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Potentials of Genetic Algorithm in the Performance of Load Frequency Control using FACT Devices, AVR and SMES for Hybrid Power System in Deregulated Environment

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ABSTRACT- In this article, the interconnection of two areas of a multi-unit hybrid interconnected power system is studied under a deregulated environment. For emergency requirements and energy-efficient building systems, the hybrid power system is studied which consists of several co-generating units thermal, hydro, nuclear, diesel, and gas power. To control the active power of the interconnected system, the Automatic Generation Controller (AGC) control loop is investigated, whereas, to control voltage, a reactive power control loop named automatic voltage regulator is applied. Effective governance requires the use of additional reliable fast energy exchange devices named superconducting magnetic energy storage (SMES) in both areas. The FACT devices considered are thyristor control series compensator (TCSC), Thyristor controlled phase shifter (TCPS), Unified power flow controller (UPFC), and Static synchronous series compensator (SSSC). For tuning of SMES, a Genetic Algorithm (GA)-based proportional integral derivative with a filter (PIDF) controller is applied to optimize integral square error (ISE). The frequency, tie-line power, and voltage profile of both the areas with various options of SMES connected to the system are studied in terms of overshoot, undershoot, rise time, and settling time. A system without SMES and with SMES in both areas are investigated. It is observed that GA-based PIDF controllers considerably enhanced system performance with SMES and SSSC gives better performance compared to other FACT devices. The response among all the FACT devices, SMES with SSSC gives a better response in terms of the settling time of frequency for two areas is settled at 8.25sec and 7.89sec. The modeling of an interconnected hybrid power system with FACT devices, SMES, and Automatic Voltage Regulator (AVR) is done in MATLAB 2016b Simulink.

General Terms: Automatic Generation Controller, Load Frequency Control, Proportional Integral Derivative, Genetic Algorithm.

Keywords: Automatic Voltage Regulator, Flexible AC Transmission, Super Magnetic Energy Storage, Static Synchronous Series Compensator, Thyristor Control Phase Shifter, Thyristor Control Series Compensator and Unified Power Flow.

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1. INTRODUCTION

Voltage and frequency control are the challenges of controlling the actual voltage of the system concerning changes in the power and system frequency while maintaining a constant voltage (VFC). Voltage control is typically handled by the Automatic Voltage Regulator (AVR) on the generator. The AVR will adjust the generator's excitation to keep the voltage within a set range. LFC, on the other hand, is typically handled by the governor of the generator. It will adjust the fuel supply to the prime mover (turbine, combustion engine, etc.) to keep the frequency within a set range. Several researchers have already given detailed literature for multi-area, thermal, and hydro systems in load frequency control systems [1]. The load frequency control may not be able to keep the frequency within its bounds [3, 5, 7]. R. Jaipal at all [8] used AVR in two areas in which comparison of with and without dc link was studied. A. Gupta at all [17] study the DFIG based wind form in which the use of AVR plays an important role to improve voltage profile. Frequency linked price control mechanism is used to obtain the system frequency and voltage within permissible limit. The detail modelling of modelling of AVR for sensor, amplifier, exciter and generator modelling is explained by O. Elgerd [20] for different types of excitation system. The SMES system utilizes a superconducting coil and a cryogenic refrigeration unit to store and release energy [9, 16].

To manage this sudden change in load a fact devices SSSC [16] Which can change their internal impedance according to the system requirement. SSSC can easily switch from inductive to the capacitive mode or vice versa very easily whenever it is required [9]. Therefore, by connecting SSSC in series with the transmission line, the balance between demand and load takes place resulting in minimum deviation in output frequency [12].

In recent years new FACT devices named as thyristor-controlled phase shifters have been used for multi-area hydro and thermal by Y. Arya et al [1, 13, 14, 18]. Ghoshal et al. [16] have much research on capacitive energy storage as well as TCPS devices to obtain steady state for thermal-hydro and diesel multi-units [6, 11, 12] have a great effort for thermal and hydro with I and PI controller for stabilizing the frequency of two-area system. Ghoshal et al. [16] earlier applied genetic algorithms for two area systems to control the gain of PI and PID controllers. Including GA Ghoshal proposed particle swarm optimization [15] to obtained gain for PID controller [2, 5, 6]. For AGC system most of the researchers proposed thermal-thermal or thermal with the hydropower system, very few works were proposed by the researcher on nuclear, diesel, and gas power plants because of their characteristics. To obtain the better regulation effect of FACT [4, 9, 10, 12, 16, 19] (TCPS, SSSC, TCSC, and UPFC) devices, AVR and fast energy storage device (SMES) [4, 9, 16, 17] were also added with the system.

FACTS controllers can also be used to improve the stability of power systems [9, 11, 16].

To overcome the research gap, following are the paper's objectives:

- Effect of FACT devices with SMES by providing different combinations for two area AGC systems.
- To investigate the different parameters like settling time, rise time, and overshoot the frequency, voltage, and tie-line disturbances are considered.
- To maintain system voltage the automatic voltage regulator controller is connected to both areas.
- To obtain optimized parameters of FACT devices and gain PID controller, a genetic algorithm is used.

2. MATHEMATICAL MODELING OF A TWO-AREA MULTI-UNIT SYSTEM

The AGC system presented in this paper is made up of two generating areas with varying capacities. Both areas are interconnected with thermal, hydro, nuclear, diesel, and gas power multi-unit systems which are shown in *fig (8)*. To maintain the voltage profile both areas relate to an automatic voltage regulator (AVR) which is the source of reactive power [17]. In recent trends FACT devices have been widely used in power system networks to improve the profile of voltage, to remove oscillation in frequency and power of tie-line [12, 15, 16].

2.1 Mathematical Modelling of TCPS

The thyristor-controlled phase shifter is connected in series with the tie-line between two areas. It is connected near to one of the areas by neglecting the resistance of the tie-line. The modeling of TCPS is explored in [12].

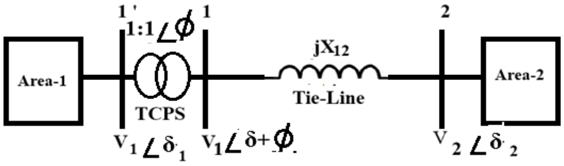

Figure 1. TCPS connected in series with the tie-line between two areas

$$\Delta P_{tie\ 12}\,(s) = \Delta P^0_{tie\ 12}(s) + \Delta P_{TCPS}\,(s) \qquad (i)$$

$$\Delta P_{TCPS}(s) = T_{12}\frac{K_\phi}{1 + T_{TCPS}}\Delta w_1(s) \qquad (ii)$$

For the best TCPS frequency controller design, two parameters must be optimized, stabilized gain K_ϕ and time constant T_{TCPS}.

2.2 Modeling of Static Synchronous Series Compensator

The SSC can regulate the active power flow and balance the AC network by controlling the voltage amplitude and phase angle [16]. It can also be used as an emergency generator to supply an islanded network or to provide damping for oscillations in the transmission line. The SSSC can also be used to provide voltage support to the interconnected areas and to compensate for power losses in the interconnection. The SSSC can also be used to control the tie-line power flow to achieve maximum power transfer capability.

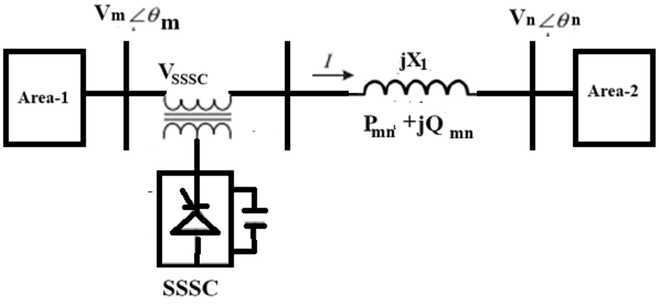

Figure 2. SSSC connected in series with the tie-line between two areas [16]

The detailed modeling of SSSC is represented by Bhatt et al [15]

$$\Delta P_{tie\ 12}\,(s) = \Delta P^0_{tie\ 12}(s) + \Delta P_{SSSC}\,(s) \qquad (iii)$$

$$\Delta P_{SSSC}\,(s) = \left(\frac{1 + sT_1}{1 + sT_2}\right)\left(\frac{1 + sT_3}{1 + sT_4}\right)\left(\frac{K_{SSSC}}{1 + T_{SSSC}}\right)\Delta w_1(s) \qquad (iv)$$

2.3 Mathematical Modeling of Unified Power Flow Controller

The very first UPFC was proposed by Gyugi in 1993 [19] and comprises two voltage source converters and a DC circuit.

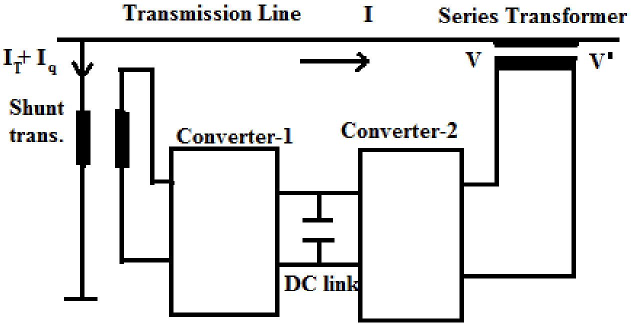

Figure 3. UPFC connected with tie-line [19]

denoted by a capacitor. The diagrammatic representation of UPFC is shown in *figure 3*. The UPFC has two main control objectives: (1) to maintain the desired voltage profile and (2) to maintain the desired active and reactive power flow. To achieve these objectives, the UPFC is equipped with several control loops for voltage, active power and reactive power.

$$\Delta P_{UPFC}\,(s) = \left(\frac{1}{1 + \; sT_{UPFC}}\right)\Delta w_1(s) \qquad (v)$$

The state space modelling of UPFC where is T_{UPFC} is the time constant of UPFC, Δw_1 is the input power of UPFC and ΔP_{UPFC} is the output power of UPFC which is further feed to the tie line to minimize the ACE. The Simulink state space model of UPFC.

2.4 Modeling of Thyristor Controlled Series Compensator (TCSC) for AGC

Thyristor Control Series Compensator (TCSC) can vary the impedance by adjusting the firing angle of the three stages of thyristors.

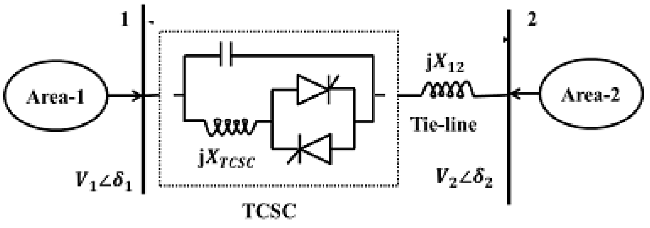

Figure 4. Equivalent circuit of TCSC connected between two areas [10]

The TCSC is particularly useful in damping out power swings in transmission lines and mitigating oscillations of frequency and voltage. Now the recent trend it can be applied in tie-line to control the power flow. The TCSC can also be used to improve the power transfer capability of an existing system [10], such as controlling the maximum power transfer limit or dampening the oscillations of voltage and frequency.

The *equation (vi)* shows the state space modelling of TCSC where T_{TCSC} is the time constant, K_{TCSC} is the gain of TCSC, Δw_1 is the input power of TCSC when connected to the system and ΔP_{TCSC} is the output power of TCSC which is further feed to the tie line to minimize the ACE.

$$\Delta P_{TCSC}\,(s) = \left(\frac{K_{TCSC}}{1 + \; sT_{TCSC}}\right)\Delta w_1(s) \qquad (vi)$$

2.5 Mathematical modeling of Superconducting magnetic energy storage (SMES)

SMES is works by storing electrical energy in an electromagnetic field. When the energy is needed, the superconducting coil is energized, creating a magnetic field. This field is then discharged back into the electrical grid, providing additional power. The main advantage of SMES systems is their ability to store large amounts of energy for a long period which is explained in [4, 9 & 16]. This makes them ideal for peak shaving applications, as they can provide large amounts of energy in a short time. In this research work SMES is allowed to exchange only 5% of total capacity of Hybrid two area interconnected system. The demand of the system may suddenly change, SMES respond with in microsecond to exchange energy. SMES systems do not involve any chemical reactions or emissions during operation, making them environmentally friendly compared to some other energy storage technologies such as batteries or pumped hydro.

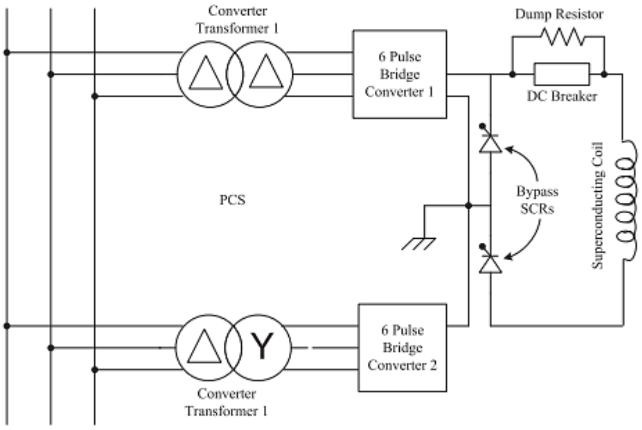

Figure 5. Circuit configuration of SMES [16]

$$\Delta P_{g,SMES}\,(s) = \left(\frac{K_{SMES}}{1 + \; sT_{SMES}}\right)\Delta w_1(s) \qquad (vii)$$

2.6 Automatic voltage Regulator Controlled loop

An Automatic Voltage Regulator (AVR) is an important component of synchronous generator for an interconnected Automatic Generation Control (AGC) system [8].

AVR loops are used to provide reactive power balancing at a generator bus, which implies that voltage is maintained at the desired level.

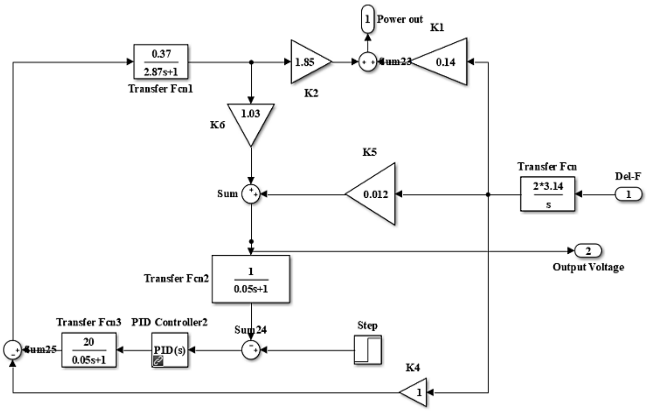

Figure 6. Simulink model of AVR loop

3. GENETIC ALGORITHM EVOLUTIONARY COMPUTATION TECHNIQUES

A population of chromosomes is formed. A fitness function is used to evaluate the chromosomes. Some chromosomes are picked for further reproductive genetic treatments. Cross-over genetic procedures are carried out. The mutation technique comes after the crossover operation. The new progeny will be evaluated using FDM just after the mutation's procedure.

Some chromosomes are picked for further reproductive genetic treatments. Cross-over genetic procedures are carried out. The mutation technique comes after the crossover operation. The new progeny will be evaluated using FDM just after the mutation's procedure. Population Size (N=50) and Crossover Rate is set in the range [0, 1]. A higher value encourages exploration, while a lower value favors exploitation. A low mutation rate can help preserve good solutions, while a high mutation rate increases exploration. There are various selection methods like roulette wheel, tournament selection, rank-based selection, etc. The tournament selection is used in this study. Crossover Operator: There are different crossover operators like one-point, two-point, uniform, and more. A uniform crossover operator was selected for this study. Mutation Operator: There are various mutation operators, such as bit-flip, swap, and inversion. An inversion operator is applied.

The lower and upper bound range of the tunning parameters

$$0 \le K_p \le 5, 0 \le K_i \le 5, 0 \le K_d \le 5, \quad 50 \le N \le 450$$

$$0 \le K_{SMES} \le 2, \qquad 0 \le T_{SMES} \le 1$$

Range of FACT Devices, SSSC, UPFC, TCPS and TCSC selected for the Gain and Time constant tunned with GA.

$$0 \le K_{SSSC} \le 2, 0 \le T_{SSSC} \le 1, 0 \le T_{UPFC} \le 0.5$$

$$0 \le K_{TCPS} \le 2, 0 \le T_{TCPS} \le 0.5,$$

$$0 \le K_{TCSC} \le 2, 0 \le T_{TCSC} \le 1$$

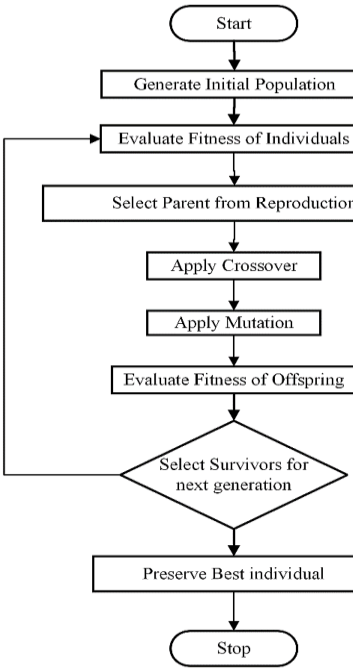

Figure 7. Flowchart of Genetic Algorithm

A distinct population is created when the order to establish a new one inherits the genome with the lowest FDM value. Screening, recombination, and mutation all result in the formation of a new population. This new group will encounter the exact same experience. Quite an iterative approach will be ended after the largest amount of iteration cycles have been completed.

4. PROBLEM FORMULATION IN MATHEMATICS

In a deregulated power system, we aim to settle frequency as quickly as possible to a desired value, optimization in tie-line power while maintaining the voltage of the line to a set value. To meet the selected criteria, the gains of the PIDF controller for area control error, as well as the SSSC, TCSC, UPFC, TCPS parameters, and SMES parameters (KSMES, TSMES), must be tuned to have the least amount of system parameters in term of rise time and settling times (ts), peak over and undershoot for voltage, frequency, and tie-line of both the interconnected area. To select the optimum value of figure of demerit, an integral square error (ISE) criterion is applied with the Simulink model. The objective function is evaluated utilizing GA-based optimal control methodologies, and the optimization methodologies' outcomes are evaluated. With the effect of superconductivity SMES can store energy at a fast rate therefore their losses are much less during the storage process, around 1.5-2.5% of total energy storage. With this accuracy, it is mostly preferred for energy exchange devices for AGC systems. It gives efficiency of around 95% or more which is extremely good to mitigate load perturbation. The steady state response is also shown in *figure 9-11* in terms of graph with SMES.

The FDM for two areas depend upon the strength of the:

$$FDM = \sum \{\Delta f_1^2 + \Delta f_2^2 + \Delta P_{tie\,1-2}^2\}\Delta T \qquad (viii)$$

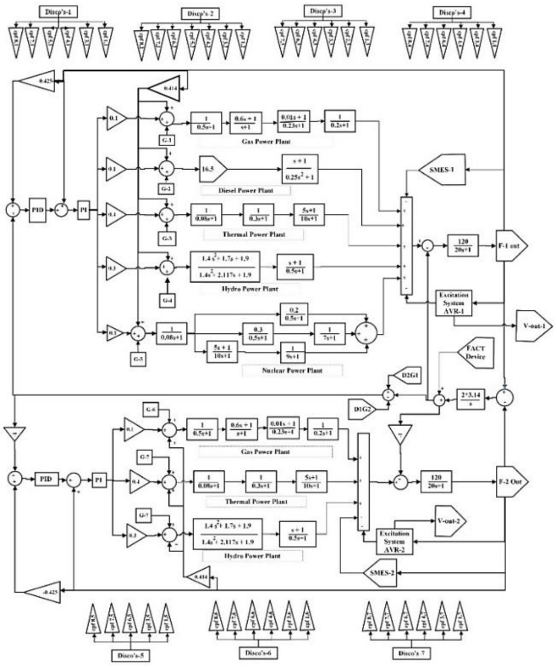

Figure 8. Transfer function simulink model of two-area multi unit interconnected system with SMES and Fact Devices

5. FACT AND SMES ARE OPTIMIZED USING GA WITH AN ENERGY STORAGE DEVICE (SMES) IS CONNECTED IN AREA-1, AREA-2

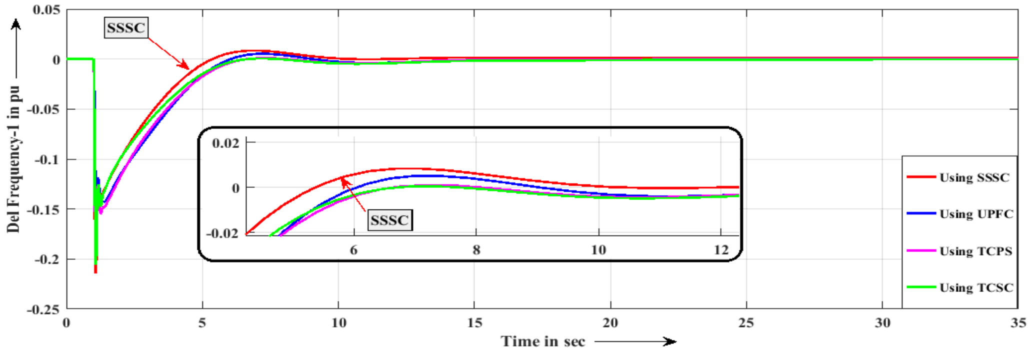

Figure 9. Frequency response of Area-1

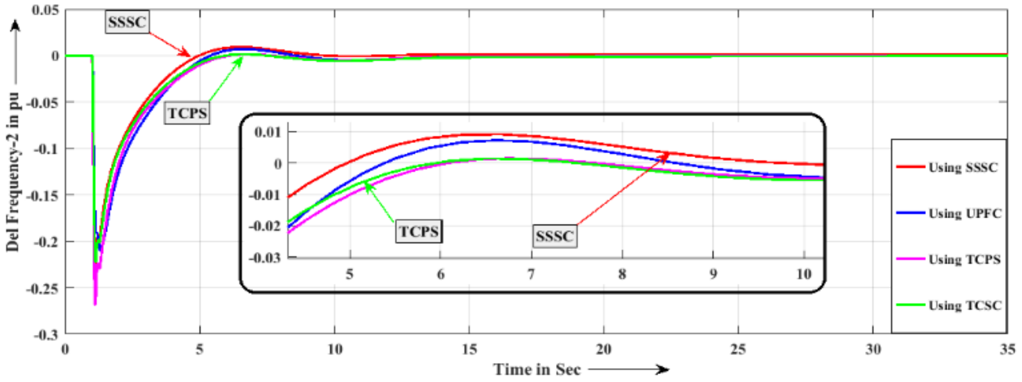

Figure 10. Frequency response of Area-2

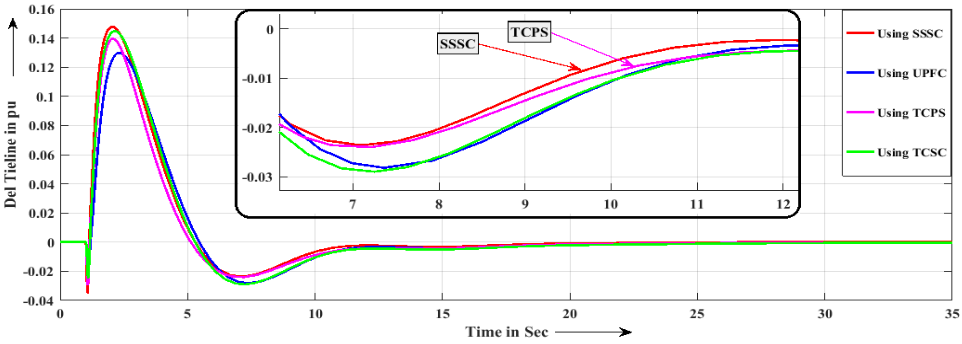

Figure 11. Tie line response between two Area

Table-1. Parameters of PID, SSSC, UPFC, TCPS, TCSC and SMES are optimized using Genetic Algorithm With an energy storage device (SMES) is connected in Area-1, Area-2

	Area-1						Area-2						FACT Device	
	Kp	**Ki**	**Kd**	**N**	**Ksmes**	**Tsmes**	**Kp**	**Ki**	**Kd**	**N**	**Ksmes**	**Tsmes**	**Gain**	**Tc**
PID	0.229	0.391	0.205	240.734	-	-	4.934	4.999	3.344	64.23	-	-	-	-
SSSC	0.439	0.033	0.198	95.045	1.945	0.114	4.767	4.994	2.963	431.67	1.988	0.287	0.040	0.0002
TCPS	1.1997	0.4837	0.3024	63.4415	1.3903	0.5929	4.9203	4.9082	1.8814	294.38	1.8903	0.0151	0.7696	0.2652
TCSC	0.3865	0.2474	0.2632	274.3837	1.9766	0.1597	4.9281	4.7936	3.4052	199.31	1.9922	0.3503	0.2140	0.9146
UPFC	1.3178	0.3238	0.6135	439.0497	1.9998	0.2642	4.9959	4.8803	4.3684	194.42	1.8695	0.4209	-	0.4894

Table-2. System parameters for the case study of PID, SSSC, UPFC, TCPS, TCSC and SMES are optimized using Genetic Algorithm With an energy storage device (SMES) is connected in Area-1, Area-2

FACT Device	F1			F2			V1			V2			Tieline_1-2		
	Rise Time (sec)	Settling Time (sec)	Peak Over shoot	Rise Time (sec)	Settling Time (sec)	Peak Over shoot	Rise Time (sec)	Settling Time (sec)	Peak Over shoot	Rise Time (sec)	Settling Time (sec)	Peak Over shoot	Rise Time (sec)	Settling Time (sec)	Peak Over shoot
Without	0.01	11.42	0.24	0	11.45	0.24	0.02	6.37	1.33	0.02	6.27	1.33	0.01	16.44	0.18
SSSC	0.07	8.25	0.21	0.06	7.89	0.23	0.02	6.3	1.32	0.02	6.23	1.32	0	16.43	0.15
UPFC	0.01	12.47	0.14	0	11.33	0.21	0.02	6.43	1.33	0.02	6.3	1.33	0.01	17.97	0.13
TCPS	5.68	12.03	0.18	5.11	11.39	0.27	0.02	6.42	1.33	0.02	6.31	1.33	0.01	17.28	0.14
TCSC	0	11.61	0.21	0	11.48	0.22	0.02	6.38	1.33	0.02	6.29	1.33	0.01	17.78	0.14

Table-3. Comparison of parameter with GA, CRPSO [16] and RGA [16]

		SMES-SMES			SSSC-SMES			TCPS-SMES		
		RGA + PI	**CRPSO + PI**	**GA + PID**	**RGA + PI**	**CRPSO + PI**	**GA + PID**	**RGA + PI**	**CRPSO + PI**	**GA + PID**
FACT Devices		Without Fact Devices			Ksssc=0.254 Tsssc= 0.032	Ksssc= 0.293 Tsssc= 0.026	Ksssc= 0.04 Tsssc= 0.01	Ktcps=2.886 Ttcps= 0.170	Ktcps =2.752 Ttcps = 0.059	Ktcps = 0.7696 Ttcps= 0.2652
Area-1	**Kp**	-	-	0.46	-	-	0.439	-	-	1.1997
	Ki	-0.3	-0.221	0.20	-0.199	-0.199	0.033	-0.412	-0.459	0.4837
	Kd	-	-	0.22	-	-	0.198	-	-	0.3024
	N	-	-	109.98	-	-	95.045	-	-	63.4415
	Ksmes	0.296	0.3	0.18	0.298	0.298	1.945	0.22	0.291	1.3903
	Tsmes	0.032	0.038	0.08	0.035	0.035	0.114	0.03	0.04	0.5929
	Ts	95	90	11.42	85	85	8.250	30	30	12.03
	OS	0.049	0.059	0.24	0.065	0.062	0.210	0.359	0.318	0.18
Area-2	**Kp**	-	-	4.97	-	-	4.767	-	-	4.9203
	Ki	-0.17	-0.292	4.99	-0.19	-0.19	4.994	-0.48	-0.469	4.9082
	Kd	-	-	3.71	-	-	2.963	-	-	1.8814
	N	-	-	401.79	-	-	431.67	-	-	294.38
	Ksmes	0.128	0.162	0.18	0.298	0.298	1.988	0.22	0.291	1.8903
	Tsmes	0.028	0.027	0.08	0.035	0.035	0.287	0.03	0.04	0.0151
	Ts	1400	1400	11.45	80	120	7.890	45	50	11.39
	OS	0.001	0.001	0.24	0.073	0.073	0.230	0.191	0.129	0.27
Tie Line	**Ts**	1400	1200	16.44	85	95	16.43	30	30	17.28
	OS	0.001	0.001	0.18	0.016	0.018	0.15	0.23	0.21	0.14

6. CONCLUSION

High Speed energy exchange device named as Superconducting magnetic energy storage (SMES) is connected with two areas, multi-unit, interconnected power system under a deregulated environment. The study of AGC is done by connecting SMES in Area-1, Area-2, Area-1, and 2 simultaneously with FACT devices. Four different FACT devices are applied which are SSSC, UPFC, TCPS, and TCSC. The Genetic algorithm (GA) optimization is used to obtain the best-fitted value for these FACT devices. PID tuner is used to get optimum results.

Tests are carried out for simultaneous tunning of SMES, Fact devices, and PID using GA. The result analysis is done for PID parameters (Kp, Ki, and Kd). System performance is analyzed using rise time, settling time, and peak value for frequency, tie-line, and voltage respectively.

- In table-1 the parameters of PID, SMES and FACT devices are given using genetic Algorithm optimization technique.
- Table-2 indicates steady state response with SMES. When SMES is applied the SSSC gives a better response in terms of the settling time of frequency for two areas is settled at 8.25sec and 7.89sec which is minimum as compared to other FACT devices. In case of tie-line power SSSC have minimum settling time of 11.43 second followed by TCPS, TCSC and UPFC. In overall performance of SSSC is better than other FACT device.
- Table-7 indicate the comparison [16] of SMES-SMES, SSSC-SMES and TCPS-SSSC using CRPSO, RGA and GA. Where it is cleared that the PID tunned with GA give better result compare with the literature [16].

7. FUTURE SCOPE

Incorporation of AI, machine learning (ML), and deep learning techniques into AGC systems will allow predictive and adaptive control strategies. These tools can optimize system parameters, forecast load variations, and provide enhanced robustness in a deregulated hybrid environment. Future AGC frameworks will leverage energy storage systems (ESS) like batteries, pumped storage, and supercapacitors to provide rapid frequency response. In deregulated markets, these storage systems can participate as ancillary service providers, improving frequency stability and system performance.

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