SMES Supported AGC Performance Evaluation of Multi Machine Multi Area Power Systems

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Abstract: In real time, due to sudden load change in a power system, Superconducting Magnetic Energy Storage (SMES) device, is very useful in arresting the frequency deviation to an acceptable limit by rapid energy exchange from the system before the supplementary controller takes over. This paper explores the performance evaluation of Automatic Generation Control (AGC) in a multi-machine multi-area complex power system by connecting SMES at suitable location in the system. By integrating SMES into AGC of a power system, the study aims to alleviate the frequency and tie line power deviations and thus enhance the system stability. Using simulations, the performance of SMES-AGC in managing frequency deviations and oscillations across different areas of the power system is analyzed and evaluated. The system performance has been assessed under three conditions: (i) power system with Integral controller without inclusion of SMES (ii) power system integrated with SMES-Integral controller (iii) power system integrated with SMES-fuzzy-integral controller for two test cases i.e with 1% and 3% load perturbations. The results demonstrate that SMES can significantly enhance AGC effectiveness with fuzzy integral controller, providing far improved Peak Overshoot (M_p), Peak Undershoot (m_p), Setting time (t_s) and stability compared to other two conditions. This analysis offers valuable insights into optimizing power system performance with SMES integration.

Keywords: area control error (ACE); automatic generation control (AGC); fuzzy logic controller (FLC); peak overshoot (M_p); peak undershoot (m_p); superconducting magnetic energy storage (SMES); tie-line power deviation

1. Introduction

Automatic Generation Control (AGC) plays a vital role in ensuring zero deviations in frequency and tie line power flow between any two areas after load disturbance. Maintaining these deviations to zero becomes more challenging in case of complex multi-machine and multi-area configurations. The primary aim of AGC is to maintain system frequency/tie-line power to their desired values and match system generation to the load demand[1-4].

A sudden load perturbation can cause electromechanical oscillations. This may cause deviations in frequency/tie-line power of different areas. Studies employing classical control methods often result in significant overshoots and transient frequency deviations[5-9]. Various AGC techniques viz. Fuzzy Logic Control (FLC)[10], Model Predictive Control (MPC)[11], and adaptive control methods, Proportional-Integral (PI) control[12], offer different benefits and drawbacks regarding response time, stability, and efficiency. The integration of Superconducting Magnetic Energy Storage (SMES) device provides rapid and efficient storage of energy and discharge capabilities that can enhance AGC performance[13]. SMES devices are capable of mitigating fluctuations in power demand and generation, which can significantly improve frequency deviations and system stability[14]. A number of researchers have done extensive studies on the impact of SMES in AGC. Some of the related works have been summarized as follows. The effectiveness of AGC strategies when integrated with SMES depends on the specific control approaches employed[15]. SMES devices are very effective for power system frequency regulation and stability in deregulated

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environments with distributed energy resources[15-17]. SMES-GCSC coordination with cascaded PID-FOPID controller improves frequency control and voltage regulation in multi-area power systems integrating renewables and electric vehicles[18]. The SMES responds more quickly as compared to the control mechanism provided by the governor. The repeated charging/discharging needed to manage power system fluctuations can shorten the lifespan and reduce the performance of battery systems. Therefore, SMES technology is preferred over battery systems[19-24].

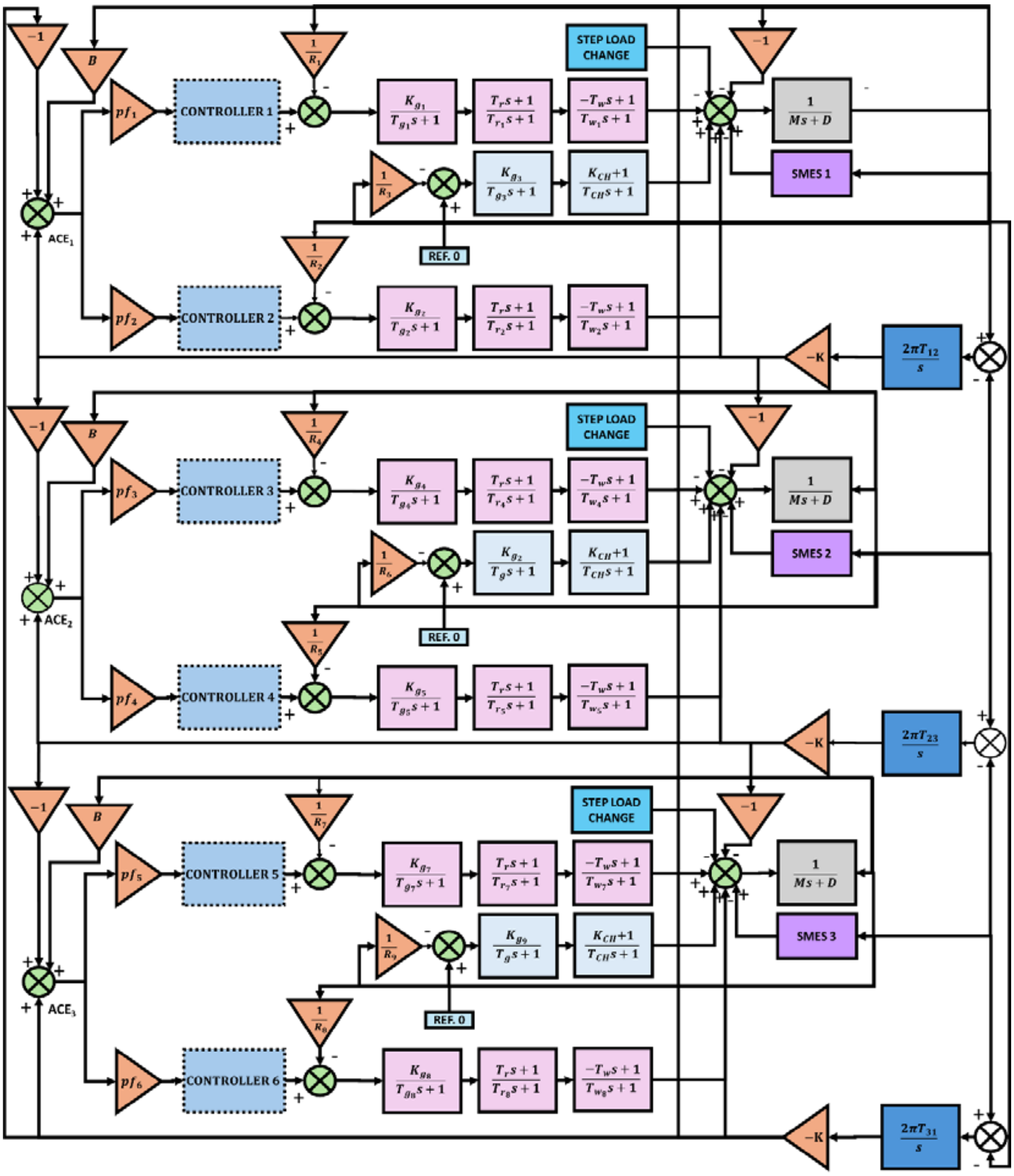

Fig. 1: Block Diagram of AGC of Multi-Machine Multi-Area Power System

In modern power systems, the challenge of maintaining stability and reliability becomes increasingly complex as systems grow in size and diversity. AGC is a fundamental mechanism used to ensure that power generation matches demand, thereby maintaining system frequency and stability. In multi-machine and multi-area power systems[25-32], where numerous generators and tie transmission lines interact, this task becomes even more challenging. Recent advancements in energy storage technologies, including Superconducting Magnetic Energy Storage (SMES), have introduced new opportunities to enhance AGC reliability and performance. In literature, several hybrid approaches have been presented for microgrid based AGC of complex power systems[33-35]. Further, Artificial Intelligence optimized control schemes yield far superior performances in comparison with classical control techniques[36].

This paper aims to provide a comparative analysis of AGC strategies tailored for multi-machine multi-area power systems equipped with SMES. The system performance has been assessed under three conditions: power system without inclusion of SMES and controller type is integral, system with SMES and controller type is integral and system integrated with SMES and controller is fuzzy integral.

This paper is organized as follows-

In section 2, Multi -Machines Multi-Area Power System Design is presented, Overview of SMES is depicted in section 3. Fuzzy Logic Controller is detailed in section 4. Section 5 shows the system example. Results are depicted in section 6 and section 7 concludes the work.

2. Multi - machines multi-area power system design

The AGC simulation was conducted on a three-area multi-machine power system, the block diagram of which is depicted in Figure 1. Each area in the system comprises two hydro units participating in AGC and one thermal unit that does not participate in AGC. Any change in load is shared by the two hydro units. As the thermal unit is not contributing to AGC, for any change in step load it responds through primary control but its scheduled generation is restored by AGC. In the computer simulation utilizing the system model, the secondary control adjusts the output of the AGC contributing hydro units and, maintains the output of the non-participating thermal unit simultaneously.

3. Overview of SMES

Superconducting Magnetic Energy Storage (SMES) is an advanced technology that harnesses the magnetic field generated by superconducting wire coils to store electrical energy with minimal losses[14)]. This innovative system is capable of quickly absorbing and releasing substantial amounts of energy, enabling the power grid to respond effectively to sudden fluctuations in power supply. By providing rapid bursts of energy, SMES helps maintain system stability and compensates for abrupt power losses, ensuring a more reliable and resilient electrical infrastructure.

The SMES unit comprises a DC superconducting inductor, a step-down transformer and an AC/DC converter as shown in Figure 2. The transfer function of SMES is depicted in Figure 3.

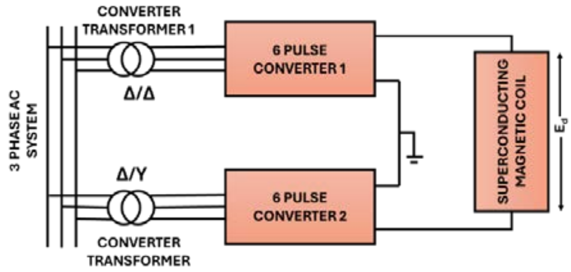

Fig. 2: SMES Configuration in a Power System

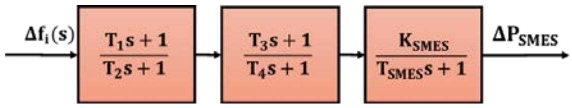

Fig. 3: Transfer function of SMES as a frequency controller

Integrating SMES into AGC systems offers several potential benefits:

Enhanced Frequency Regulation: SMES can provide fast and precise adjustments to maintain system frequency within desired limits.

Improved Stability: By damping oscillations and compensating for sudden changes in load or generation, SMES can enhance overall system stability.

Reduced Operating Costs: Although SMES systems are initially costly, their high efficiency and long lifespan can lead to reduced operating costs over the time.

However, integrating SMES with AGC also presents challenges:

Control Complexity: The addition of SMES introduces another layer of complexity to the AGC system, requiring advanced control strategies to manage effectively.

System Coordination: Ensuring that SMES operations are well-coordinated with other system components is crucial for achieving optimal performance.

4. Fuzzy Logic Controller

In this work, a fuzzy controller block is connected with Integral SMES controller so as to improve its performance in AGC. In one of the models[10)], a Fuzzy Logic Controller (FLC) has been integrated with the existing controller to enhance system performance further[37-41)]. The FLC, which operates based on fuzzy logic, mimics natural language with human thinking more closely than traditional systems. It is particularly useful for managing complex processes. The proposed fuzzy logic controller block is depicted in Figure 4.

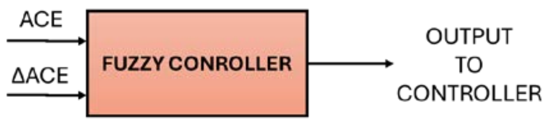

Fig. 4: Fuzzy Controller Block

The inputs to the proposed FLC are the Area Control Error (ACE) and the time rate of change in ACE.

In this study, the control rules and membership functions are designed to exhibit a superior performance in comparison with conventional controller. The membership functions are responsible to exhibit the experience and the preference by fuzzy logic. There may be various shapes of membership functions. These shapes rely on the expertise of system professionals. The membership functions that are chosen are as depicted in Figure 5.

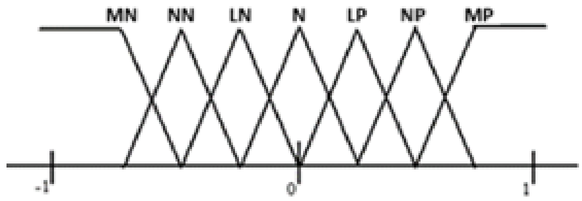

Fig. 5: Membership functions

The rule base, containing the minimum number of rules necessary to achieve these controller characteristics, is provided in Table 1.

Table 1: Fuzzy Membership Rules

ACE / ΔACE	MN	NN	LN	N	LP	NP	MP
MN	MN	MN	MN	MN	NN	LN	N
NN	MN	MN	NN	NN	LN	N	LP
LN	MN	NN	LN	LN	N	LP	NP
N	MN	NN	LN	N	LP	NP	MP
LP	NN	LN	N	LP	LP	NP	MP
NP	LN	N	LP	NP	MP	MP	MP
MP	N	LP	NP	MP	MP	MP	MP

MN = More Negative
MP = More Positive
NN = Normal Negative
N = Nil
LP = Less Positive
LN = Less Negative
NP = Normal Positive

5. System example

In this study, a three area multi machine power system, each area comprising of two hydro units participating in AGC and one non AGC participating thermal unit has been taken for simulation. The system parameters (nominal) used in several works have been taken as follows [2),4)]:

B = 25 pu; D = 0.01 pu; M = 22 s;
AGC Sample Rate = 4 s;
$R = R_1 = R_2 = R_4 = R_5 = R_7 = R_8 = R_9 = 0.04$ pu;
$R_3 = R_6 = R_9 = .05$ pu;
$T_g = 0.2$ s; $R_T = 0.38$ pu; $T_r = 5$ s;
$T_{r1} = T_{r2} = T_{r4} = T_{r5} = T_{r7} = T_{r8} = 47.5$ s
$T_W = 1$; $T_{W1} = T_{W2} = T_{W4} = T_{W5} = T_{W7} = T_{W8} = 0.5$ s;
$T_{CH} = 0.3$ s
$K_{g1} = K_{g2} = K_{g3} = K_{g4} = K_{g5} = K_{g6} = K_{g7} = K_{g8} = 1$

6. Result and discussion

In this work, AGC of Multi-area multi-machine system is carried out in MATLAB environment. The performance of three configurations: a conventional integral controller, an integral controller assisted with SMES, and a fuzzy integral controller with SMES has been compared.

The integral controller is required to eliminate the steady state error and enhance the system stability.

In order to judge the AGC of the multi-area multi-machine system, two cases have been studied (i)1% load perturbation (ii) 3% load thrown off. In both the test cases step change in load is introduced in one area, causing a transient disturbance. In response, the three units adjust their output through primary control. As the hydro units are participating in AGC, the secondary controllers in these units eventually restore the frequency and tie-line power variations to zero.

6.1. Test case 1- a step change (1%) in load is introduced in one area

With 1% sudden step variation in load in area 1, the resulting deviations in frequency in different areas and the tie-line power are plotted and shown in Figure 6–11. The quantitative comparison of the three control schemes of area 1-3 is shown in Table 2-3.

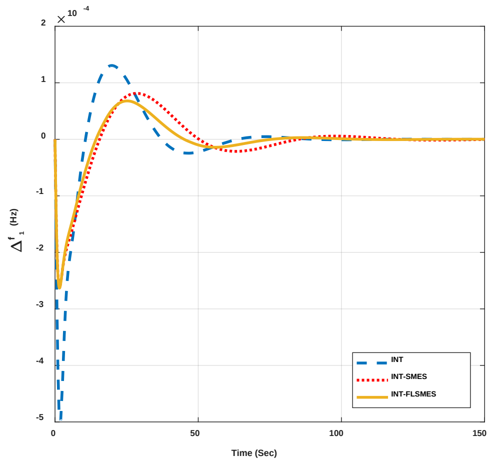

Fig. 6: Frequency change in area 1 with 1% load perturbation in area 1

The plot in Figures shows that the steady state error (ess) with Integral, Integral-SMES and Integral-Fuzzy-SMES controllers is zero in area 1-3. The peak overshoot (Mp) values with three controllers in area 1 are 1.30 x10-4 pu, 8.12 x10-5 pu and 6. 6.79 x10-5 pu respectively. The Mp values with controllers in area 2 are 1.99 x10-6 pu, .08x10-6 pu and 9.33x10-7 pu respectively. Similarly, the Mp values with three controllers in area 3 are 2.13 x10-6 pu, 1.15 x10-6 pu and 9.86 x10-7 pu respectively. Thus, the best overshoot values are obtained with Integral-Fuzzy-SMES controller.

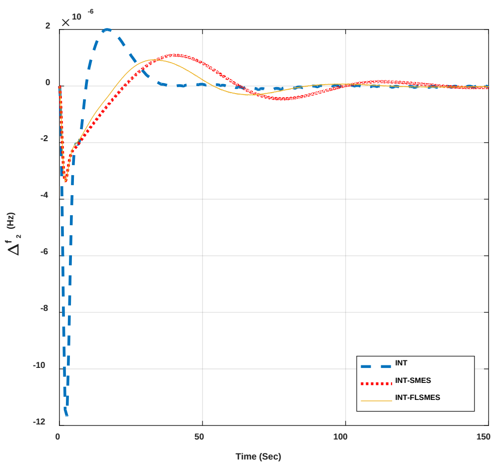

Fig. 7: Frequency change in area 2 with 1% load perturbation in area 1

From the plots, it has also been observed that the peak undershoots (m_p) values with three controllers in area 1 are -4.97 $x10^{-4}$ pu, -2.61 $x10^{-5}$ pu and -2.63 $x10^{-4}$ pu respectively. The m_p values in area 2 are -1.16$x10^{-5}$ pu,-3.35 $x10^{-6}$ pu and -3.36 $x10^{-6}$ pu respectively. Similarly, m_p values in area 3 are -1.28 $x10^{-5}$ pu, -3.52 $x10^{-6}$ pu and -3.53 $x10^{-6}$ pu respectively. The Integral-fuzzy-SMES control scheme results in optimum peak undershoot value.

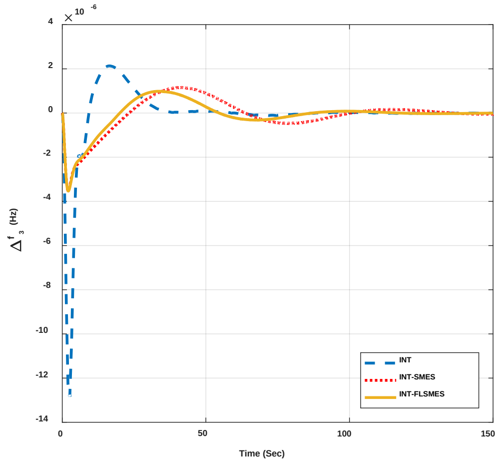

Fig. 8: Frequency change in area 3 with 1% load perturbation in area 1

The plots show that the settling time (ts) with three controllers in area 1 are 57.24 s, 101.98 s and 68.55 s respectively as shown in Figures. The ts values in area 2 with three controllers are 32.47 s, 149.99s and 103.07 s respectively. Similarly, ts values in area 3 with three controllers are 32.17 s, 128.50 s and 104.58 s respectively. The least peak time is obtained with Integral controller, however, the overshoot and undershoot values are very high. Therefore, the Integral-SMES-Fuzzy controller yields in moderately good peak time (ts).

For tie-line power deviation, it has been observed in the plots of Figure 9-11 that the steady state error (ess) with Integral, Integral-SMES and Integral-Fuzzy-SMES controllers is zero in area 1-3. The peak overshoot (Mp) values with three controllers in area 1 are 6.75 x10-4 pu, 4.23 x10-4 pu and 3.3 x10-4 pu respectively.

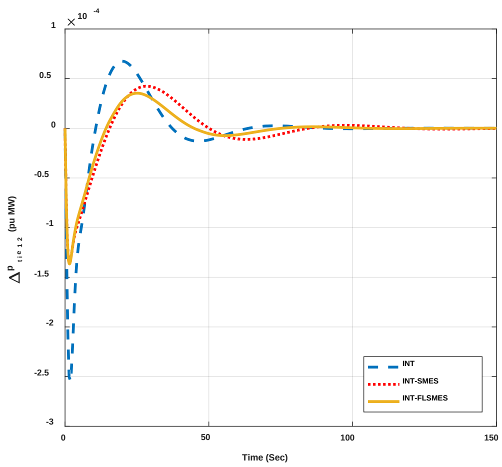

Fig. 9: Tie line power deviation area 1-area 2 with 1% load perturbation in area 1

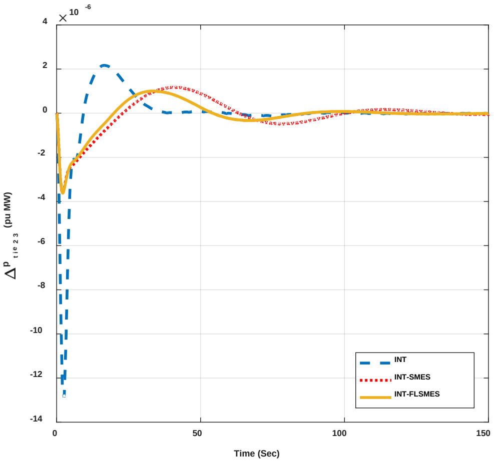

Fig. 10: Tie line power deviation area 2-area 3 with 1% load perturbation in area 1

For tie-line power deviation, it has been observed in the plots of Figure 9-11 that the steady state error (ess) with Integral, Integral-SMES and Integral-Fuzzy-SMES controllers is zero in area 1-3. The peak overshoot (Mp) values with three controllers in area 1 are 6.75 x10-4 pu, 4.23 x10-4 pu and 3.3 x10-4 pu respectively.

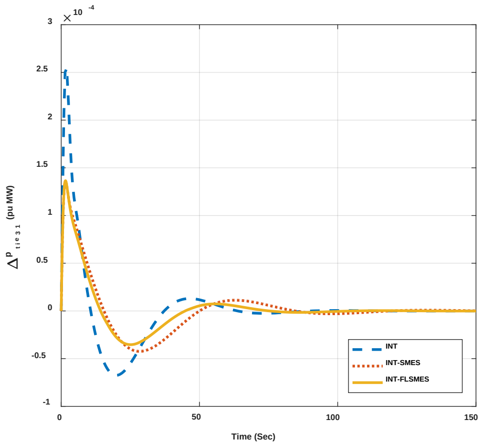

Figure 11: Tie line power deviation area 3-area 1 with 1% load perturbation in area 1

The M_p values with controllers in area 2 are 2.16 x 10^{-5} pu, 1.17 x 10^{-5} pu and 1.01 x 10^{-5} pu respectively. Similarly, the M_p values with three controllers in area 3 are 0.0026 pu, 0.0014 pu and 0.0014 pu respectively.
Thus, the best overshoot values are obtained by Integral- Fuzzy-SMES controller.
The peak undershoot (m_p) values with three controllers in area 1 are -2.54 x10^{-4} pu, -1.35 x10^{-4} pu and -1.36 x10^{-4} pu respectively. The m_p values in area 2 are -1.28x10^{-5} pu, -3.61 x10^{-6} pu and -3.62 x10^{-6} pu respectively. Similarly, m_p values in area 3 are -6.75 x10^{-5} pu, -4.23 x10^{-5} pu and -3.53 x10^{-5} pu respectively. Therefore, the Integral-fuzzy-SMES control scheme results in optimum peak undershoot value.
The plot also shows that the settling time, t_s with three controllers in area 1 are 57.38 s, 102.01 s and 768.23 s respectively. The t_s values in area 2 with three controllers are 32.33 s, 149.47 s and 103.24 s respectively. Similarly, ts values in area 3 with three controllers are 57.40 s, 102.05 s and 68.23 s respectively. Integral-SMES-Fuzzy controller yields in moderately good peak time t_p. The least settling time is obtained with Integral controller, however, the overshoot and undershoot values are very high.

Table 2: Comparison of Results for Frequency Deviation when 1% load is added

	CONTROLLER / PARAMETER	INTEGRAL	INTEGRAL-SMES	INTEGRAL-SMES-FUZZY
Frequency Deviation in area 1	M_p (pu)	1.30 x10^{-4}	8.12 x10^{-5}	6.79 x10^{-5}
	t_s (sec)	57.24	101.98	68.55
	m_p (pu)	-4.97 x10^{-4}	-2.61 x10^{-5}	-2.63 x10^{-4}
	e_{ss}	0	0	0

Frequency Deviation in area 2	M_p (pu)	1.99 x10^{-6}	1.08x10^{-6}	9.33x10^{-7}
	t_s (sec)	32.47	149.99	103.07
	m_p (pu)	-1.16x10^{-5}	-3.35 x10^{-6}	-3.36 x10^{-6}
	e_{ss}	0	0	0
Frequency Deviation in area 3	M_p (pu)	2.13 x10^{-6}	1.15 x10^{-6}	9.86 x10^{-7}
	t_s (sec)	32.17	128.50	104.58
	m_p (pu)	-1.28 x10^{-5}	-3.52 x10^{-6}	-3.53 x10^{-6}
	e_{ss}	0	0	0

Table 3: Comparison of Results for Tie Line Power Deviation when 1% load is added

	CONTROLLER / PARAMETER	INTEGRAL	INTEGRAL-SMES	INTEGRAL-SMES-FUZZY
Tie-Line power Deviation between area 1 and area 2 (Δp_{tie12})	M_p (pu)	6.76 x10^{-5}	4.23 x10^{-5}	3.33 x10^{-5}
	t_s (sec)	57.38	102.01	68.23
	m_p (pu)	-2.54 x10^{-4}	-1.35 x10^{-4}	-1.36 x10^{-4}
	e_{ss}	0	0	0
Tie-Line power Deviation between area 2 and area 3 (Δp_{tie23})	M_p (pu)	2.16 x10^{-6}	1.17 x10^{-6}	1x10^{-6}
	t_s (sec)	32.33	149.47	103.24
	m_p (pu)	-1.28x10^{-5}	-3.61 x10^{-6}	-3.62 x10^{-6}
	e_{ss}	0	0	0
Tie-Line power Deviation between area 3 and area 1 (Δp_{tie31})	M_p (pu)	2.54 x10^{-4}	1.35 x10^{-5}	1.36 x10^{-5}
	t_s (sec)	57.40	102.05	68.23
	m_p (pu)	-6.75 x10^{-5}	-4.23 x10^{-5}	-3.53 x10^{-5}
	e_{ss}	0	0	0

6.2. Test case 2 - a step change (3%) in load is thrown off in one area)

With 3 % sudden step change in load in area 1, resulting deviations in frequency in different areas and the tie-line power are plotted and shown in Figure 12–17. The quantitative comparison of the three control schemes of area 1-3 is shown in Table 4 and Table 5.

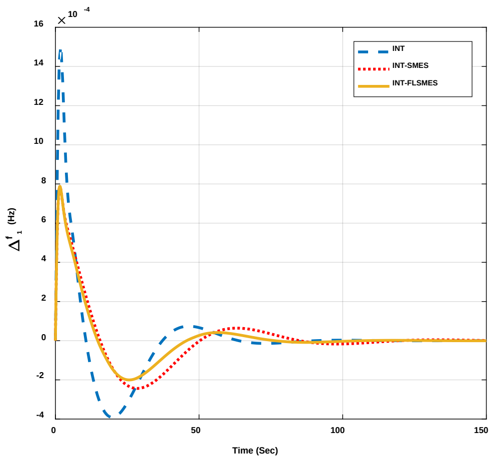

Fig. 12: Frequency change in area 1 with 3% load perturbation in area 1

The plot in Figures shows that the steady state error (ess) with Integral, Integral-SMES and Integral- Fuzzy-SMES controllers is zero in area 1-3. The peak overshoot (Mp) values with three controllers in area 1 are 0.0015 pu, 7.85 x10-4 pu and 7.88 x10-4 pu respectively. The Mp values with controllers in area 2 are 3.55 x10-5 pu, 1.0 x10-5 pu and 1x10-5 pu respectively. Similarly, the Mp values with three controllers in area 3 are 3.9 x10-5 pu, 1.05 x10-5 pu and 1.05 x10-5 pu respectively. Thus, the best overshoot values are obtained with Integral- Fuzzy-SMES controller.

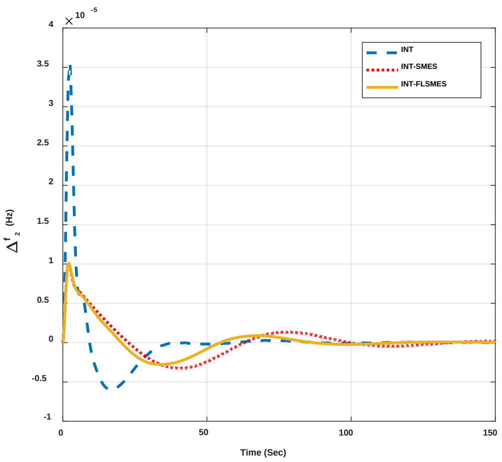

Fig. 13: Frequency change in area 2 with 3% load perturbation in area 1

Form the plots, it has also been observed that the peak undershoots (m_p) values with three controllers in area 1 are -3.91 x10^{-4} pu, -2.43 x10^{-4} pu and -2 x10^{-4} pu respectively. The m_p values in area 2 are -5.99 x10^{-6} pu, -3.27x10^{-6} pu and -2.79 x10^{-6} pu respectively. Similarly, m_p values in area 3 are -6.4x10^{-6} pu, -3.46 x10^{-6}pu and -2.95 x10^{-6} pu respectively. The Integral-fuzzy-SMES control scheme results in optimum peak undershoot value.

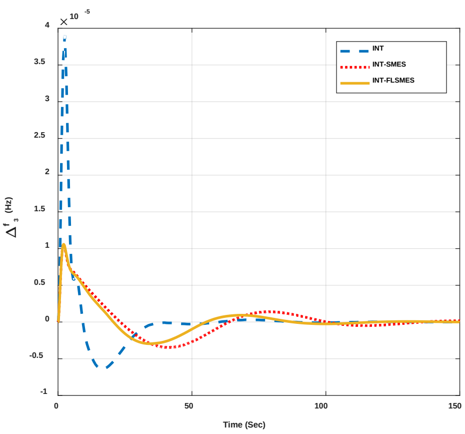

Fig. 14: Frequency change in area 3

The plots show that the settling time (ts) with three controllers in area 1 are 57.20 s, 101.90 s and 69.11 s respectively as shown in Figures. The ts values in area 2 with three controllers are 32.49 s, 127.21 s and 104.12 s respectively. Similarly, ts values in area 3 with three controllers 32.13 s, 128.58 s and 105.69 s respectively. The least peak time is obtained with Integral controller, however, the overshoot and undershoot values are very high. Therefore, the Integral-SMES-Fuzzy controller yields in moderately good peak time (ts).

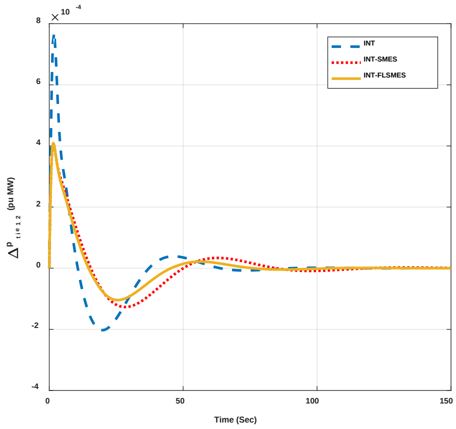

Fig. 15: Tie line power deviation area 1-area 2 with 3% load perturbation in area 1

For tie-line power deviation, it has been seen in the plots of Figure 15-17 that the steady state error (ess) with Integral, Integral-SMES and Integral- Fuzzy-SMES controllers is zero in area 1-3. The peak overshoot (Mp) values with three controllers in area 1 are 7.72 x10-4 pu, 44.07 x10-4 pu and 4.09 x10-4 pu respectively. The Mp values with controllers in area 2 are 3.91 x10-5 pu, 1.08x10-5 pu and 1.08x10-5 pu respectively. Similarly, the Mp values with three controllers in area 3 are 2.02 x10-4 pu, 1.27 x10-4 pu and 1.04 x10-4 pu respectively.
Thus, the best overshoot values are obtained by Integral-Fuzzy-SMES controller

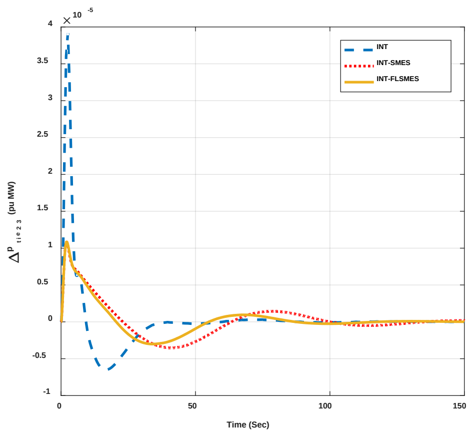

Fig. 16: Tie line power deviation area 2-area 3 with 3% load perturbation in area 1

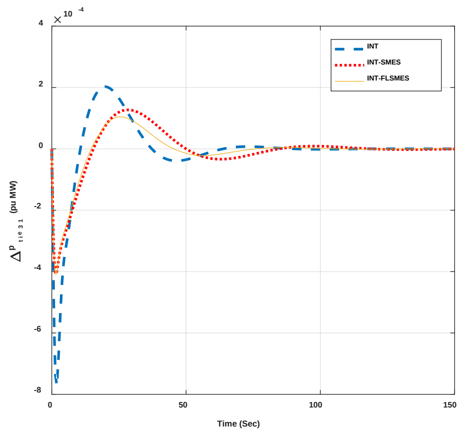

Fig. 17: Tie line power deviation area 3-area 1 with 3% load perturbation in area 1

The peak undershoot (m_p) values with three controllers in area 1 are -2.02 x10^{-4} pu, -1.27 x10^{-4} pu and -1.04 x10^{-4} pu respectively. The m_p values in area 2 are -6.5 x10^{-6} pu, -3.53x10^{-6} pu and -3.01x10^{-6} pu respectively. Similarly, m_p values in area 3 are -7.71 x10^{-4} pu, --4.07 x10^{-4} pu and --4.08 x10^{-4} pu respectively. Therefore, the Integral-fuzzy-SMES control scheme results in optimum peak undershoot value.

The plots also show that the settling time, t_s with three controllers in area 1 are 57.33 s, 101.99 s and 68.83 s respectively. The t_s values in area 2 with three controllers are 32.31 s, 127.81 s and 105.06 s respectively. Similarly, ts values in area 3 with three controllers are 57.35 s, 102.05s and 68.82 s respectively. Integral-SMES-Fuzzy controller yields in moderately good peak time t_p. The least settling time is obtained with Integral controller, however, the overshoot and undershoot values are very high.

Table 4: Comparison of Results for Frequency Deviation when 3% load is thrown off

	CONTROLLER / PARAMETER	INTEGRAL	INTEGRAL-SMES	INTEGRAL-SMES-FUZZY
Frequency Deviation in area 1	M_p (pu)	0.0015	7.85 x10^{-4}	7.88 x10^{-4}
	t_s (sec)	57.20	101.90	69.11
	m_p (pu)	-3.91 x10^{-4}	-2.43 x10^{-4}	-2 x10^{-4}
	e_{ss}	0	0	0
Frequency Deviation in area 2	M_p (pu)	3.55 x10^{-5}	1.0 x10^{-5}	1x10^{-5}
	t_s (sec)	32.49	127.21	104.12
	m_p (pu)	-5.99 x10^{-6}	-3.27x10^{-6}	-2.79 x10^{-6}
	e_{ss}	0	0	0
Frequency Deviation in area 3	M_p (pu)	3.9 x10^{-5}	1.05 x10^{-5}	1.05 x10^{-5}
	t_s (sec)	32.13	128.58	105.69
	m_p (pu)	-6.4x10^{-6}	-3.46 x10^{-6}	-2.95 x10^{-6}
	e_{ss}	0	0	0

Table 5: Comparison of Results for Tie Line Power Deviation when 3% load is thrown off

	CONTROLLER / PARAMETER	INTEGRAL	INTEGRAL-SMES	INTEGRAL-SMES-FUZZY
Tie-Line power Deviation between area 1 and area 2 (Δp_{tie12})	M_p (pu)	7.72 x10^{-4}	4.07 x10^{-4}	4.09 x10^{-4}
	t_s (sec)	57.33	101.99	68.83
	m_p (pu)	-2.02 x10^{-4}	-1.27 x10^{-4}	-1.04 x10^{-4}
	e_{ss}	0	0	0

Tie-Line power Deviation between area 2 and area 3 (Δp_{tie23})	M_p (pu)	3.91 x10^{-5}	1.08x10^{-5}	1.08x10^{-5}
	t_s (sec)	32.31	127.81	105.06
	m_p (pu)	-6.5 x10^{-6}	-3.53x10^{-6}	-3.01x10^{-6}
	e_{ss}	0	0	0
Tie-Line power Deviation between area 3 and area 1 (Δp_{tie31})	M_p (pu)	2.02 x10^{-4}	1.27 x10^{-4}	1.04 x10^{-4}
	t_s (sec)	57.35	102.05	68.82
	m_p (pu)	-7.71 x10^{-4}	-4.07 x10^{-4}	-4.08 x10^{-4}
	e_{ss}	0	0	0

Therefore, the integral controller alone results in large value of overshoot, undershoot with reduced settling time. The Integral-SMES control scheme gives overshoot and undershoot values better than the integral controller alone. The Integral-SMES-Fuzzy control scheme yields in the minimum overshoot, undershoot and zero steady state error in frequency and power deviations for both the cases. Thus, among all the three schemes, the Integral-SMES-Fuzzy control scheme provides far superior overshoot, undershoot, better response time and enhanced AGC effectiveness.

7. Conclusion

In this work, the Superconducting Magnetic Energy Storage (SMES) systems are utilized to enhance the Automatic Generation Control (AGC) in multi-machine multi-area power systems. The performance of three configurations: a conventional integral controller, an integral controller assisted with SMES, and a fuzzy integral controller with SMES has been compared for two test cases. The simulations in both cases showed that integrating SMES with these control strategies significantly improves the stability as well as dynamic response of the power system.

Among the configurations tested, the Fuzzy integral controller with SMES exhibited superior performance for frequency and tie line power regulation. The adaptive nature of the Fuzzy integral controller enables it to handle system nonlinearities and uncertainties more effectively, resulting in more robust and efficient control. This approach not only enhances the overall stability of the power system but also contributes to the efficient use of energy resources. Thus, incorporating fuzzy integral controller with SMES into the AGC of multi-machine multi-area power systems offers a remarkable improvement in power system stability and performance.

Nomenclature

ACE_i	Area Control Error
pf	Participation Factor
B_i	Bias factor
Δf_i	Frequency Perturbation
f	Nominal frequency
ΔP_{tieij}	Tie-line power deviation (between two areas *i*, *j*)
M	Inertia Constant
D	Damping Constant
K	Load Reference Actuator Gain
R_i	Governor speed regulation parameters
T_w	Water starting time
T_{gi}	Governor time constants
T_{ri}	Reheat time constant of steam turbine
R_T	Transient speed droop
T_{CH}	Steam Chest Time Constant
T_{ij}	Synchronizing Coefficient
i	Show Area (i =1,2.3)
j	Show Area (j =1,2.3)
T_g	= Steam governor time constant

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