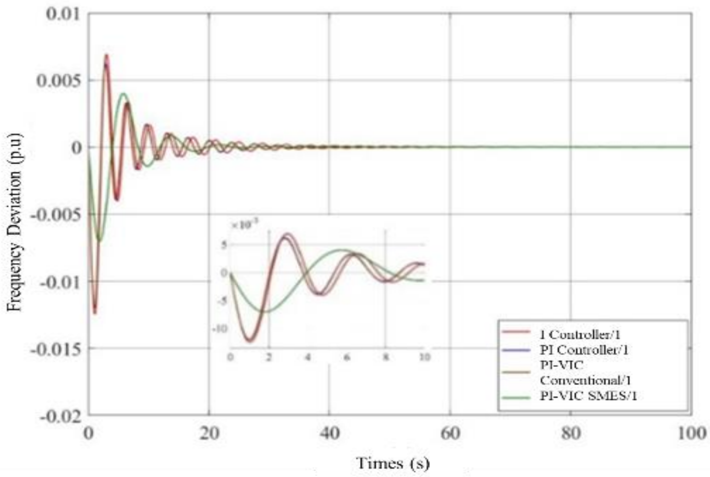

Figure 5. Area one frequency deviation

4.2. Case Study 2

In case study two, the effectiveness and robustness of the automatic generation control (AGC) coordination plan using an optimal virtual inertia control (VIC) and a modified control signal into a VIC based on superconducting magnetic energy storage (SMES). The VIC evaluation applies a new renewable energy plant (REP) in the form of a wind power plant (WPP) by utilizing wind fields with low and high fluctuations and static loads. Some of the operating conditions can be seen in Table 1. Case study two is divided into the following three scenarios.

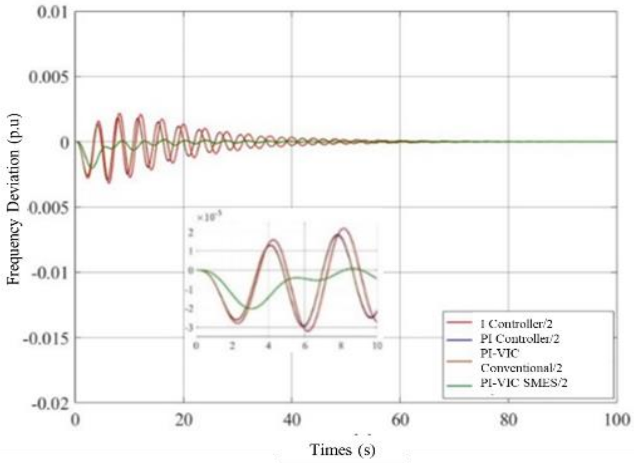

Figure 6. Area two frequency deviation

Table 1. Performance specifications using the controller

No.	Source	Start time (s)	Finish time (s)	Output power (*per unit*)
1.	Load Power I	*Initial*	-	0.1875
2.	WPP I	200	400	0.0498

4.2.1. Scenario 1

The first scenario assumes that an automatic generation control (AGC) system that has been integrated by static loads and a new renewable energy generator (REP) in the form of a wind power plant (WPP) has a nominal inertia value (0% penetration of new renewable energy plants). In this scenario, the two-area power system with AGC is examined to maintain frequency stability due to the high wind power penetration. To show the robustness of this proposed PI controller and VIC based on SMES, the performances of other control schemes are also observed under different condition as shown in Figure 7.

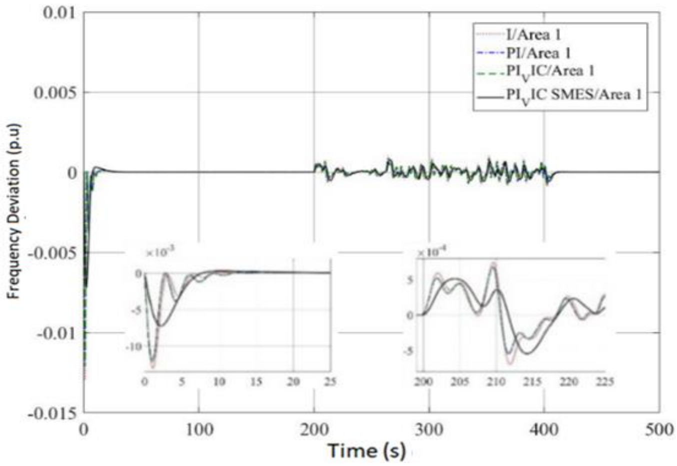

Figure 7. Area one frequency deviation

The frequency deviation of area one is more dominant than area two because the load is only connected to area one. Frequency deviation may occur when the REP is integrated into a two-area AGC system. REP is connected to the system in area one, so that area one experiences more frequency deviation than area two, which is not connected by load or REP.

The difference in the results of the control strategy simulation in Figure 5 can clearly be seen in the difference between each controller used in the simulation. The use of SMES is able to reduce the frequency deviation to -0.00721 p.u or equivalent to -0.4326 Hz. While the controllers I, PI, and PI–VIC are only able to reduce frequency deviations to -0.01297 p.u, -0.01213 p.u, and -0.01208 p.u, or there are frequency deviations of -0.7782 Hz, -0.7278 Hz, and -0.7248 Hz, respectively. Therefore, the proposed control strategy using an energy storage system in the form of SMES will provide a fast response to reduce frequency changes when there is the penetration of REP.

4.2.2. Scenario 2

In this second scenario, it assumes an automatic generation control (AGC) system that has been integrated by static loads and a new renewable energy generator (REP) in the form of a wind power plant (WPP) has a value of 75% nominal inertia or penetration of new renewable energy plants of 25%. The performance of frequency from the system is depicted in Figure 8. When there is load change in the system, the frequency will drop from its nominal value where it means that the power supply decrease to supply the load. Otherwise, when the wind power is connected to the power system, the frequency will increase from its nominal value where it means that there is additional power to the AGC system supplied by the wind power.

From Figure 8, it can be observed that a system that does not use SMES will experience a frequency deviation of -0.01498 p.u or 0.8988 Hz on controller I. In comparison, the system connected to SMES provides a frequency deviation of -0.00745 p.u or 0.447 Hz when the load is connected to the system. When compared to a system using the PI-VIC SMES controller, it will show a better response than the I, PI, and PI-VIC controller methods during REP penetration or interference. In addition, the use of SMES will provide strong stability and have a faster settling time than other controllers.

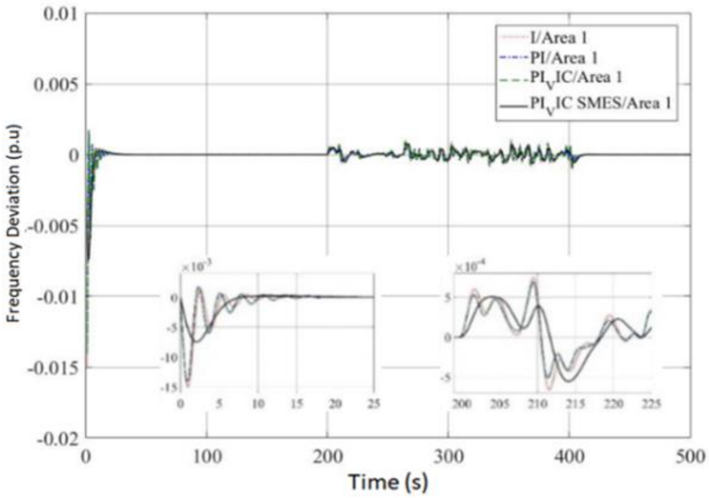

Figure 8. Area one frequency deviation

4.2.3. Scenario 3

The third scenario assumes that an automatic generation control (AGC) system that has been integrated by static loads and a new renewable energy generator (REP) in the form of a wind power plant (WPP) has a value of 50% of the nominal inertia. The declining inertia value will cause the AGC difficulties damping the frequency oscillation. Moreover, the robustness of VIC-based SMEs in this scenario is examined whether it can reduce the effect of WPP penetration on the AGC system. The effect of WPP integration and decreasing the inertia value is shown in Figure 9.

In the simulation results, Figure 9 shows the frequency deviation of the system considering the penetration of new and renewable energy plants at a condition of 50% of the nominal system inertia. The simulation results of this third scenario conclude that there is a higher frequency fluctuation compared to the previous scenarios 1 and 2. In a PI-VIC installed system, it is not much different from using a PI controller, which means that the PI-VIC controller performance is still not optimal, so that additional SMES is needed to become PI-VIC SMES which is able to reduce oscillations and frequency deviations that occur in the system. The oscillations are caused by a decrease in the value of inertia, but the ripple pattern on the SMES has an impact on area two. However, the oscillations that occur are very small, around 9.12x10-5 p.u or about 0.00547 Hz.

Based on the simulation results, the use of superconducting magnetic energy storage has the lowest integral time absolute error performance index from case studies one and two. In the block diagram representation of the simple SMES control scheme in Figure 3, there are SMES current, voltage, and power. The inductor current is required to be able to return to the rated value of the system very quickly after a disturbance/penetration occurs in the system. The next effect is that the SMES system becomes very responsive to respond to further load disturbances. The performance of the electric power system depends on the controller values of K_p, $K_{i,}$ and K_{smes}. It was observed that a higher $K_p$value will decrease the overshoot but will increase the settling time of the system. However, if the value of $K_p$is lower, on the other hand, it will increase the overshoot but decrease the settling time. K_{smes}will affect the settling time. If K_{smes}has a high value, then the system will be unstable and too aggressive. However, if K_{smes}has a low value, then the system will tend to be stable but not aggressive. In other words, the system response is very slow. Therefore, the adjustment of the optimal values K_p, $K_{i,}$ and K_{smes}. must go through the minimization of the ITAE perform performance index. Table 2 shows the comparison ITAE performance index under different scenarios.

Table 2. ITAE performance index

No.	Controller	Case Study 1 Using the Controller	Case Study 2 Scenario 1 (100% Inersia)	Scenario 2 (75% Inersia)	Scenario 3 (50% Inersia)
1.	I	17.88	443.5	462.2	540.3
2.	PI	15.43	397.5	413.8	699.5
3.	PI-VIC	15.03	395.7	411.3	689.5
4.	PI-VIC SMES	5.975	351.8	355.8	442.8

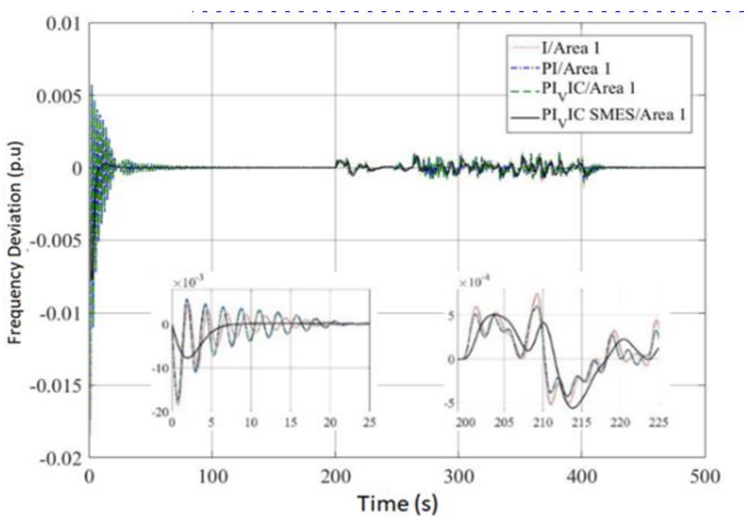

Figure 9. Frequency deviation one

5. CONCLUSION

The use of virtual inertia control based on superconducting magnetic energy storage to improve frequency stability due to the penetration of new renewable energy plants. The modeling design of the two-area AGC power grid system will be connected to virtual inertia control (VIC) based on superconducting magnetic energy storage (SMES) by determining the required parameter data for each variable. Or in other words, it is necessary to do several tests to get the optimum parameter values so as to be able to maintain the stability of the system frequency. The use of SMES-based PI-VIC controllers has better results than other controllers. In the case of study two, scenario three, there is a decrease in REP penetration by lowering the inertia value of the system, which shows that the use of the PI-VIC SMES controller has a smaller ITAE value than the controller I, PI, and PI-VIC. The ITAE value for the PI-VIC SMES controller is 422.8, while the I, PI, and PI-VIC controllers are 540.3, 699.5, and 689.5. A two-area AGC system that does not use SMES gives a poor frequency response and takes a long time to suppress frequency oscillations compared to a system that uses SMES.

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