Performance Comparison of Various Energy Storage Devices in Combined LFC and AVR of Multi Area System with Renewable Energy Integration

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Abstract- This paper demonstrates the performance comparison of various energy storage devices (ESDs) like ultra-capacitors (UCs), Superconducting magnetic energy storage (SMES) and redox flow batteries (RFBs) in combined load frequency control (LFC) and automatic voltage regulation (AVR) of two area interconnected system. The test system comprises of thermal, hydro and gas plants in one area, another area consists diesel, wind and solar photovoltaic plants. To get more realistic study generation rate constraints (GRC) is considered for thermal and hydro plants. Proportional-integral-derivative (PID) controller is chosen as secondary controller and the gains are optimized with proposed differential evolution- artificial electric field (DE-AEFA) algorithm. To showcase the superiority of proposed algorithm, its performance is compared with available algorithms of DE and AEFA. However, the performance of proposed algorithm is demonstrated by tested on widely used two area non reheat thermal power system available in literature. Later, the ESDs are incorporated in the system to damp out the oscillations in system frequency and terminal voltage further. The performance comparison of ESD in presence of proposed DE-AEFA based PID controller spotlights the significant impact of RFBs in combined frequency and voltage control.
Keywords Combined LFC and AVR, Energy Storage Devices, Generation rate constraints (GRC), DE-AEFA Optimization.

1. Introduction

In modern day power system, more number of generating utilities with high capacities is interconnected together forms complex network. These utilities are subdivided, results in formation of control areas. Each control area is connected to other through tie-lines, responsible for power exchange. The amount of power generation in each area depends on rating of synchronous generator. Operating the complex power system is not an easy task. Frequency deviations in each area, tie-line power flow variations and voltage profile must be maintained at scheduled values irrespective of the condition [1]. The total power generated by the interconnected system must match with the load demand, unless results in frequency fluctuations. This can be safeguard by the primary controller which regulates the governor and turbine action to deal with varying load demand. However, the performance of primary controller is not sufficient to bring system to normal operating conditions under sudden large disturbances. So, an additional controller is needed named as secondary controller. Moreover the system voltage is maintained by changing the synchronous generator field excitation. The frequency and voltage in an interconnected power system can be controlled by controlling the real and reactive powers [2]. Lot of literature is available on LFC and AVR separately [3-14]. Various test system models had been considered by the researchers for investigation. Some of them are mentioned here. Two area non-reheat thermal power plant was considered in [3-5], with and without considering system non linearity's. In [6, 7] investigation is done on two area hydro-thermal system with reheat turbines. Authors in [8, 9] done the analysis by considering two-area hydro-thermal-gas plant. In [10-14], analysis is carried by integrating renewable energy sources like solar, wind and geothermal power plants along with conventional generation units. The above literature is restricted to investigations on LFC only and the effect of AVR coupling is not considered.

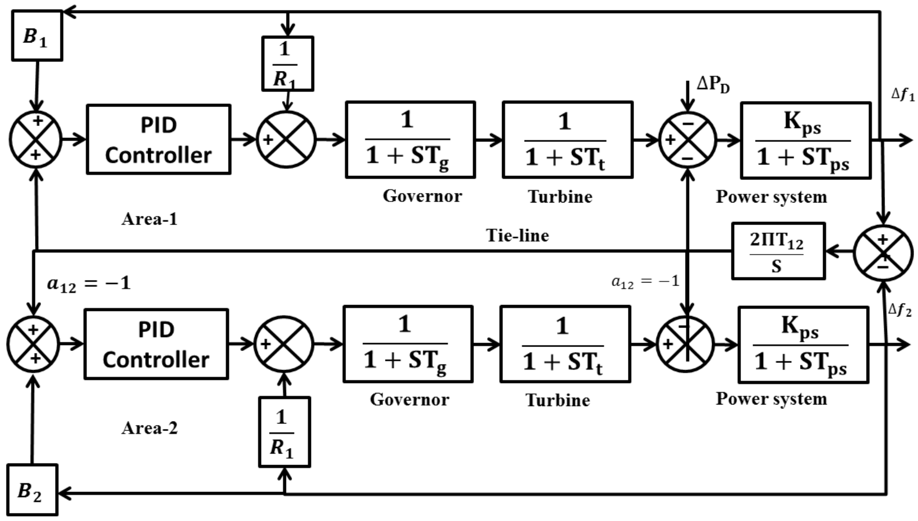


Fig.1. Two area non reheat thermal power system (test system-1)

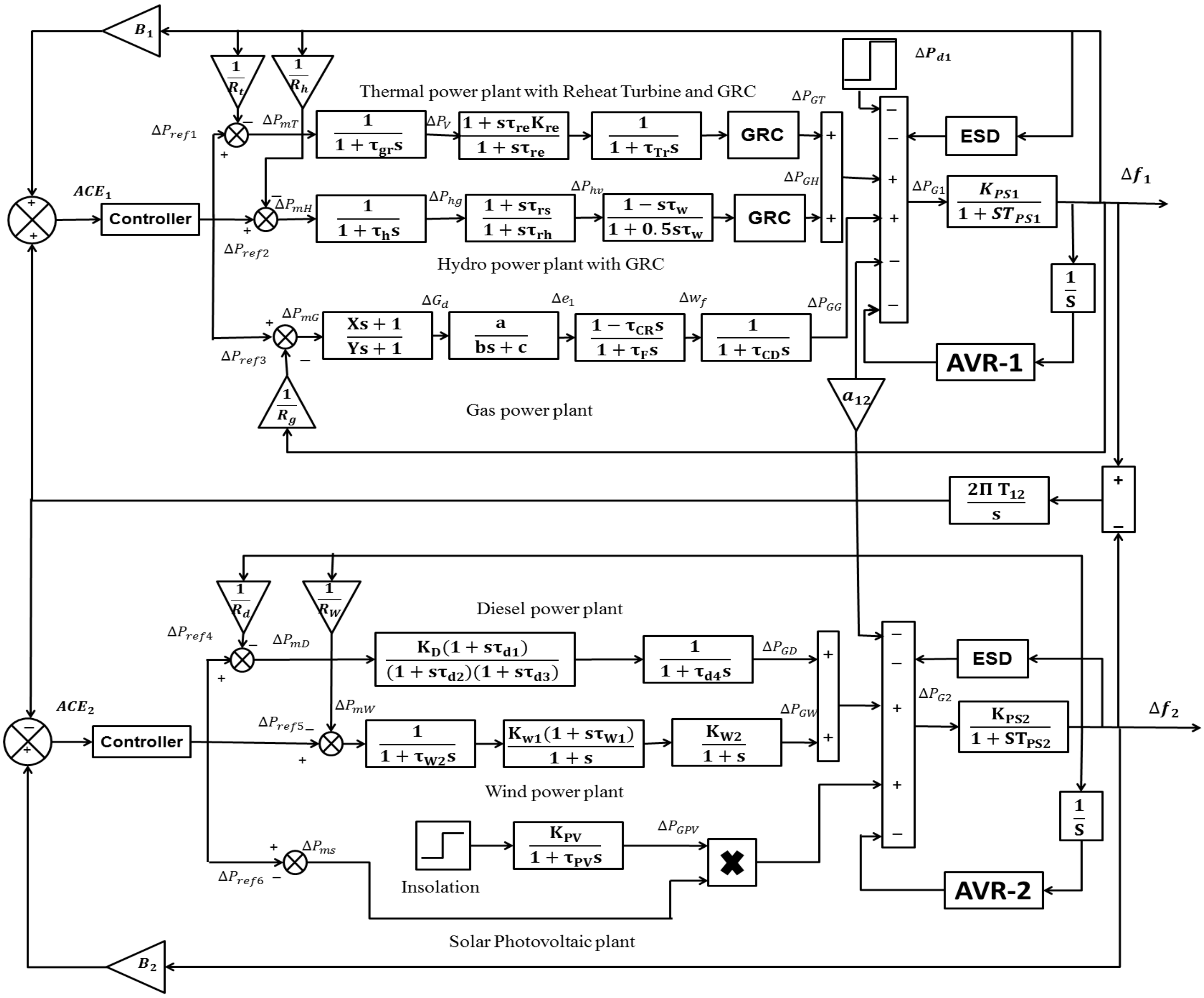


Fig.2. Transfer function model of combined LFC and AVR of considered test system (test system-2)

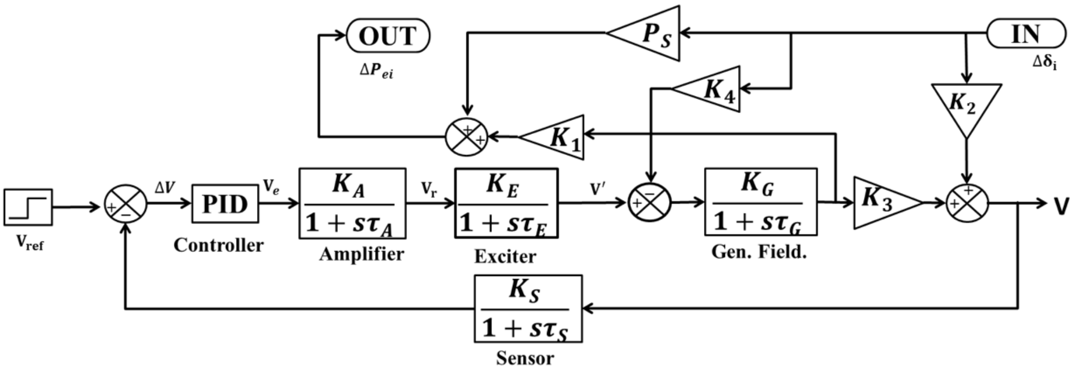


Fig.3. Block diagram representation of AVR with cross coupling coefficients

Many authors have investigated AVR system using various heuristic optimization algorithms [15, 16]. In [17, 18] investigation was done on combined frequency and voltage control of single area thermal power plant. Authors in [19], analysed the multi-area multi-source system for combined effect, but renewable energy integration is not considered as they are gaining momentum now-a-days. Later on, it was extended by [23, 24], by incorporating solar thermal power plant (STPP) to analyse combined LFC and AVR model. However, controller design in both LFC and AVR domains is a recent trend of research. Controllers like I/ PI/ PID/PIDN [4, 5, 9, 12-16, 17], fractional order (FO) [14] controllers and intelligent based controllers [6, 7, 13] had been proposed by authors in their work. Moreover, optimization algorithms have been utilized to optimize controller parameters. Algorithms like particle swarm optimization (PSO) [20, 22], Genetic algorithm (GA) [9], backtracking search algorithm (BSA) [3], differential evolution (DE) [11], imperialist competitive algorithm (ICA) [7], grey wolf optimization (GWO) [21], hybrid GA-PSO (HGA-PSO) [5] etc. are available in literature. But most of the above algorithms are having tendency to easily trap in to local solution and lack in maintaining the average balance between exploration and exploitation. So, a new DE-AEFA algorithm is proposed in this work to optimize the PID controller, which is employed as secondary controller in both LFC and AVR loops because of its design simplicity and operational efficiency.

On reviewing the literature, the objectives of this present work is as follows:

- To design a combined LFC and AVR of two area system consists of both conventional and renewable generation utilities with considering GRC.
- To optimize the controller gains with proposed DE-AEFA algorithm and dynamic responses are to be compared with controller tuned with other algorithms in order to prove its effectiveness.
- To validate the efficacy of proposed DE-AEFA algorithm, a widely used test system reported in literature is need to be considered and to compare the performance of proposed algorithm with algorithms available in literature.
- To incorporate various ESD in both areas one at a time and performance comparison has to be made to retrieve the best device among them.

2. Power System Models

The power system models considered for investigation in this work are two-area non-reheat thermal system named test system-1 depicted in Fig.1 and combined LFC and AVR of two-area hybrid system named test system-2 depicted in Fig.2. The gain and time constants of the test system-1 are considered from [3, 4] and the detail mathematical modeling is also represented. The test system-2 considered for investigation consists of two unequal areas having generation capacity of 2:1 in ratio. Thermal, hydro and gas plants are in area-1, diesel, wind and solar PV units are in area-2. GRC considered for thermal plant is 3%/min considered and the lowering and raising values for hydro plant is 360%/min and 270%/min respectively. The system parameters of gain and time constants for thermal, hydro and gas plants are taken from [8], for diesel, wind and solar PV units parameters are considered from [14, 21]. AVR loop is coupled to LFC loop through cross coupling coefficients and power system synchronizer (P_S) as shown in Fig.3. The AVR modeling and cross coupling coefficients are taken from [2]. The test systems shown in Figs.1and 2 are constructed in MATLAB/SIMULINK algorithm and the optimization algorithms are coded in (.mfile).

3. Energy Storage Devices Modelling

ESD devices are playing a vital role in maintaining power system stability because of their quick response characteristics. Frequency deviation in the grid is undesired quantity and can be restored quickly. Variation in system frequency depends on real power mismatch between generation and load. ESD performs two tasks, drawing power from the grid for energy storage and injecting back to the grid whenever necessary. When sudden rise in load occurs on grid, the generators must cope up with varying load demand. But, this cannot be done instantly because of time lag nature of governor and turbine characteristics of generation units. In this interim these ESD injects power in to the grid and regulates system frequency. Though usages of ESD are costly, their performance outrages it. In this paper UCs, SMES and RFBs are installed in considered test system one at a time and their performances are analyzed. The single line diagram of test system with ESD is represented in Fig.4.

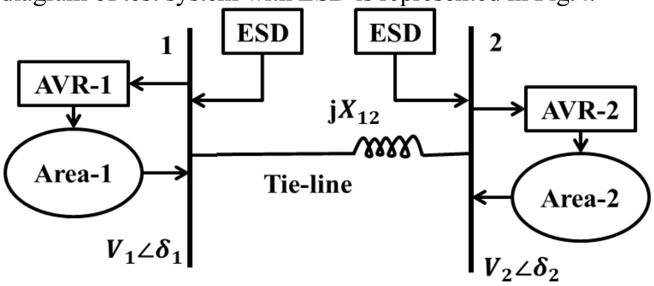


Fig.4. Single line diagram representing combined LFC and AVR with ESD

The mathematical modeling of these devices is as follows:

3.1. Ultra Capacitors (UCs)

UCs also called as super capacitor, having capability to store huge amount of power between two plates. This device is normally employed at peak power requirements and can also be used in combination with batteries. Though UC is costly, its maintenance is easy and having high life time in addition to high power density. The transfer function is given by

$$G_{UC} = \frac{K_{UC}}{1+ST_{UC}} \tag{1}$$

3.2. Super Conducting Magnetic Energy Storage (SMES)

SMES unit consists of superconducting coil with nearly zero resistance and is enclosed in a chamber filled with helium or liquid nitrogen to maintain low temperatures for attaining super conductivity. It also has a step down transformer and power conversion unit. The charging and discharging of magnetic coil in SMES is done through this step down transformer and the power conversion unit acts as interface between coil and grid. SMES stores energy in off peak load time periods and discharges during generation loss. This device can be put into wide time range of operation since static operation, its performance is superior to other ESD. The transfer function is given by

$$G_{SMES} = \frac{K_{SMES}}{1+ST_{SMES}} \tag{2}$$

3.3. Redox-flow Batteries (RFBs)

RFBs are come under electrochemical ESDs. Oxidation reaction and chemical reductions are performed in RFBs. During charging and discharging process electrolytic solutions are flown through battery cells. In discharging process, oxidation reaction dislodges electron from anode and it is accepted by cathode through reduction reaction. During charging process, flow of current and chemical reaction will be done in reverse direction. The EMF developed in RFBs depends on active elements between chemical states. The operational range of this device lies on size and quantity of electrolytic chemical. The transfer function is given by

$$G_{RFBs} = \frac{K_{RFBs}}{1+ST_{RFBs}} \tag{3}$$

4. Objective Function

ISE performance index is considered for error minimization. PID controller is employed as secondary controller for combined LFC and AVR of system under investigation. The controller gains are optimized using DE-AEFA algorithm with in the specified range. [0 5] chosen as search space to find the controller parameters. A total of 12 parameters are optimized with 50 populations for a maximum of 50 iterations. Same parameters are employed for other algorithms also, to demonstrate the effectiveness of proposed algorithm. The parameters gains of the controller are optimized by minimizing the error subjected to the objective function given in EQ.4. The objective function formulated in this work for combined LFC and AVR system comprising of deviations in terminal voltages along with variations in frequency and tie-line power. By considering the coupling of AVR with LFC to investigate the research in more practical approach, any changes in AVR system has been a considerable effect on LFC loop. So, the objective function with variations in system frequency and terminal voltages are need to be considered together for optimizing the secondary controller gains. The optimization process is diagrammatically shown in Fig.5.

$$J = \int_0^{T_{sim}} \left[\Delta f_1^2 + \Delta f_2^2 + \Delta P_{tie1,2}^2 + \Delta V_1^2 + \Delta V_2^2\right] dt \tag{4}$$

$$K_{Pmin} \le K_P \le K_{Pmax}, K_{Imin} \le K_I \le K_{Imax}, \\ K_{D\,min} \le K_D \le K_{D\,max} \tag{5}$$

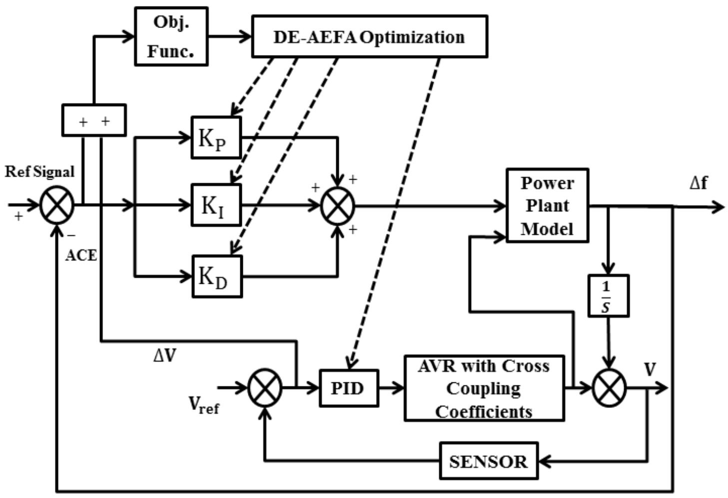


Fig.5. PID controller optimization in combined LFC and AVR system

5. Differential evolution- artificial electric field algorithm

Differential evolution algorithm (DE) was proposed by [25], resembles the structure of evolutionary algorithms but differs in generation of new population. DE comprises of mutation, recombination and selection operations.

Recombination operator assists the population to move towards the best solution and mutation operator tends to spread the populations into uncovered search space to find optimal solution. The superiority of DE was demonstrated in [26], by testing on several standard benchmark functions. DE includes the benefits of creating new population from mutant and target vector, also owns capability to avoid destroying of best solution while creating next generation. However, DE suffers from slow and premature convergence and also endures weak local searching limits the application boundary.

On the other hand, artificial electric field algorithm (AEFA) was proposed by [27], inspired from coulomb's law of electrostatic force. AEFA involves few initial parameters and can be implemented easily. In AEFA charged particles acts as searching agents and can move in search space by making use of attraction and repulsion forces between them. AEFA nearly locates the optimal solution with high speed of convergence and having better exploration and exploitation capability which lacks in DE algorithm. But AEFA is inferior to DE in global convergence. However, the major drawback of AEFA algorithm is the procedure involved in adjusting the step size of particles position and velocity up gradation, which may leads to untimely convergence.

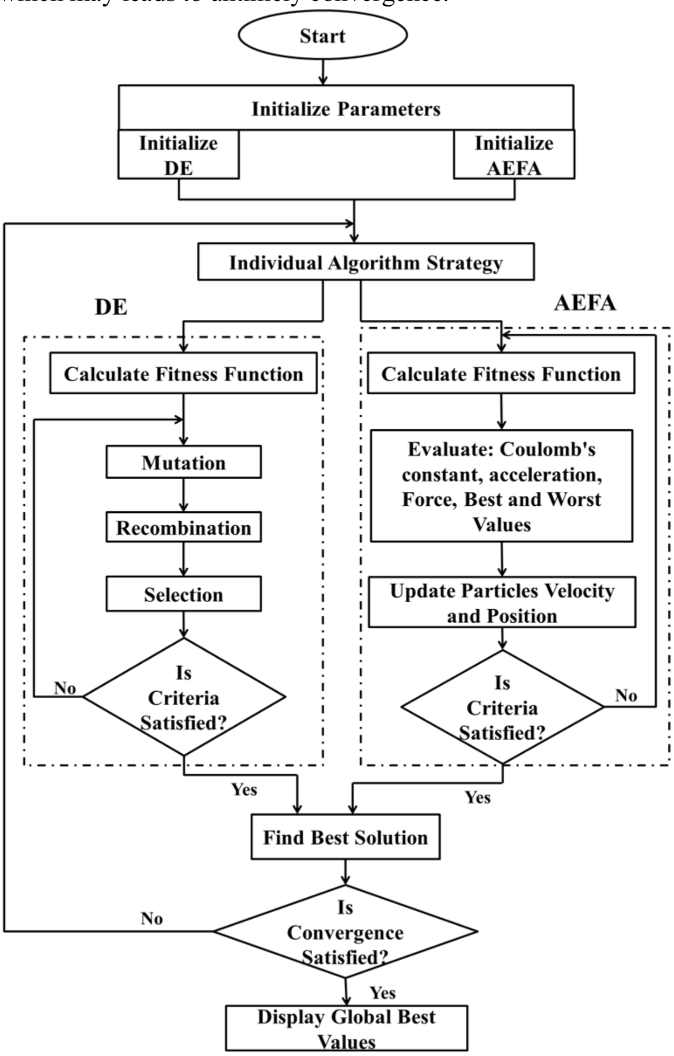


Fig.6. Flow chart of proposed DE-AEFA algorithm

The performance of both DE and AEFA algorithms are complementary with each other. So, in order to make use of the benefits of individual algorithms in collectively, a new combined DE-AEFA algorithm is proposed in this work which over rules the drawbacks of individual algorithms. In this proposed DE-AEFA algorithm, half of the total population is utilized to search the optimal solution with DE strategy and the remaining half done the process with AEFA structure, and the total population information is shared among each search agent. The particle with highest fitness value gets the opportunity to enter next generation's optimization. Therefore, this proposed algorithm acquires evolution information, enhances the searching capability of searching agents and also guarantees the accurate and quick global convergence. However, the effectiveness of proposed DE-AEFA algorithm is validated on standard benchmark sphere function for 100 trails. The variation of initial and final values for 100 trails is depicted in Fig.7. From Fig.7, it is revealed that the function final values with proposed DE-AEF algorithm are below the mean value in most of the trails. This happens only, if the algorithm maintains the average balance between exploration and exploitation. This shows the effectiveness of proposed algorithm.

The procedural flow of proposed algorithm is as follows:

Step 1: Initialize initial parameters, number of populations in DE (N_{DE}); number of populations in AEFA (N_{AEFA}); total number of populations in DE-AEFA is ($N_{DE\text{-}AEFA}$); then initialize other parameters in DE, AEFA.

Step 2: Randomly initialize the population of DE, AEFA individually.

Step 3: calculate fitness of each population, evaluate solution when fitness is highest in the current population, and save as optimal global solution.

Step 4: From step- 3, population having highest fitness value is survived and wipe out other individuals.

Step 5: The searching of DE and AEFA is carried on to the survived individuals as procedure in step-4.

- AEFA phase: Particles positions and velocities are updated as mentioned in [24].
- DE phase: Mutation, Recombination and selection operations are performed.

Step 6: Scrutinize the derived solutions. If convergence criteria met, terminate iterations and display best solution, or else go to Step-3.

6. Simulation results and Discussion

6.1. Dynamic analysis of test system-1

The power system model widely available is literature is a two-area non reheat thermal power plant is considered as test system-1 in this work to validate the performance of proposed DE-AEFA algorithm. The test system is investigated by applying 1%SLP applied in area-1 and the controller gains are optimized with various optimization algorithms available in literature. The dynamic responses are depicted in Fig.8, and the corresponding settling times and the controller parameters are noted in Table 1.

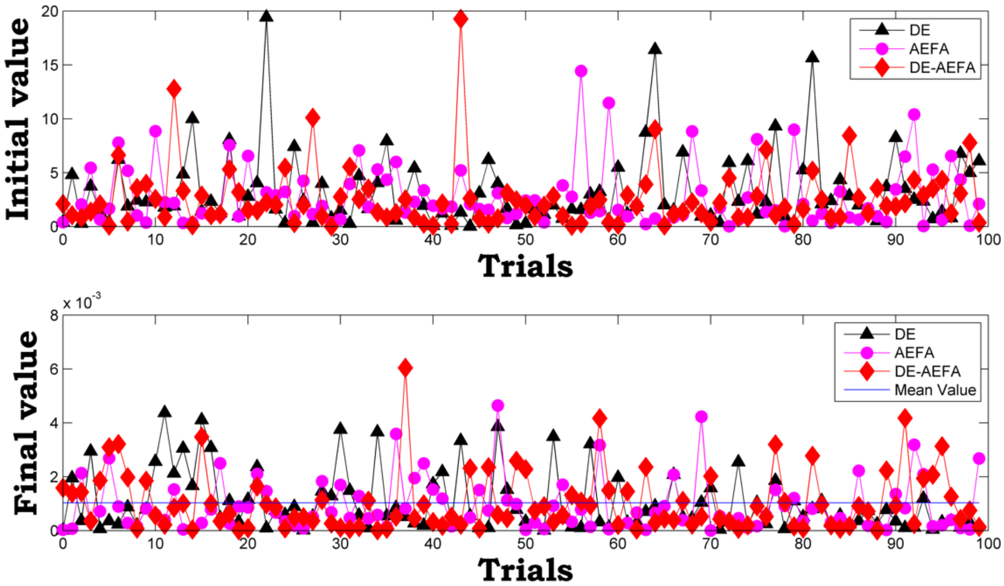


Fig.7. Variation of initial and final function values of sphere function

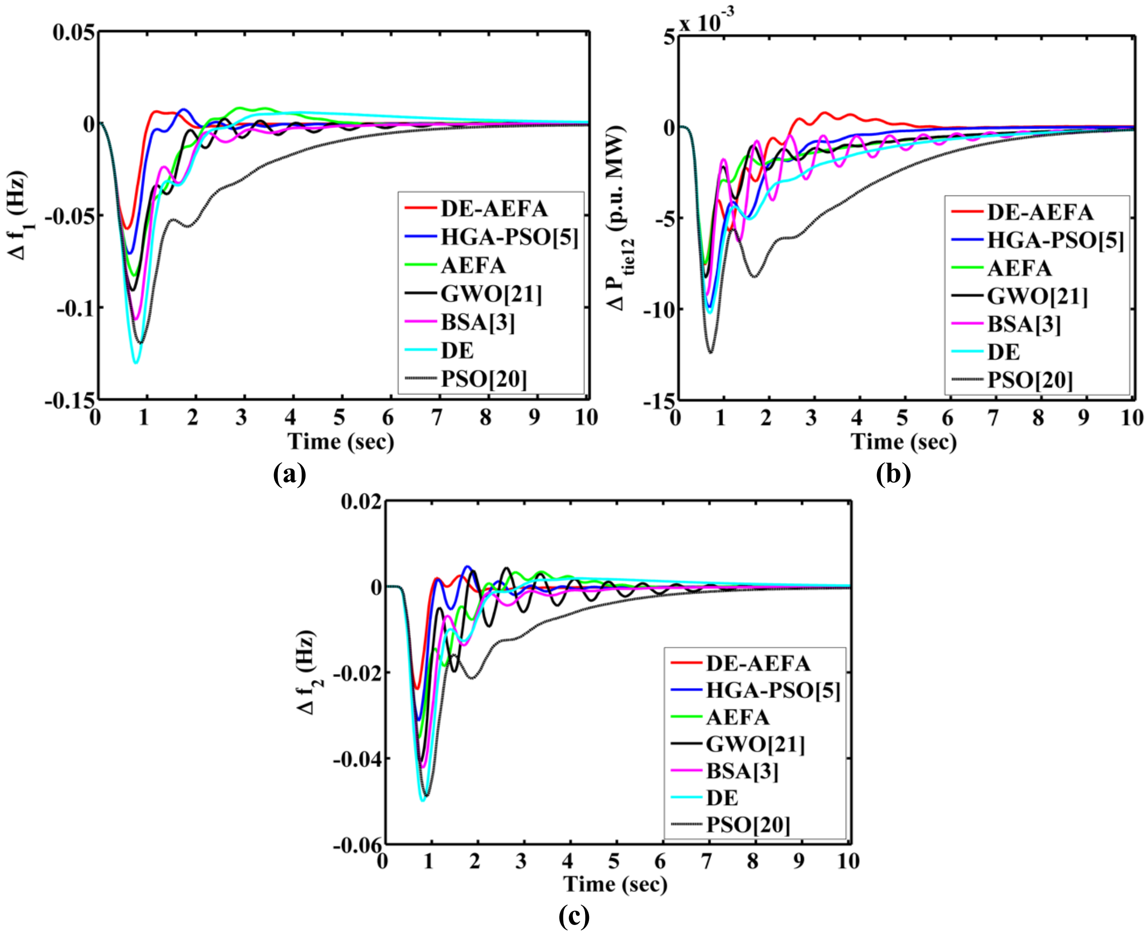
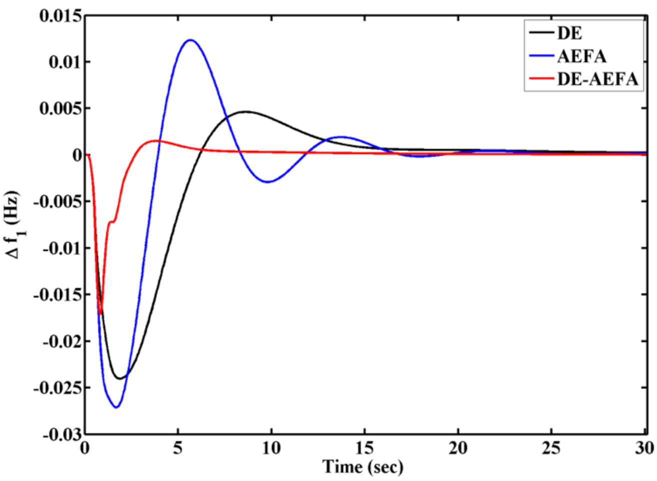


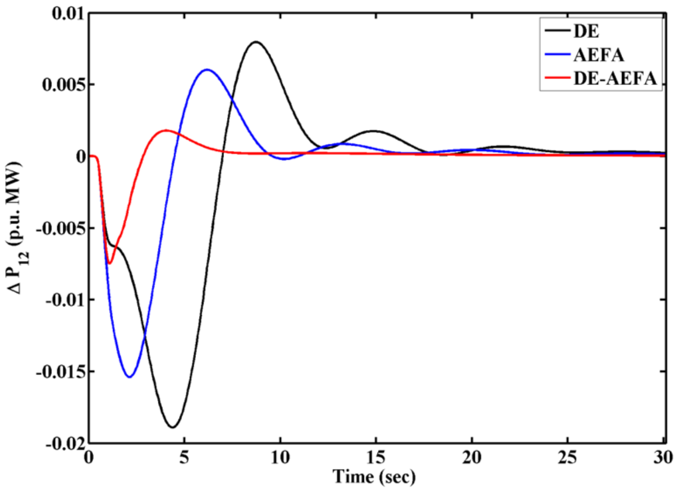
Fig.8. Dynamic responses of test system-1. (a) Δf_1, (b) ΔP_{tie12}, (c) $\Delta f2$

Table 1. Settling time of responses and optimum parameters of PID controller for test system-1

Parameters	Optimization algorithms						
	DE-AEFA	HGA-PSO[5]	AEFA	GWO[21]	BSA[3]	DE	PSO[2]
K_{P1}	1.975	1.647	1.544	1.227	0.916	0.929	0.757
K_{P2}	1.829	1.776	1.641	1.246	0.939	1.002	0.877
K_{I1}	0.009	0.044	0.035	0.005	0.055	0.020	0.301
K_{I2}	0.013	0.041	0.009	0.019	0.001	0.019	0.301
K_{D1}	1.062	0.721	0.907	0.914	0.729	0.586	0.126
K_{D2}	1.142	0.763	1.091	0.853	0.692	0.574	0.137
ISE	0.105	0.329	0.590	0.763	1.098	1.105	1.630
Settling time: Δf_1 (Sec)	2.724	4.141	4.890	7.485	7.981	8.962	9.752
Settling time: ΔP_{tie} (Sec)	5.126	6.207	8.470	8.573	8.738	9.323	9.693
Settling time: Δf_2 (Sec)	3.214	4.276	4.991	5.184	8.275	8.708	9.752



(a)



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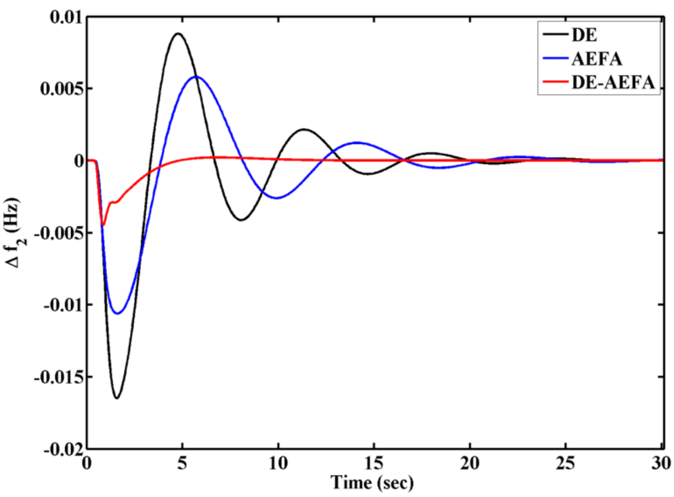
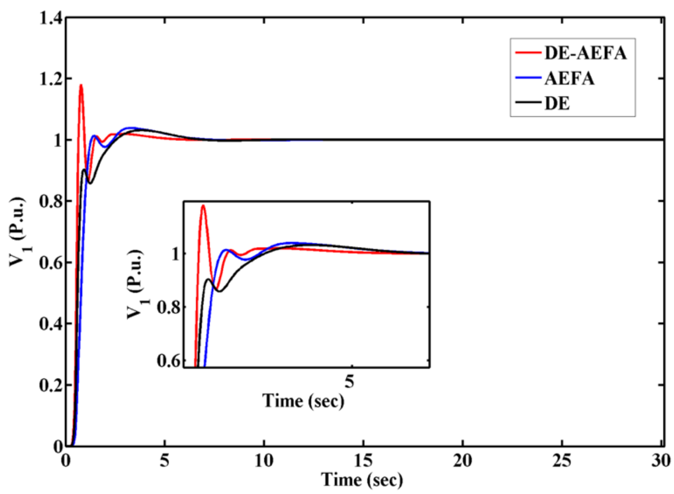


(c)



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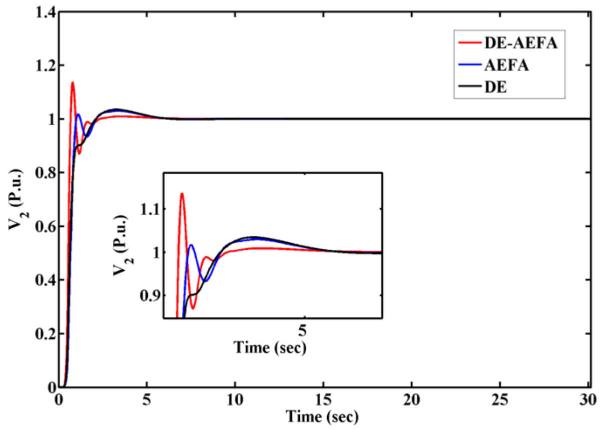


(e)

Fig.9. Dynamic responses of combined LFC and AVR system when 1% SLP applied in area-1 in presence of Optimized PID controller (a) Δf_1, (b) ΔP_{tie}, (c) Δf_2 , (d) V_1, (e) V_2.

From Fig.8, it is observed that the system responses with proposed algorithm are greatly improved compared to other optimization algorithms available in literature.

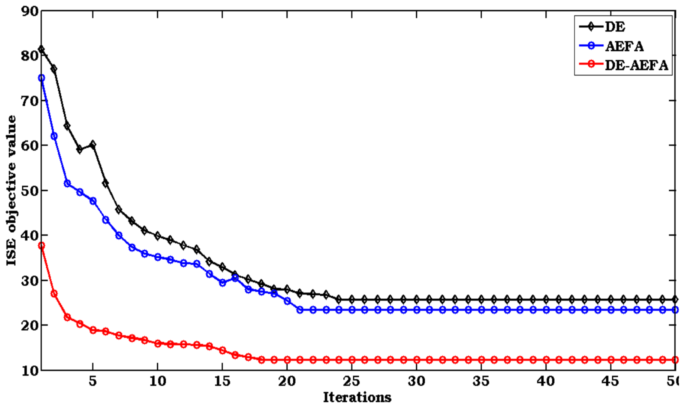


Fig.10. Comparing convergence characteristics of Optimization algorithms

6.2. Dynamic analysis of test system-2

6.2.1. Performance analysis of DE-AEFA optimized Controller

The test system-2 incorporating both conventional and renewable energy sources is investigated with PID controller whose gains are optimized with DE, AEFA and DE-AEFA algorithms individually. System is subjected to a step load perturbation (SLP) of 1% in area-1. Voltage and frequency are controlled simultaneously subject to the objective function expressed in section4. The dynamic responses are compared in Fig.9, on observing these responses in terms of peak magnitude variations and settling time PID controller optimized with DE-AEFA algorithm is more predominant when compared to other two optimization algorithms. Also the objective function value with proposed algorithm is improved by 52.24% and 46.17% with DE and AEFA algorithms respectively. The numerical results are given in Table-2 and the corresponding controller gains are given in Table-3. The convergence characteristics of these algorithms are compared in Fig.10 reflects the effectiveness of proposed combined DE-AEFA algorithm in view of quick convergence and error minimization. ISE values obtained with various optimization algorithms are compared in Fig.11.

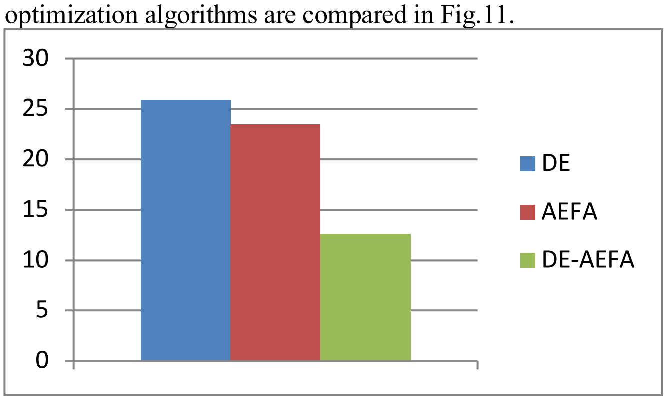


Fig.11. PID controller ISE indices comparison

Table 2. Numerical result of dynamic responses of combined LFC and AVR system when 1%SLP applied in area-1

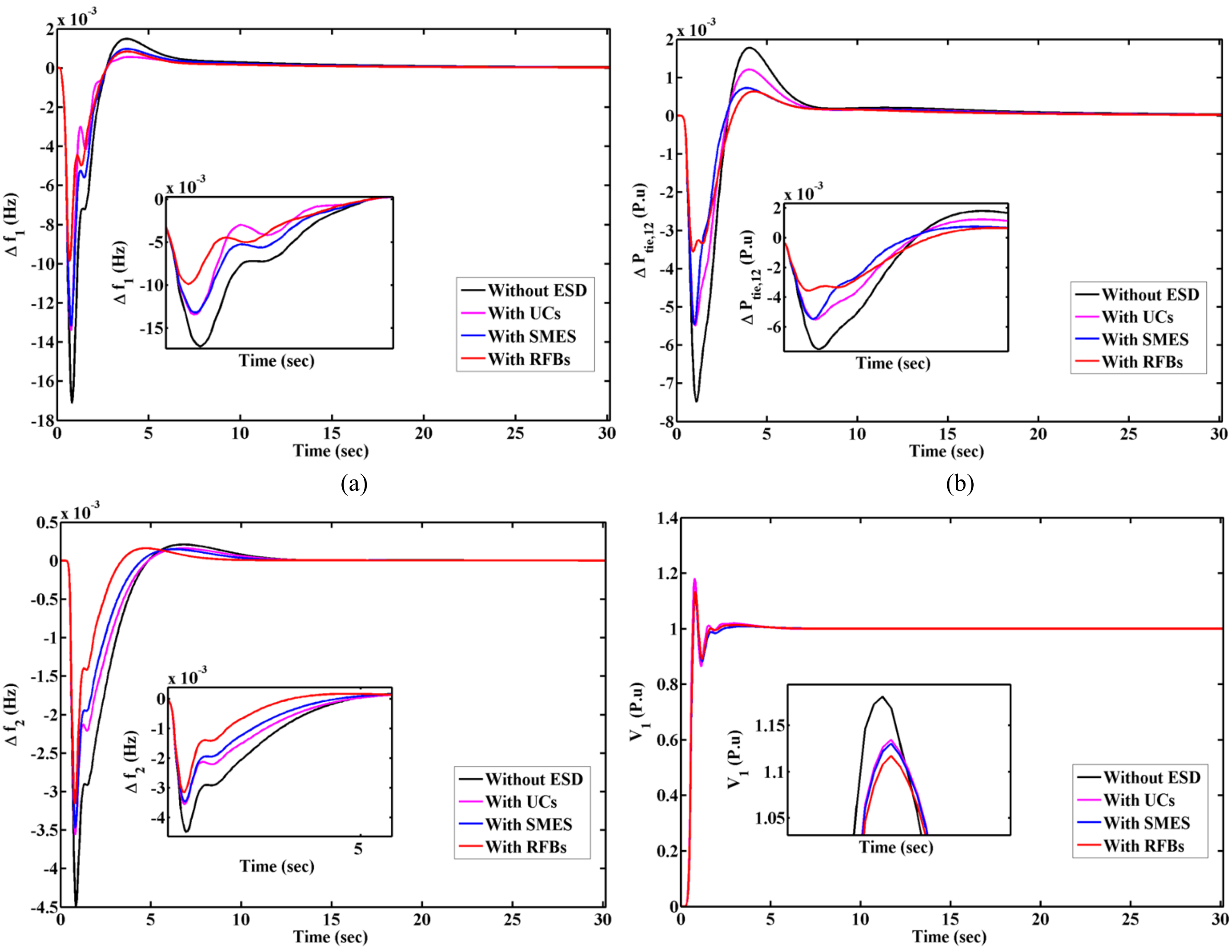
Optimized controller	**Settling time T_S (Sec)**					**ISE**
	Δf_1	Δf_2	ΔP_{tie12}	V_1	V_2	
DE:PID	25.77	25.75	28.85	7.011	8.982	25.925
AEFA:PID	22.54	23.26	23.20	6.615	7.920	23.487
DE-AEFA:PID	**14.34**	**10.52**	**18.43**	**5.018**	**4.096**	**12.641**

6.2.2. Performance comparison of some ESDs

Later the test system is incorporated with various ESD like UCs, SMES, RFBs in both the areas one by one and DE-AEFA based PID controller is used as a secondary controller for a 1% SLP applied in area-1.

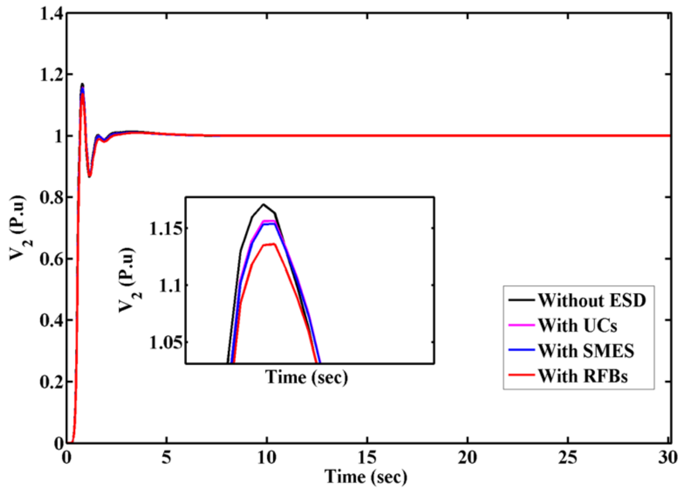
Table 3. Optimal Parameters of PID controller and ESDs

Controller	**Area-1**		**Area-2**		**ESDs Parameters [14]**
	LFC Loop	AVR Loop	LFC Loop	AVR Loop	
DE: PID	$K_P=3.2435$ $K_I=2.1487$ $K_D=1.5469$	$K_P=2.0119$ $K_I=1.1576$ $K_D=0.9340$	$K_P=2.9034$ $K_I=1.8270$ $K_D=1.7431$	$K_P=1.9085$ $K_I=1.0975$ $K_D=0.7792$	---
AEFA: PID	$K_P=3.3517$ $K_I=2.4854$ $K_D=0.9649$	$K_P=2.1622$ $K_I=1.2583$ $K_D=0.5285$	$K_P=2.8909$ $K_I=2.1869$ $K_D=0.9595$	$K_P=2.3413$ $K_I=1.3718$ $K_D=0.8693$	---
DE-AEFA: PID	$K_P=3.7679$ $K_I=1.9755$ $K_D=1.2769$	$K_P=2.0457$ $K_I=1.0844$ $K_D=0.9961$	$K_P=3.4509$ $K_I=1.9924$ $K_D=0.9133$	$K_P=2.3015$ $K_I=1.1554$ $K_D=0.9419$	---
DE-AEFA: PID with UCs	$K_P=3.7636$ $K_I=2.2961$ $K_D=1.8742$	$K_P=2.1450$ $K_I=1.1361$ $K_D=0.9133$	$K_P=3.8258$ $K_I=1.9983$ $K_D=2.0149$	$K_P=2.1009$ $K_I=1.7632$ $K_D=1.2111$	$K_{UCs}=-0.7$ $T_{UCs}=0.9s$
DE-AEFA: PID with SMES	$K_P=3.6916$ $K_I=2.4460$ $K_D=2.0152$	$K_P=2.7398$ $K_I=1.9961$ $K_D=1.2290$	$K_P=3.5413$ $K_I=2.3403$ $K_D=1.9831$	$K_P=2.9927$ $K_I=1.7733$ $K_D=1.2417$	$K_{SMES}=0.12$ $T_{SMES}=0.03s$
DE-AEFA: PID with RFBs only	**$K_P=3.8744$ $K_I=2.7783$ $K_D=2.5641$**	**$K_P=3.0593$ $K_I=2.0782$ $K_D=1.9285$**	**$K_P=3.7990$ $K_I=2.6296$ $K_D=2.2111$**	**$K_P=2.9929$ $K_I=2.3481$ $K_D=1.9924$**	**$K_{RFBs}=1.000$ $T_{RFBs}=0.093s$**



(a) (b)

(c) (d)



(e)

Fig.12. Dynamic responses of combined LFC and AVR system when 1% SLP applied in area-1 when various ESD are incorporated (a) Δf_1, (b) ΔP_{tie}, (c) Δf_2 , (d) V_1, (e) V_2.

Table 4. Numerical result of Combined LFC and AVR system with various ESD when 1%SLP applied in area-1

DE-AEFA:PID	Settling time T_S (Sec)					ISE
	Δf_1	Δf_2	ΔP_{tie12}	V_1	V_2	
Without ESD	14.34	10.52	18.43	5.018	4.096	12.641
With UCs	13.77	10.26	17.71	3.630	3.513	10.746
With SMES	13.30	9.93	16.90	3.303	2.912	10.013
With RFBs	**12.27**	**8.19**	**15.71**	**2.122**	**2.012**	**9.070**

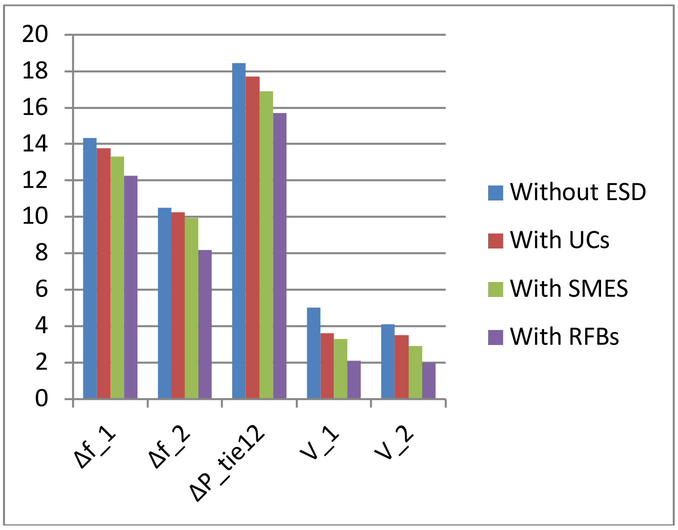


Fig.13. Settling time (in Sec) comparison of system dynamic responses under various cases.

The dynamic responses reflect the predominance of incorporating ESD in the system by comparing them with the dynamic responses without considering ESD. Performance comparisons of various ESD are shown in Fig.12 reveals the superiority of RFBs performance in mitigating peak magnitude deviations, oscillations and settling time point of view compared to UCs and SMES. The numerical results of this case are consolidated in Table-4 and the corresponding controller parameters are noted in Table 3.The system frequency and terminal voltages are greatly enhanced by incorporating RFBs in both the areas. The settling time of the system responses are diagrammatically represented in bar chart as shown in Fig.13.

7. Conclusion

The frequency and voltage of interconnected power system is controlled simultaneously by connecting LFC and AVR loops with cross coupling coefficients. The total dynamic response analysis is carried out by injecting 1% SLP in area-1.DE-AEFA tuned controller performs better compared to tune with other optimization algorithms. Moreover, the performance of the proposed algorithm is demonstrated by comparing with other optimization algorithms like PSO, BSA, GWO, HGA-PSO available in literature by testing on widely used tow-area non-reheat thermal power system reported in literature. Furthermore, the combined LFC and AVR system is incorporated with ESD in both the areas and their performance is compared in combined LFC and AVR control for the first time in research domain of power system operation and control environment. The system performance is enhanced by incorporating ESD in view of reduction in magnitude of undershoots and upper shoots and also settling time, RFBs are stated as preferable ESD compared to others.

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