Design type-2 fuzzy for superconducting magnetic energy storage to enhance frequency transient response

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ABSTRACT

Renewable energy has become a new trend in power systems. Renewable-based power plants such as wind power systems and photovoltaics. This paper proposed a novel method for inertia emulation based on superconducting magnetic energy storage (SMES). To get better inertia support for the system, a type-2 fuzzy controller is used as the SMES controller. An area power system is used as the test system to investigate the performance of type-2 fuzzy controller on SMES. Time domain simulation is carried out to show the efficacy of the proposed method. From the simulation results, it is found that the proposed controller can reduce the overshoot of frequency by up to 20% compared to the type-1 fuzzy controller. It is also hoped that the proposed method can be used as a reference of the Industrial people.

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1. INTRODUCTION

Frequency is one of the important elements for maintaining the reliability of the power system. Frequency is also one of the important factors in power system stability. To control the frequency of the power system, maintaining the balance between the load and generating power is essential. In addition, there are different control strategies to control the frequency of the power system [1]. The controller strategy is divided into four different steps namely inertia control, primary control, secondary control, and tertiary control [2].

Inertia control is done by the inertia of the machine itself. If the machine has high inertia the first overshoot of frequency can be reduced. The second controller is the primary controller. The primary controller can be done by adding a droop controller at the governor of the synchronous generator. The third controller is the secondary controller which is done by adding an integral controller to the governor. The secondary controller is used to ensure the frequency is back to the nominal value [3]. Lastly is the tertiary controller [4]. The tertiary controller can be done by adjusting the load of the generator. This last controller is active only in severe conditions, as in this controller the load of the system must be shed. Hence it is important to maintain the first three controllers to handle the frequency oscillation when a small disturbance occurs. In the traditional power system, it is easy to maintain the frequency by only adjusting the primary and secondary controllers (since the inertia controller cannot be changed). However, with the more and more inertia-less power plant, the total inertia of the system is reduced significantly [5]. In addition, primary, and secondary controller only is not sufficient to handle the problem of the modern power system. Hence it is important to add additional devices that can help the primary and secondary controllers for maintaining frequency by giving inertia emulation to the system. One of the devices that can be used to emulate inertia in the system is energy storage [6].

There are several types of energy storage that have been used in recent years such as battery energy storage (BESS), capacitor energy storage (CES), proton exchange membrane (PEM) electrolyzer, flywheel energy storage (FES), and superconducting magnetic energy storage (SMES). The research effort in [7] proposed an application of BESS for the frequency regulation of power systems. The application of CES to support automatic generator control (AGC) of power systems is reported in [8]. The application of PEM for the dynamic stability of the power system is reported in [9]. It is found that adding PEM to the interconnected power system can enhance the dynamic performance of the system. The application of FESS in power system studies is reported in [10]. It is noticeable that FESS could enhance the performance of the power system. Among numerous types of energy storage, SMES become favorable due to their fast response and efficiency of the SMES.

The application of SMES for power flows stabilization is reported in [11]. It is reported that by adding SMES to the microgrid, the power flow of the microgrid is improved even though there is a wind power plant in the system. The application of SMES in the dynamic stability of the power system is reported in [12]. From Mughees *et al*. [12], it is stated that SMES can enhance the dynamic performance of the power system. The essential part of SMES for enhancing the performance of the power system is the controller. Generally, the controller of SMES can be designed using the fuzzy logic controller (FLC). FLC has been widely used around the world and outperforms conventional control systems as an alternative control design for a wide range of linear and nonlinear system models [13]. Type-1 fuzzy logic control (T1FLC) is still widely used in some applications. The T1FLC, on the other hand, has limited capabilities in dealing with complex system uncertainties.

Hence it is important to improve the FLC method using type-2 fuzzy logic control (T2FLC). Several studies have demonstrated that interval type-2 fuzzy logic control (IT2FLC) performance is superior [14]-[16]. Prof. Lotfi Zadeh created IT2FLC in 1975 as a solution to this problem. However, due to an adequate computing system, the IT2FLC method was popular in the early 2000s. The structure of the IT2FLC modeling is nearly identical to that of T1FLC, except for the output after the inference process, which is continued to the reduction process to convert the set of IT2FLC outputs to T1FLC for later defuzzification [17].

This paper proposed a method to emulate inertia in the system using SMES. To get better emulation IT2FLC is used as the controller of the SMES. The rest of the paper is organized as follows: section 2 described the modeling of the system. The method for designing the controller is explained in section 3. Results and discussion are presented in section 4. The conclusion and contribution of the paper are highlighted in section 5.

2. METHOD

2.1. Fuzzy type-2

Prof. Lotfi A. Zadeh first introduced fuzzy logic in the Journal of Information and Control in 1965 through his research, on fuzzy sets. Fuzzy logic is a method that is inspired by human cognition and response [18]. In ordinary logic, there are only two values: true and false, and the system only recognizes 0 and 1 digitally. While fuzzy logic distinguishes between true and false values. In fuzzy logic, truth is expressed as degrees of truth with values ranging from 0 to 1. With the advancement of science. T1FLC has a limited ability to deal with complex system uncertainties. Prof. Lotfi Zadeh created IT2FLC in 1975 as a solution to this problem [15].

The inputs are fuzzified in the IT2FLC control system mechanism, where the input values are mapped into fuzzy sets. However, there is a footprint of uncertainty in IT2FLC (FOU). The degree of primary membership uncertainty of the type 2 membership function is contained in FOU. Membership functions that limit FOU are classified as upper membership function (UMF) and lower membership function (LMF) [19]. UMF is the FOU subset with the highest degree of membership. Meanwhile, LMF is a subset with the lowest degree of membership in the FOU that can be derived from the T1FLC membership function [20].

The next process is the same as the mechanism in T1FLC, namely creating a rule base that contains a collection of fuzzy settings for controlling the system and the inference process, namely evaluating the relevant control rules and making input decisions to be used by the system in the form of IF-THEN [21]. The reduction process, which converts the output of IT2FLC into a set of T1FLC with a firm membership function so that it can proceed to the defuzzification process, is what distinguishes IT2FLC from T1FLC. The defuzzification process produces output that is sent into the system [22]. IT2FLC is used as a control system in this study to optimize the performance of the SMES system, which is automatically used to minimize errors between the AGC system output and the reference.

2.1.1. Fuzzification

Fuzzification is the conversion of crisp fuzzy input into the fuzzy form. This is because the amount of input obtained from the plant in the application of a control system is always in the form of non-fuzzy (crisp) data that is definite and quantitative, whereas data processing in FLC is based on fuzzy set theory, which uses fuzzy linguistic variables, so the initial stage of FLC requires fuzzification carried out by a fuzzifier. The IT2FLC set is generally written as (1) [16]:

$$\tilde{A} = \{(x,u), \mu_{\tilde{A}}(x,u) | \forall u \in J_x \subseteq [0,1] \} \quad (1)$$

where, $J_x \subseteq [0,1]$ represents the primary membership function of x and $\mu_{\tilde{A}}(x,u)$ is the T1FLC membership function or is called the secondary membership function.

2.1.2. Rule base

In addition to verbal logic, observations from the output and error response graphs from the system can be used to determine the rule base. Figure 1 depicts an example of an error response graph and plant output [23]. From Figure 1 it can be determined the form of the fuzzy rule base in the following way.

- At t=0, the error (e) is in the "*Positive Besar*" position or abbreviated as "BP". Then the output response (u) from t=0 to t=2 requires a "Big Positive" control signal. So that the rule base is obtained, IF e="PB", THEN u="PB".
- At t=2, the error (e) is in the "*Positive Kecil*" position or abbreviated as "PK". Then the output response (u) from t=2 to t=4 requires a "*Positive Kecil*" control signal. So that the rule base is obtained, IF e="PK", THEN u="PK".
- At t=4, the error (e) is in the "*Negative Kecil*" position or abbreviated as "NK". Then the output response (u) from t=4 to t=6 requires a "*Negative Kecil*" control signal. So that the rule base is obtained, IF e="NK", THEN u="NK".
- At t=6, the error (e) is in the "Zero" position or abbreviated as "Z". Then the output response (u) from t=6 to t=8 requires a "Zero" control signal. So that the rule base is obtained, IF e="Z", THEN u="Z".

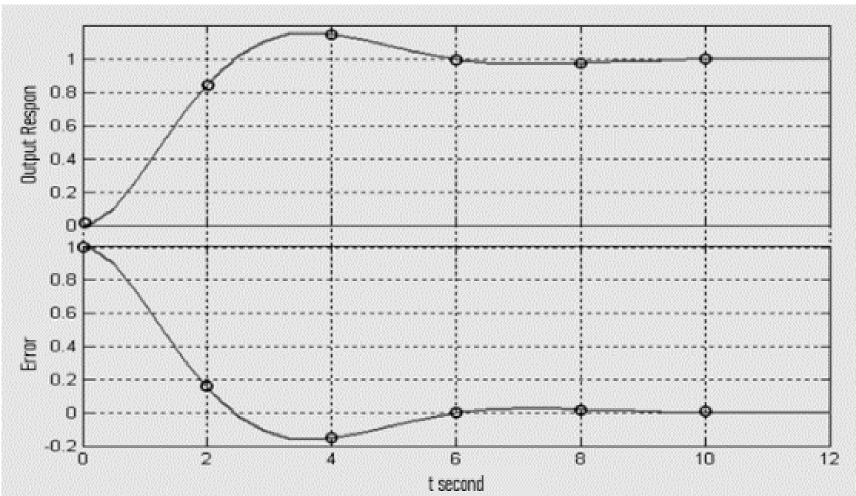


Figure 1. Output response and plant error

2.1.3. Inferential

If more than one fuzzy rule from the rule base has been evaluated in this process, the output of the implication process is combined into a single fuzzy set. The Max method is one of the inference methods employed. Whereas the Max inference method uses the implication process's maximum value [24].

2.1.4. Reduction type

There is an additional step in the IT2FLC interval in the form of a reduction type where this reduction process is used to change to the set of T1FLC. The center of sets method is one of several methods for carrying out the reduction process [14]. The reduction process in IT2FLC is nearly identical to the calculation of the center of the area in T1FLC defuzzification. It's just that, because IT2FLC has fixed intervals, there are two endpoints, *xi* as the middle point and *xr* as the middle point. The following, which are frequently used, are written in (2) and (3) [25]:

$$x_l = \frac{\sum_{i=1}^{M} A_l^i x_l^i}{\sum_{i=1}^{M} A_l^i} \tag{2}$$

$$x_r = \frac{\sum_{i=1}^{M} A_r^i x_r^i}{\sum_{i=1}^{M} A_r^i} \tag{3}$$

where, M is quantization rate, i is i-th element, x_l is the midpoint of the x-axis of the shape l, x_r is the midpoint of the x-axis of the shaper, A_l is area of *l*, and A_r is area of *r*.

2.1.5. Defuzzification

The defuzzification process is a process of changing the crisp value of the fuzzy quantity. IT2FLC is slightly different from T1FLC. The defuzzification process in IT2FLC is a continuation of the method in the reduction process. In the previous reduction process, the center of the set method was used where the values of x_l and x_r were obtained. So, to get the price of the control signal in the defuzzification process, it is only necessary to calculate the average values of x_l and x_r as written in (4) [26]:

$$x = \frac{x_l + x_r}{2} \tag{4}$$

2.2. Procedure of designing the controller

This paper discusses the use of IT2FLC for parameter tuning on SMES, which is used in the interconnection of five areas (multi-area) electric power systems. In the AGC system, SMES is used as a secondary control for oscillation at tie-lie frequency power. The use of the SMEs system with IT2FLC results in more optimal frequency oscillation and tie-line power attenuation in the AGC system. This paper contains several steps, which are as follows.

The first step is modeling the AGC in two areas of the electrical power system from the *Multi-area* AGC linear equation. The second step, adding *close-loop* control system modeling on the AGC in the form of an integrated amplifier controller *Ki* placed in the area control error (ACE). *Ki* control is inserted into the load reference value of the governor unit. The integral control function is to adjust the ACE signal so that the AGC system's frequency output returns to an optimal condition or in this case goes to a working point that is zero.

The third step provides input to the data needed by the system, such as governor data, turbine, load, and integral controller according to reference [3]. The fourth step is to incorporate a SMES modeling system into AGC areas 1 and 2. SMES systems are used as a secondary control to adjust the frequency oscillation attenuation of the AGC system due to load changes. The SMES system is depicted on the AGC block diagram as a secondary close-loop with negative feedback in load power. SMES owns a charge and discharge capability, which can be used as a load value regulator. The SMES input value is derived from the AGC frequency system output value.

The fifth step involves fine-tuning the SMES parameter with IT2FC. The trial-and-error method is used in this paper to determine the membership function and rules in FLC. However, it is still based on the analysis of the control signal response graph and its error. The control signal in question is a frequency signal, where the AGC system frequency signal is used as a control input for the SMES system. In this paper, the component for the fuzzy system uses two inputs and one output. The simulation was carried out in this paper by changing the load's power demand.

The goal of this paper is to compare the most optimal controller to arrange the frequency areas 1 and 2 on a multi-area AGC system using SMES tuning gain that is installed on a multi-area AGC system. In this simulation, the use of a multi-area AGC system without a controller is compared to the use of an integral controller on a multi-area AGC system, also known as AGC conventional control multi-area, and the addition of a SMES controller to AGC conventional control multi-area, as well as the addition of a controller on SMES system, also known as an optimal SMES control. In this paper, additional controls on SMES are added, namely a T1FLC controller on SMES for AGC conventional control multi-area system and an IT2FLC interval controller on SMES for AGC conventional control multi-area system.

SMES is installed as the AGC system's feedback frequency response, which is then fed back into the generator's input side in the form of. The power generated by the SMES system is itself. The SMES system installed as secondary control acts as a damper for the AGC system oscillations caused by the additional load in area 1. Figure 2 depicts the block diagram of the installed SMES.

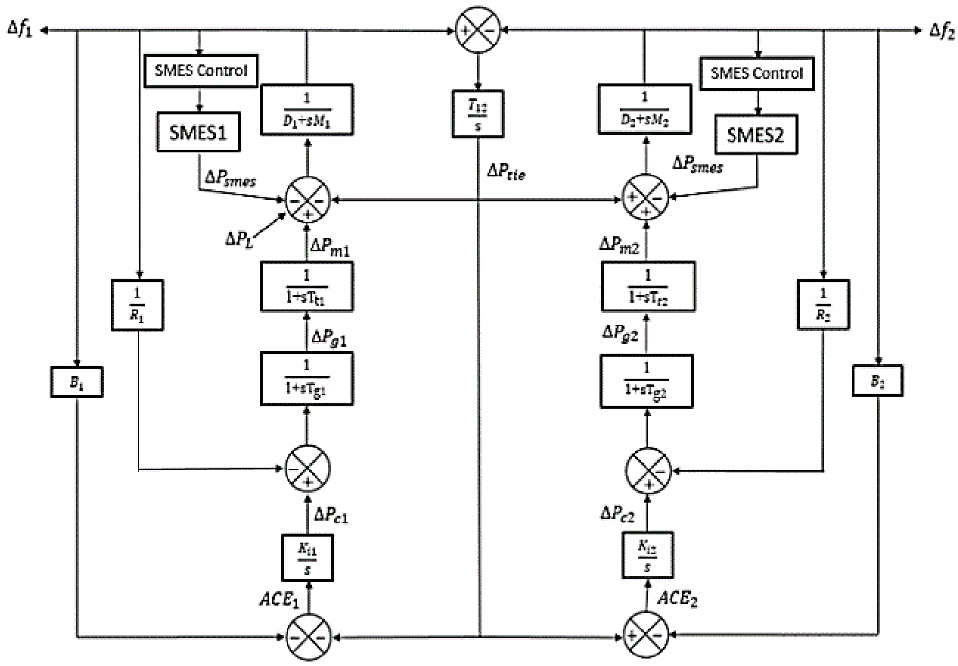
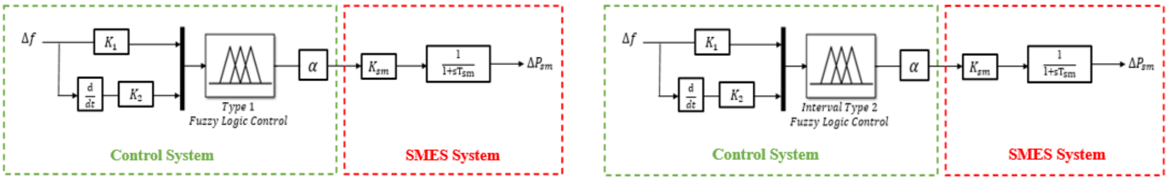


Figure 2. AGC+SMES control conventional multi-area block diagram

Figure 2 depicts AGC's conventional multi-area system block diagram with additional secondary control in the form of a SMES energy storage system added to the control system at the SMES input or frequently offered as optimal SMES. A control system's function in the SMES system is to optimize SMES performance in damping oscillations and accelerating response in AGC multi-area systems. The control system used varies, but in this paper, T1FLC and T2FLC are used. Figures 3(a) and (b) depict a SMES block diagram with additional control variations. Instead of the SMES or gain value, the control system on SMES is installed. As is well known, SMES control is equivalent to proportional control. so that the controller schema on the SMES system can be modified.



(a) (b)

Figure 3. AGC conventional control multi-area block diagrams; (a) +SMES T1FLC and (b) +SMES IT2FLC

3. RESULTS AND DISCUSSION

Following the completion of the design process, a dynamic analysis is performed on the AGC system, which is linked to the interconnection network of two areas. This simulation yields information about dynamic system performance based on area 1 frequency deviation, area 2 frequency deviation, and tie-line deviation for comparing the performance of the control strategy already installed in the system. The performance of the system is also evaluated using the error value information contained in the ACE.

3.1. Case study 1

To improve the performance of the AGC system, an additional controller in the form of a SMES system is added. However, by adding a controller in the form of fuzzy logic to the SMES input to be more optimal, where this fuzzy logic function adjusts the SMES gain value so that the AGC system's performance can work optimally. To optimize the performance of SMES, two types of control systems are compared in this scenario: T1FLC and interval type-1 fuzzy logic control (IT1FLC). Figures 4-6 show the resulting graph of the frequency and power of the tie-line.

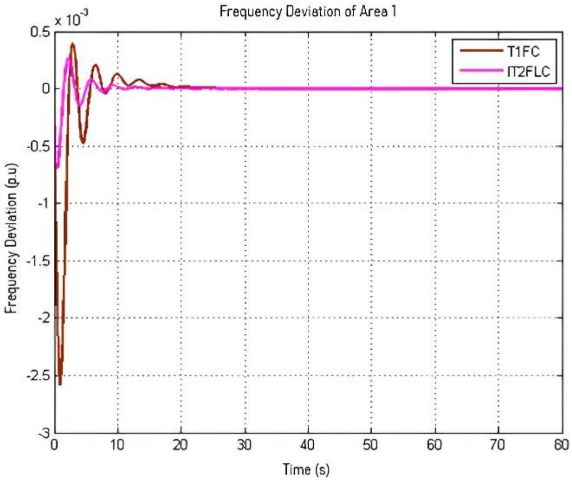


Figure 4. Area 1 frequency response system using T1FLC SMES and IT2FLC SMES

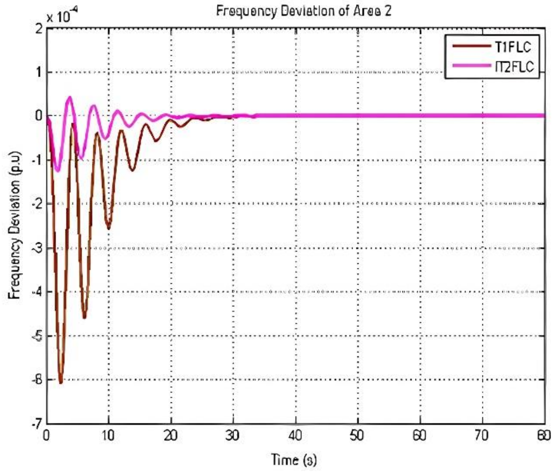


Figure 5. Area 2 frequency response system using T1FLC SMES and IT2FLC SMES

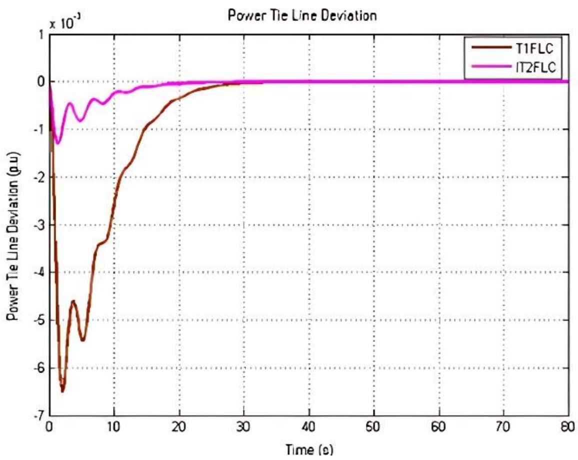


Figure 6. Tie-line power response system using T1FLC SMES and IT2FLC SMES

The undershoot value produced by the conventional AGC multi-area system with the addition of secondary control in the form of SMES optimal in area 1 is lower than that produced by the conventional AGC multi-area system using SMES. The IT2FLC control system outperforms the T1FLC control system in terms of undershoot value and response speed in the SMES system. The IT2FLC control method can dampen the frequency undershoot in area 1 by 0.000423 p.u., which means it can dampen 16.3% of the undershoot produced by the T1FLC control method, which produces an undershoot of 0.0026 p.u. in this system. IT2FLC can reduce 20.71% of the undershoot produced by the T1FLC method as of area 2. The IT2FLC method can dampen 19.99% of tie-line power undershoot. When compared to the T1FLC method, the time required for the system to reach the nominal value is shorter when using the IT2FLC method.

From these results, it is found that by using IT2FLC, SMES could provide detailed active power that could support the system in the transient time. This can be happened because IT2FLC could reduce the error from the frequency more detail. Furthermore, IT2FLC could provide signal control to give detailed firing angle/ modulation index to the converter of the SMES. If the firing angle is more detail than the converter could charge and discharge more detail. Hence, active power that could charge and discharge from SMES could more specific.

3.2. Case study 2

Then, in case study 2, two types of control systems are compared to optimize SMES performance: T1FLC and IT2FLC. The T1FLC and IT2FLC control systems are then used to optimize the two SMES that have been installed in each area of the AGC multi-area system. Figures 7-9 depict the dynamic response of areas 1, 2, and tie-line power.

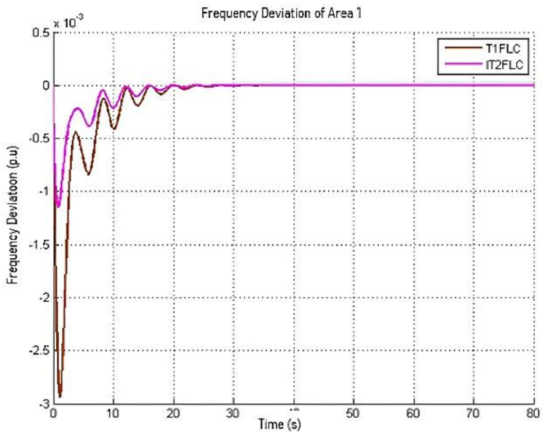


Figure 7. Area 1 frequency response system using T1FLC SMES and IT2FLC SMES

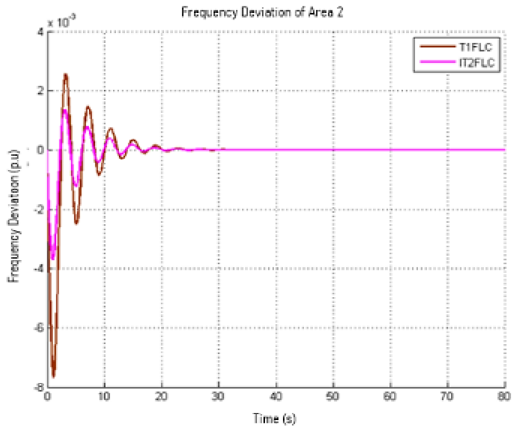


Figure 8. Area 2 frequency response system using T1FLC SMES and IT2FLC SMES

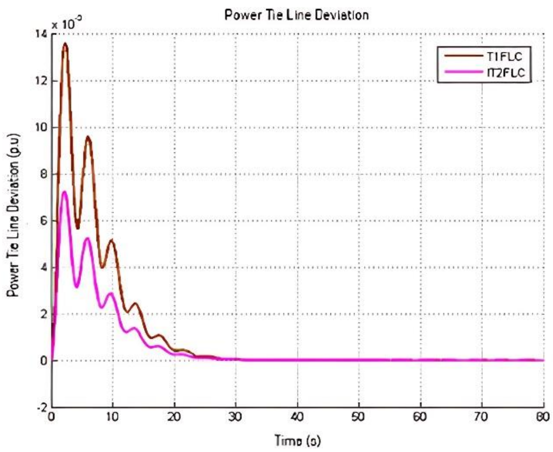


Figure 9. Tie-line power response system using T1FLC SMES and IT2FLC SMES

According to the obtained performance results, the frequency value and tie-line power in an AGC system with optimal T1FLC SMES and IT2FLC SMES have a lower undershoot performance and settling time than an AGC system with only SMES. The undershoot value produced by the conventional AGC multi-area system with the addition of secondary control in the form of SMES in both areas is lower than the conventional AGC multi-area system with one SMES. IT2FLC control systems outperform T1FLC control systems in terms of undershoot value and response speed in SMES systems. The IT2FLC control method can dampen 0.00115 p.u of undershoot frequency in area 1, which means it can dampen 39.07% of the undershoot produced by the T1FLC control method, which produces an undershoot of 0.002943 p.u. in this system. IT2FLC can dampen 48.1% of the overshoot produced by the T1FLC method in area 2. The IT2FLC method can dampen 53.08% of tie-line power undershoot. The IT2FLC method takes less time than the T1FLC method to return the system to its nominal value.

From these results, it is found that by using IT2FLC, SMES could provide detailed active power that could support the system in the transient time. This can be happened because IT2FLC could reduce the error from the frequency more detail. Furthermore, IT2FLC could provide signal control to give detailed firing angle/ modulation index to the converter of the SMES. If the firing angle is more detail than the converter could charge and discharge more detail. Hence, active power that could charge and discharge from SMES could more specific.

4. CONCLUSION

This paper proposed a novel inertia controller concept in a power system using SMES. As a SMES additional controller, a type-2 fuzzy controller is used to improve inertia emulation (behaves as a virtual inertia controller). To investigate the efficacy of the proposed method, a two-area power system is used as the test system. The proposed method is tested using time-domain simulation to see if it can improve the frequency response of power systems. According to the simulation results, the proposed control method can be used to add inertia emulation to the system. This is indicated by the smallest frequency overshoot when compared to the other scenarios.

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