PERFORMANCE EVALUATION OF REDOX FLOW BATTERY UNITS AND SUPERCONDUCTING MAGNETIC ENERGY STORAGE DEVICES IN INTERCONNECTED POWER SYSTEM STABILITY

Abstract

This work implements the Differential evolution (DE) algorithm tuned fractional order (FO) proportional-integral-derivative (PID) (FOPID) for the dynamic stability of two area multi fuel (TAMF) power system. Initiated the analysis for the step load disturbance (SLD) of 10% in area-1 and the performance superiority of FOPID is deliberated with the FOPI and conventional PID controllers. Moreover, the TAMF system is individually integrated with the energy storage devices (ESDs) of redox flow batteries (RFBs) and superconducting magnetic energy storage devices (SMES) as additional controllers at territorial level. Simulation result revealed that a considerable improvement in TAMF performance is reported and the dominance of RFBs over the SMES is noticed in terms of enhancement in the dynamical behaviour. At last, sensitivity analysis is conducted to validate the robustness of the suggested control technique as well as the implemented additional control mechanism.

Keywords: FOPID controller, grey wolf optimization, 10%sSLD, SMES and RFBs.

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I. INTRODUCTION

The most challenging task that have been facing by the electrical operators of the IPS is maintain the system operation pertaining to the continuous variations in load demands. The maintenance of the IPS involves the regulation of control area frequencies. Moreover, the IPS is segregated in to numerous control areas and each one is linked with the other through the tie-line. These lines facilitate to transfer the power from surplus to deficit generation areas. The variations in the control area frequency occur with the imbalance in generation of power and available load demand.

As the demand changes continuously, the amount of generation must have to alter in order to meet the demand. Thus, an automatic control approach is necessitated for altering the real power generation to meet the varying load continuously. This control action is coined the name as load frequency control (LFC) [1].

The LFC is having the significant impact on the stability of electrical power system, which employs two control loops. One that regulates the governor to alter the power generation is called as primary control and the other is secondary control action that adjusts the turbines set point valve. The achievement of robust frequency control is only possible through the secondary controller. A detailed review on literature revealed that, a bulk quantity of literature is available in the recent years on LFC that are relating to the development of secondary controllers.

However, the developed regulator’s efficacies are tested and validated by the researchers on numerous IPS models. Authors in [2], briefed the power system models investigated by the researchers from the past two decades. After going through the [2], it is disclosed that a significant studies are performed on IPS networks like one area thermal, one area thermal-hydro, dual area thermal, dual area thermal-hydro, dual area thermal-hydro-gas and the above units with the penetration of renewables such as doubly fed induction generators, and solar photovoltaic systems are rigorously adopted. Moreover, the research work on the aforementioned models is performed with the conventional PI and PID controllers [3]. Further, the modified conventional regulators [4] like PID with filter (N), proportional with double integral (PI2), PID with double derivative (PIDD), modified PID, cascade PI-PD, and one minus PI (1-PI) etc. are also considerably adopted. However, the effective operation of these regulators requires the optimization techniques to locate the mere optimal parameters.

Optimization techniques like backtracking search algorithm [5], harmony search optimization [6], skill optimization method, falcon optimizer, levy flight optimization, krill herd optimizer, symbiotic organisms search algorithm [7], atom search algorithm, culinary chef algorithm, grasshopper optimization [8], Egyptian vulture algorithm, moth flame algorithm, crow search algorithm, cat search algorithm, cuckoo search algorithm, spider optimization, spotted hyena algorithm, elephant herd algorithm [9], bee hives algorithm, chaotic whale optimization, quasi-oppositional grey wolf algorithm, marine predators algorithm [10],firefly algorithm, simulated annealing, path finder optimizer, lion optimization algorithm, bumble bees algorithm, donkey-smuggler algorithm, artificial bee colony algorithm, ant colony optimization, and multi-verse optimizer [11] etc. are implemented. However, the traditional are being only suitable for the linearized systems and practically no system is having the linear characteristics. Thus, the usage and the design of soft computing technique based conventional controllers are no longer suitable as LFC regulators.

Further, the study of fuzzy logic control (FLC) [12], degree-of-freedom (DOF) and FO controllers [13] to the LFC is also carried extensively in the literature. But, the complexity in the design ofLFC and DOF aided controllers made the researchers to focus on the FO controllers in the recent years. Thus, FOPID is enacted as LFC controller in this work for the dual area system with conventional and renewable energy penetration.

Though, plenty of new optimization algorithms are reported in the LFC study, this paper carried the FOPID tuning with the DE algorithm. The DE algorithm is having the benefit of displaying the effective global solution and quick convergence. Furthermore, the investigative model is integrated with the ESDs of RFBs and SMES to evaluate the performance efficacy. Integrating the ESDs with the IPS networks facilitate the additional control approach to make the system more stable during large load disturbances. Considering the above, the contributions of this work are

- Designed the FOPID controller based on DE algorithm.
- The dynamical behaviour of TAMF is assessed for 10%SLD.
- FOPID efficacy is validated with PID and FOPI.
- Performance efficacy of SMES and RFBs in the context of IPS stability is investigated.
- TAMF is prone to variations SLD’s to validate the robustness of suggested control approach.

1. **Power System Model:** The TAMF system consists of traditional units in area-1 and the renewable units in area-1. The traditional plants such as gas, hydro and thermal units are employed in area-1 and the units like solar photo voltaic, wind energy conversion unit and diesel plants are considered in area-2. The capacity in generation of the TAMF is 3:2 with respect to the area 1 and 2. The transfer function model of TAMF is shown in Fig.1 and is developed in MATLAB/SIMULINK (R2016a) and the appropriate parameters are considered from [14].

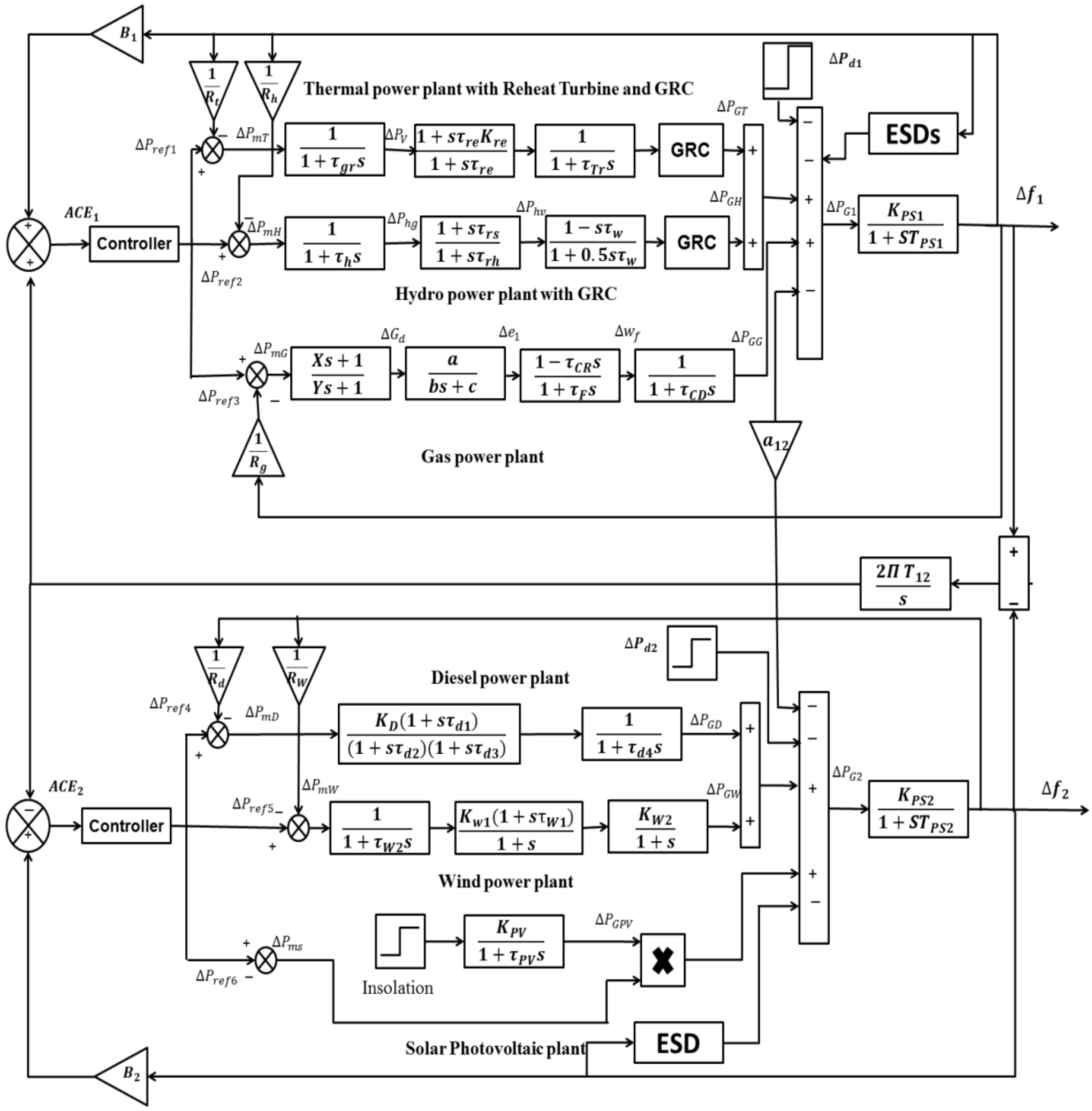


Figure 1: Model of TAMF under Investigation.

2. **FOPID Controller:** The FOPID is rigorously implemented in the control theory to regulate the system behaviour. This has been evolved from the concept of fractional calculus which employs additional parameters that dominates the performance of the classical controllers. The structure of FOPID is shown in Fig.2 and the parameters K_P, K_I, K_D, λ and μindicates the proportional, integral, derivative and FO gains. However, the FOPID performance depends on the optimal settings of the aforementioned gains and hence this work adopts the DE algorithm. The optimization process is under gone in this paper with respect to the Equation (1). The Equation (1) represents the integral square error which comprises of the deviations in area-1 (Δf_1) and area-2 (Δf_2) frequency as well as the tie-line power (ΔP_{tie12}).

$$J_{ISE} = \int_{0}^{T_{Sim}} (\Delta f_1^2 + \Delta P_{tie12}^2 + \Delta f_2^2)\, dt \qquad (1)$$

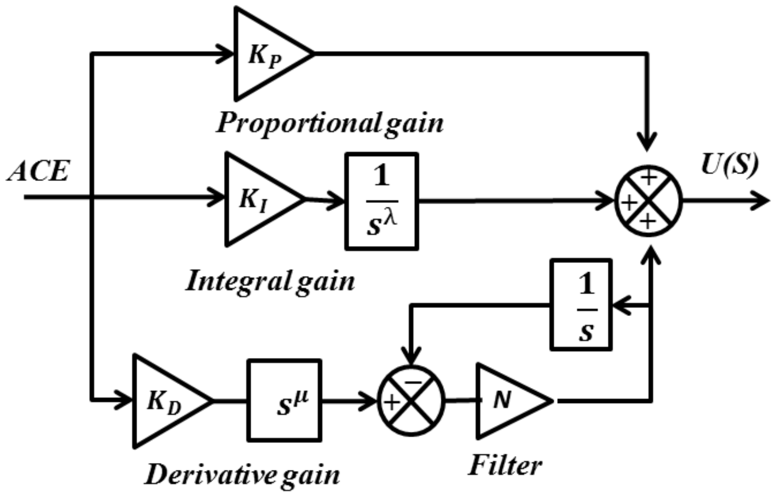


Figure 2: Structure of FOPID Controller.

3. Energy Storage Devices (SMES-RFBs)

- **SMES Device:** The SMES devices take the advantage of the super conducting coil for energy storage purpose. The SMES is the technology in storing and releasing the electrical energy in magnetic form using the DC coil. The DC coil is placed in a container maintained at cryogenic temperature to impart the nature of loss less to it. SMES are having greater efficacy, rapid charge/discharge and moreover, they have the disadvantage of limited energy capacity and the other technical challenges. The modelling of SMES is given in Equation (2).

$$G_{SMES} = \frac{K_{SMES}}{1 + sT_{SMES}} \qquad (2)$$

- **RFBs:** The RFBs are the electrochemical ESDs which are usually applicable for load levelling, grid integration, and renewable energy penetration. The two tanks in the RFBs comprises of independent electrolytic solution and based on the oxidation and reduction of this solution, the charging and discharging process takes place. The detailed operation of the RFBs is available in the literature [15] and its modelling is given in Equation (3).

$$G_{RFBs} = \frac{K_{RFBs}}{1 + sT_{RFBs}} \qquad (3)$$

4. Differential Evolution Algorithm: DE is a population based optimization algorithm with stochastic nature and was proposed by (R.Storn and K.price) [16] in 1997. DE involves model of simple mathematical equations representing large and complex procedure of natural evolution. Implementation of DE is easier as it needs only less parameters of initialization. It possesses the parameter controls of mutation, crossover and selection operators. The performance of DE was demonstrated by (Vesterstorn and Thomson, 2004) [17] up on implemented on 34- standard benchmark problems and is compared with PSO algorithm. Investigation results, shows that DE is superior to PSO except for 2- noisy functions.

- **Steps Involved in DE [17]:** DE utilizes a pair of population which consisting of real valued parameters Dimensional vectors. Current population can be symbolically represented as framed with floating point individuals is population size which remains constant until completion of optimization process in Equation (4-5).

$$P^{(G)} = \left[X_i^{(G)}, \ldots\ldots\ldots\ldots\ldots, X^{(G)}{}_{N_p} \right] \quad (4)$$

$$X_i^{(G)} = \left[X_{1,i}^{(G)}, \ldots\ldots\ldots, X_{D,i}^{(G)} \right]^T, \quad i = 1, \ldots\ldots, N_p \quad (5)$$

- **Initialization:** Before initializing the initial parameters, upper and lower boundaries of each parameter must be specified. After specifying the parameter boundaries, a random number is generated and distributed uniformly win in the range of [0-1] in Equation (6).

$$X^{(0)}{}_{j,i} = X_j^{\min} + rand_j(0,1).(X_j^{\max} - X_j^{\min}) \quad (6)$$

Where $i = 1, \ldots\ldots, N_p$ and $j = 1, \ldots\ldots\ldots, D$; $X_j^{\max}$ and $X_j^{\min}$ are upper and lower boundaries of the jth control parameter.

- **Mutation:** Generation of off spring is possible only through mutation and cross over operators. Different strategies are available for implementing mutation and cross over operations; the basic strategy is implemented here. The responsibility of introducing new particles into population is taken up by the operator mutant. In this regard, the operator mutation creates new mutant vector by concerning a vector which is randomly selected along with the difference of other vectors which are randomly selected. All the generated vectors must be different from each other.

$$X_i^{'(G)} = X_a^{(G)} + F(X_b^{(G)} - X_c^{(G)}), \quad i = 1, \ldots\ldots, N_p \quad (7)$$

In order to regulate the perturbation and to enhance the convergence, the scaling factor is used for the difference vectors in the range of [0-1]. This scaling constant or mutant constant is represented as. The mutant vector construction is represented in two-dimensional space is illustrated in Fig.3.

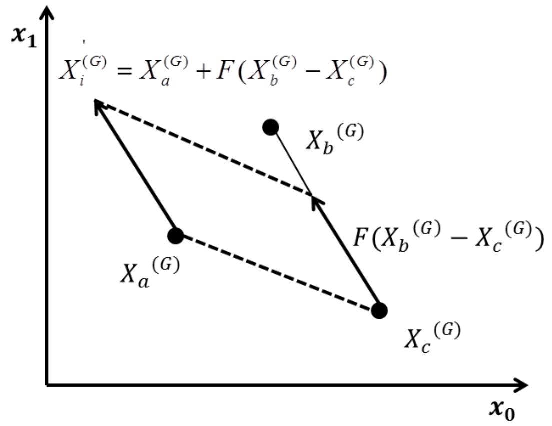


Figure 3: Mutation in Two-Dimensional Space

- **Crossover:** The trail vectors will be generated by the operator cross over, which are used in selection process. The combination of target vector or parent vector and mutant vector is the trail vector. The common types of crossover operations implemented in DE are binomial and exponential. The binomial operation is performed here and is explained as, in the range of [0, 1] a random number will be generated and is compared with crossover constant (Cr). If the random number value is less than or equal to crossover constant, the parameters will come from mutant vector, otherwise it will come from target vector as given in Equation (8).

$$X_{j,i}^{''(G)} = \left\langle \begin{array}{ll} X_{j,i}^{'(G)} & if \quad rand_j(0,1) \leq C_r \; or \; j = j_{rand} \\ X_{j,i}^{(G)} & Otherwise \end{array} \right\rangle \tag{8}$$

The operator crossover tries to prevent the local convergence by maintaining the population diversity. The constant of crossover must be in the range of [0-1], if Cr=1 then the trail vector is completely composed of mutant vector. If the Cr is more close to zero then the trail vector is more likely to be from target vector or parent vector. Fig.4. illustrates the possibility of getting the trail vector from mutant and target vector.

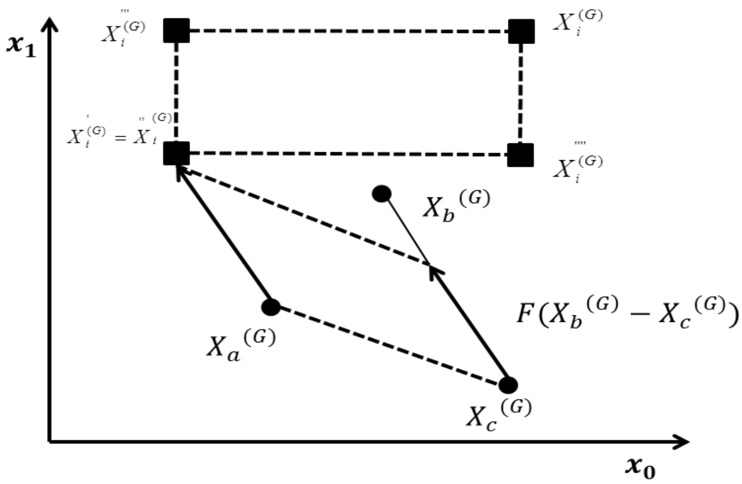


Figure 4: Crossover in DE.

- **Selection:** The final step in DE strategy is the selection operation. In this stage, the operator selects the vectors that are going to be composed in next generation. The selection operator compares the fitness value of trail vector and its corresponding target vector, and selects the vector which performs better according to the given Equation (9).

$$X_i^{(G+1)} = \begin{cases} X_i^{''G} & if \quad f(X_i^{''G}) \le f(X_i^G),\ i = 1,......,N_p \\ X_i^G & Otherwise \end{cases} \qquad (9)$$

Once the population is newly installed in the next generation, the process of mutation, crossover and selection procedure will be repeated for several generations which allow the individuals to improve their fitness value by optimal exploration in search space. The procedural flow of DE algorithm is illustrated in Fig.5.

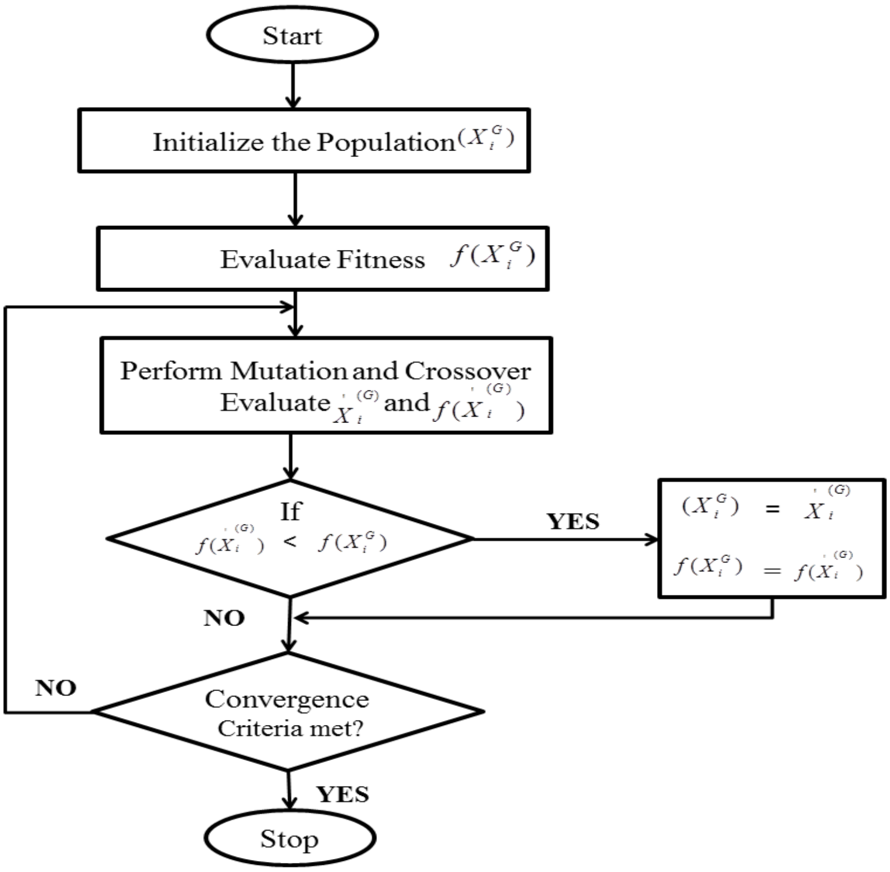
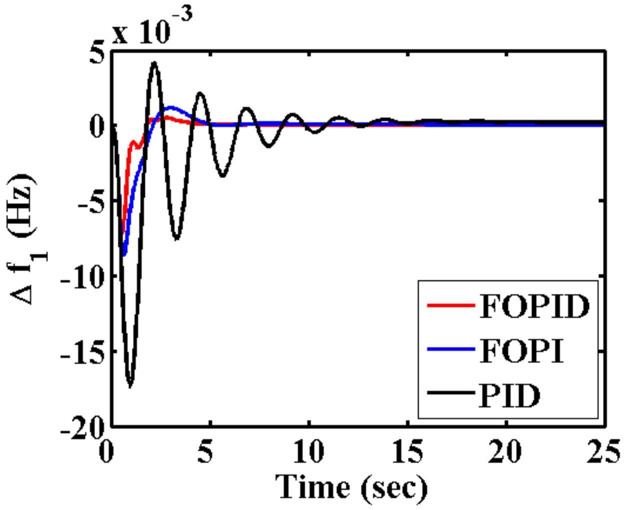


Figure 5: Flowchart of DE algorithm

5. Simulation results

- **Case-1: Analysis of TAMF with Different Controllers**

The TAMF system dynamic behaviour is analysed in this subsection, subjected to the condition of area-1 with 10%SLD. The controllers like FOPID, FOPI and conventional PID are individually placed in the two areas of TAMF system and for the comparative assessment all these controllers are optimized with the DE algorithm. The corresponding responses are shown in Fig.6 and assessed numerically in terms of settling time given in Table 1. Noticing the Table 1 and observing the Fig.6, it is preliminarily concluded that FOPID is more dominating over the others in providing the better dynamical regulation. Further, the ISE function is effectively treated by the FOPID and is increased by 58.91% with FOPI and 73.62% with traditional PID controller. The gains of FOPID, FOPI and PID using DE that are employed with the TAMF system are given in Table 2.



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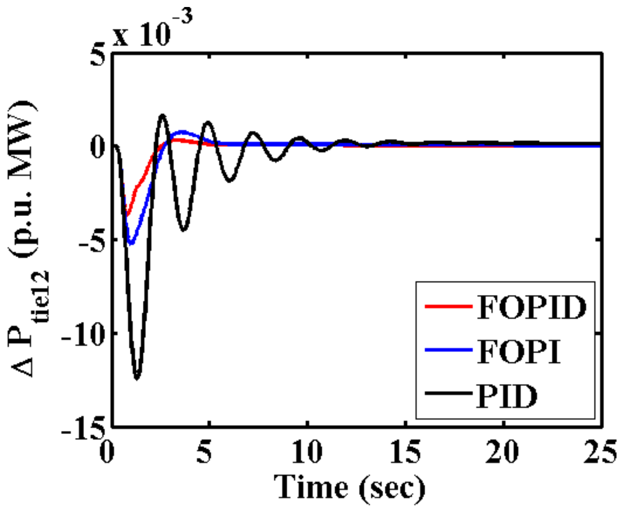

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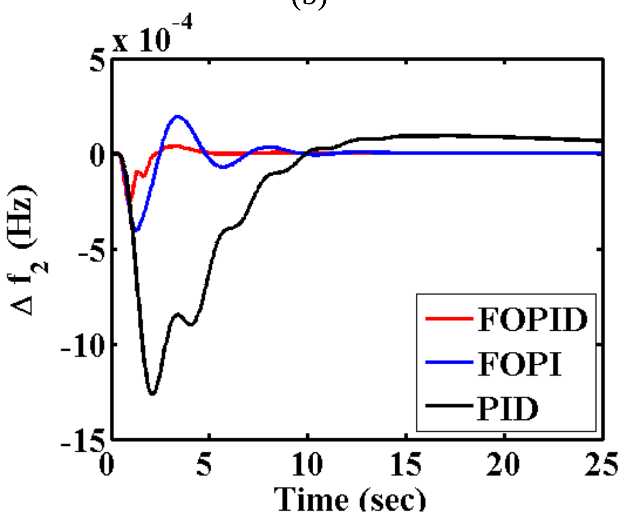

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Figure 6: a.Δf_1 b.ΔP_{tie12} c.Δf_2.

Table 1: Responses Settling Time

Settling time (Seconds)	PID	FOPI	FOPID	SMES	RFBs
Δf_1	16.39	9.33	6.86	5.04	4.28
ΔP_{tie12}	16.89	8.14	6.06	5.36	4.89
Δf_2	18.18	11.45	8.85	6.26	5.31
ISE*10^{-3}	88.53	56.83	23.35	-	-

Table 2: Controller Gains

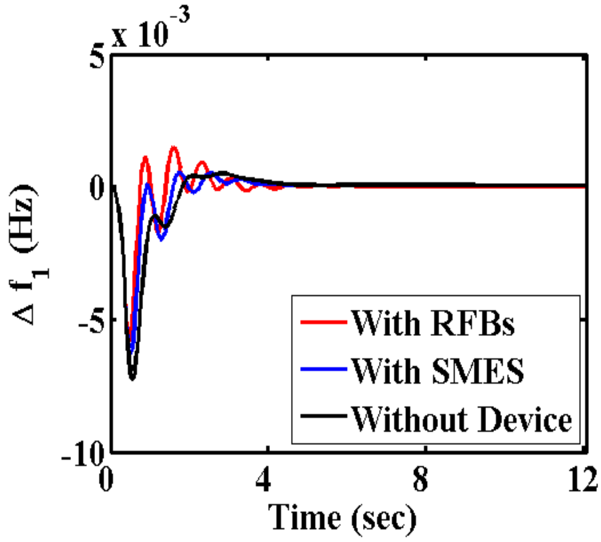
Parameters	Area-1			Area-2		
	PID	FOPI	FOPID	PID	FOPI	FOPID
K_P	2.577	1.144	1.799	1.716	1.595	1.778
K_I	1.057	0.834	1.325	0.939	0.635	1.125
λ	-	0.590	0.025	-	0.331	0.326
K_D	1.225	-	1.187	0.989	-	1.983
μ	-	-	0.036	-	-	0.127

- **Case-2: Analysis of TAMF with ESDs**

Further, under the DE based FOPID regulation the TAMF is individually integrated with ESDs like RFBs and SMES in area 1 and 2. For this sub section, the TAMF responses are shown in Fig.7 and up on noticing them it is clear that a considerable enhancement in TAMF dynamic behaviour is reported.

Moreover, it is found that with the usage of the RFBs in the IPS model of TAMF system a significant reduction in peak undershoot and enrichment in the settling time of the responses is observed. The TAMF system responses settling time with the consideration of RFBs and SMES are depicted in the bar chart of Fig.8.

This happens due to the rapid response nature of the RFBs over the SMES and further the RFBs have the quick charging/discharging capability. With this, the RFBs can deliver the energy in less time to the IPS whenever required and restores the energy during less peak hours. Thus, this paper suggests integrating the RFBs for obtaining additional improvement in the electric IPS network performance.



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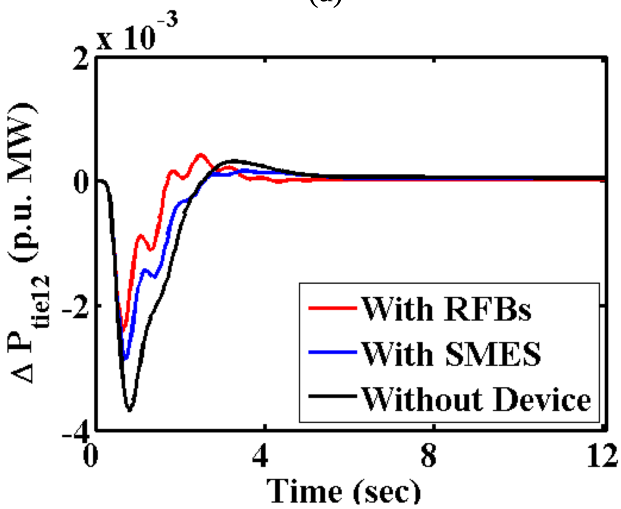

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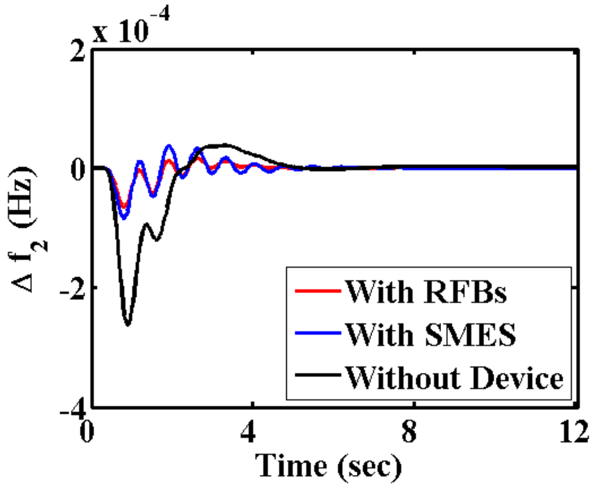

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Figure 7: a.Δf_1 b.ΔP_{tie12} c.Δf_2.

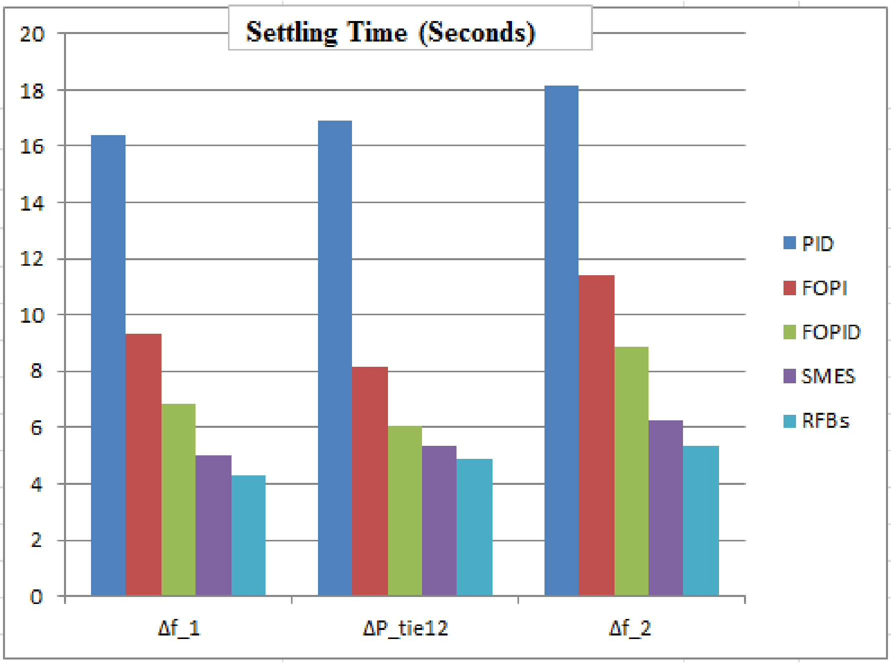

Figure 8: Bar Chart Represents the Responses Settling Time (in Seconds) under Various Cases.

- **Case-3: Sensitivity Analysis**

From the above two subsections, the dominance of the FOPID based on DE algorithm is demonstrated and further the performance evaluation of RFBs and SMES are carried and the efficacy of the RFBs is showcased. Thus, this work is implementing the FOPID and RFBs as the secondary and territorial controllers respectively. To check the robustness of the implemented control strategies, it is required to conduct the sensitivity test. Here, in this paper the sensitivity test in terms of load change is performed on the TAMF system under the suggested control methods.

The area-1 of TAMF system is laid with 5%LD, 10%SLD and 15%SLD one after the other and the respective responses are shown in Fig.9. Noticing the responses depicted in the Fig.9 it is clear that the changes in the system dynamic behaviour under different load disturbances are hardly noticed. This means the adopted control methods at the secondary and territorial level are robust and it is not necessary to optimize the control parameters for load variations on the TAMF system.

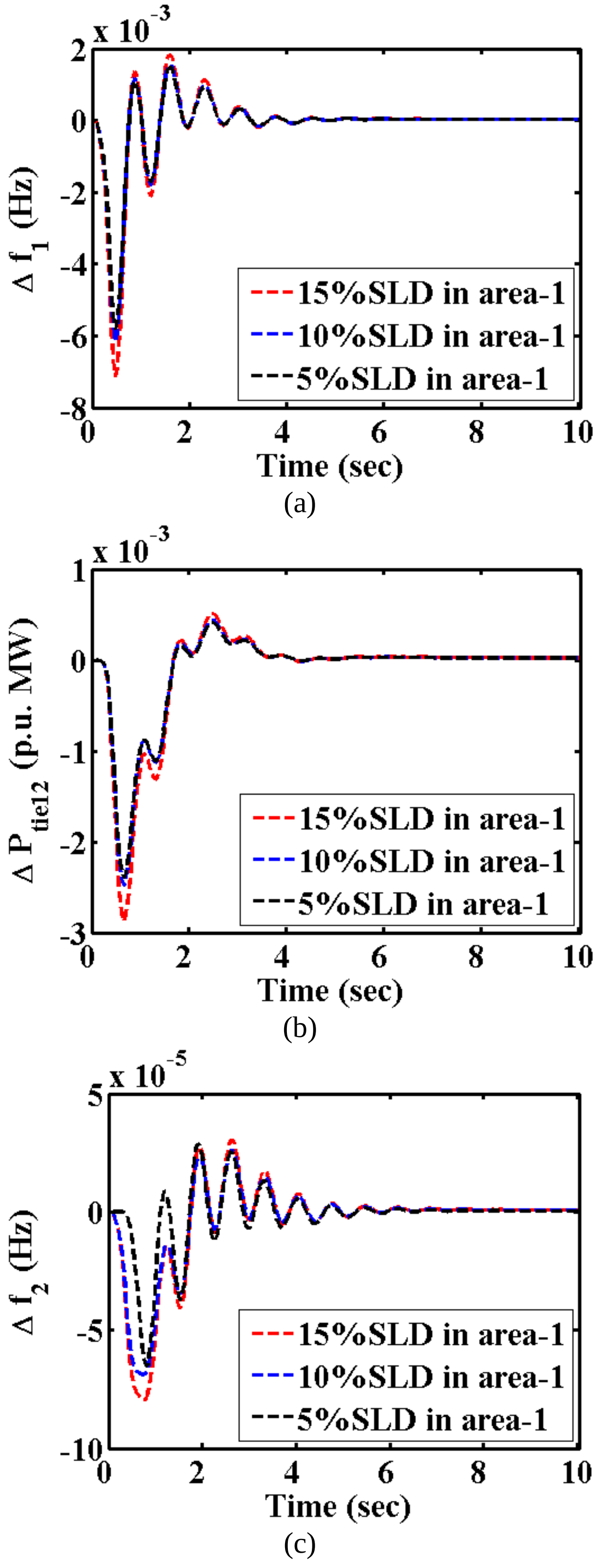

Figure 9: a.Δf_1 b.ΔP_{tie12} c.Δf_2.

II. CONCLUSION

The DE based FOPID is suggested successfully for the TAMF model of IPS to regulate its dynamic behaviour during load fluctuations. The investigation revealed that, the designed controller successfully handled the TAMF dynamic behaviour and its efficacy is validated with the FOPI and PID performances. Investigation is initiated by laying the area-1 of TAMF with 10%SLD. Later, under the regulation of FOPID based on DE, an additional control approach of integrating the ESDs like SMES and RFBs are individually integrated with TAMF system in both the areas. A considerable enhancement in TAMF performance is noticed with the integration of SMES and RFBs and moreover, the RFB is more dominating in dealing the system fluctuations and guiding the deviations to the steady state condition. Thus, this work recommends integrating the RFBs with the IPS models as an effective additional controller at territorial level. Finally, the robustness of adopted control strategy is validated with the sensitivity analysis by targeting the area-1 of TAMF system with various load disturbances.

REFERENCES

[1] C. N. S. Kalyan, and G. S. Rao, "Frequency and voltage stabilisation in combined load frequency control and automatic voltage regulation of multiarea system with hybrid generation utilities by AC/DC links", International Journal of Sustainable Energy, Vol.39, No.10, pp. 1009-1029, 2020.
[2] M. Ranjan, and R. Shankar, "A literature survey on load frequency control considering renewable energy integration in power system: Recent Trends and future prospects", Journal of Energy Storage, Vol.45, pp.103717, 2022.
[3] Y. V. Hote, and S. Jain, "PID controller design for load frequency control: Past, Present and future challenges", IFAC-PapersOnline, Vol.51, No.4, pp.604-609, 2018.
[4] J. Sharma, Y. V. Hote, and R. Prasad, "PID controller design for interval load frequency control system with communication time delay", Control Engineering Practice, Vol.89, pp.154-168, 2019.
[5] D. Guha, P. K. Roy, and S. Banerjee, "Application of backtracking search algorithm in load frequency control of multi-area interconnected power system", Ain Shams Engineering Journal, Vol.9, No.2, pp.257-276, 2018.
[6] M. Shivaie, M. G. Kazemi, and M. T. Ameli, "A modified harmony search algorithm for solving load-frequency control of non-linear interconnected hydrothermal power systems", Sustainable Energy Technologies, Vol.10, pp.53-62, 2015.
[7] S. P. Singh, T. Prakash, and V. P. Singh, "Coordinated tuning of controller-parameters using symbiotic organisms search algorithm for frequency regulation of multi-area wind integrated power system", Engineering Science and Technology, an International Journal, Vol.23, No.1, pp.240-252, 2020.
[8] S. M. Nosratabadi, M. Bornapour, and M. A. Gharaei, "Grasshopper optimization algorithm for optimal load frequency control considering predictive functional modified PID controller in restructured multi-resource multi-area power system with redox flow battery units", Control Engineering Practice, Vol.89, pp.204-227, 2019.
[9] S. Dewangan, T. Prakash, and V. P. Singh, "Design and performance analysis of elephant herding optimization based controller for load frequency control in thermal interconnected power system", Optimal Control Applications and Methods, Vol.42, No.1, pp.144-159, 2021.
[10] M. A. Sobhy, A. Y. Abdelaziz, H. M. Hasanien, and M. Ezzat, "Marine predators algorithm for load frequency control of modern interconnected power systems including renewable energy sources and energy storage units", Ain Shams Engineering Journal, Vol.12, No.4, pp.3843-3857, 2021.
[11] P. K. Sahoo, S. Mohapatra, D. K. Gupta, and S. Panda, "Multi verse optimized fractional order PDPI controller for load frequency control", IETE Journal of Research, Vol.68, No.5, pp.3302-3315, 2022.
[12] S. Jasmine, M. Mary, K. Tenmalar, "Fuzzy logic based load frequency control of power system", Materialstoday: Proceedings, Vol.45, pp.8170-8175, 2021.
[13] N. K. Gupta, M. K. Kar, and A. K. Singh, "Design of a 2DOFPID controller using an improved sine-cosine algorithm for load frequency control of a three-area system with non-linearity's", Protection and Control of Modern Power Systems, 7(33), 2022.

[14] C. N. S. Kalyan, and G. S. Rao, "Combined frequency and voltage stabilisation of multi-area multisource system by DE-AEFA optimised PID controller with coordinated performance of IPFC and RFBs", International Journal of Ambient Energy, Vol.43, No.1, pp.3815-3831, 2022.
[15] S. Oshnoei, A. Oshnoei, A. Mosallanejad, and F. Haghjoo, "Novel load frequency control scheme for an interconnected two-area power system including wind turbine generation and redox flow battery", Electrical power & Energy Systems, Vol.130, 107033, 2021.
[16] R. Storn, and K. Price, "Differential evolution- A simple and efficient heuristic for global optimization over continuous spaces", Journal of Global Optimization, Vol.11, pp.341-359, 1997.
[17] J.Vesterstorn, R.Thomson, "A comparative study of differential evolution, particle swarm optimization and evolutionary algorithms on numerical benchmark problems", in Proceedings of 2004 IEEE Congress on Evolutionary Computation, pp.1980-1987, 2004.