Fractional-Order Load Frequency Control of a Two-Area Interconnected Power System with Uncertain Actuator Nonlinearities

Akhilesh Kumar Mishra, Puneet Mishra, and H. D. Mathur

Abstract Nonlinearities in power system cause severe degradation in quality of power being generated. A robust controller is often needed to compensate for uncertainties caused by nonlinear components present in the control loop. In this paper, a robust fractional order controller is designed and investigated for tackling with inherent nonlinearities in an interconnected two-area non-reheated thermal power system. The presence of these inherent nonlinearities is due to generation rate constraint (GRC) and governor deadband (GDB), which can cause delayed disturbance rejection and/or sustained oscillations in power system variables. On considering both nonlinearities simultaneously into account, the complexity in controlling the power system increases, and conventionally optimized controllers fail to produce satisfactory dynamic performance. To address these issues, a robust fractional-order-proportional-integral-derivative (FOPID) controller has been designed utilizing a lately introduced Salp Swarm Algorithm (SSA). Extensive simulation studies have been performed and comparative studies have been drawn with controllers designed with available techniques in literature. Based on investigations carried out in the article, it is found that SSA optimized FOPID shows remarkable enhancement investigated in load frequency control performance of investigated plant in presence of significant parametric variations in comparison with particle swarm optimization optimized controllers.

Keywords Automatic generation control (AGC) · Actuator nonlinearity · Fractional-order calculus · Salp swarm algorithm (SSA)

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1 Introduction

The frequency regulation is our prime concern in interconnected electrical power system (IEPS) to have a quality power. As the IEPS consists of diverse control areas, they are coupled via an electrical linkage commonly referred to as tie lines with one another. If the load demanded by the consumer from any control area gets altered, then its leads to deprivation of the dynamic performance of the IEPS due to variation in frequencies as well as scheduled electrical energy transfer via tie-lines from their predefined values. These deviations can be mitigated partially by the speed regulation mechanism present in IEPS by regulating the generator output by varying the valve position. The speed governing mechanism is also referred to as the primary control, but to augment the dynamic performance of IEPS, supplementary controller must add with primary controller, which can provide persistent frequency and tie-line power exchange (TLPE). Automatic generation control (AGC) or load frequency controller (LFC) is typically utilized to deal with such scenarios and their main objective makes the deviations of different control areas frequency as well tie-line power to zero [1].

In load frequency controller (LFC), the area control error (ACE) acts as an input to LFC, where ACE is the combination of deviation in TLPE and frequency deviation multiplied with frequency bias constant. In order to implement LFC in a realistic IEPS, the various inherent nonlinearities found must be incorporated. The utmost noteworthy nonlinearities present in load frequency control loops are governor deadband (GDB) and generation rate constraint (GRC). The governor deadband (GDB), which mainly comes into existence due to either friction or physical geometry of rack and pinion arrangement in speed governing mechanism. The purpose of the speed governing mechanism is to rotate the camshaft that operates the control valves to manipulate steam input to the turbine. The GDB has disrupting nature on the transient as well steady-state response, as it can produce continuous oscillation in the response of frequency and TLPE [2]. Whenever an excessive steam is demanded from the boiler system to increase the generated power instantly, then due to adiabatic process occurring in boiler steam get condensed and causes reduction in life span of the turbine blades of thermal power plant. Hence for the acceptable operation of boiler system, with the help limiters, the maximum speed of opening and closing of the valve is constrained. The GRC curbs the ability of instant disturbance rejection in IEPS [3]. In IEPS, these nonlinearities can severely disrupt the performance of LFC. Many researches have proposed the LFC structure for IEPS with considering various aspects of modern IEPS and [4, 5] have presented an exhaustive literature review [6].

In the contrast of literature discussed and Table 1, we can infer that usually the nonlinearities associated with the interconnected power system have been either ignored or considered individually moreover its variation effect never considered simultaneously. Nevertheless, this is of prime importance to consider the simultaneous presence of GRC and GDB for the accurate implementation of LFC. Because their simultaneous presence has an undesirable effect on the dynamic performance of the system and can cause longer settling time with load frequency variation and

Table 1 A brief summary of LFC for IEPS with system nonlinearities

References	System under investigation	Non-linearities	Controller structure	Optimization algorithm	Performance index
[9]	2-area	GRC	PID	GA, BFOA	ITAE
[7]	2-area	None	FOPID	PSO	ITAE
[10]	3-area	GRC, GDB	Fuzzy FOPID	COA	ITSE
[11]	2, 4-area	None	FOPID	BBBC	ISE
[12]	4-area	None	Fuzzy FOPID	BBO	ITAE, ITSE
[13]	2-area	GDB, GRC	FOPID	IPSO	ITSE
[14]	3-area	GDB, GRC	PID	FA	ITAE
[15]	5-area	GRC	IDD	BFOA	ITAE
[16]	2-area	GRC, GDB	IMC-FOPID	None	ITAE
[17]	2-area	GDB	FOPID	GBMO	ITAE

large oscillations in tie-line power. Therefore, for load frequency control problem inherent nonlinearities associated with the power system needs further attention with variation in magnitude of GRC and GDB to achieve more refined control operation to have better power quality in terms of lesser frequency deviations and reduced tie-line power deviations. The integral order-based classical controller is not much efficient to provide satisfactory dynamic performance, under significant change in magnitude for step load perturbation [7]. To address the aforementioned issues, an effort has been made for investigation of two-area non-reheated thermal IEPS in this work. The simultaneous presence of GRC and GDB in the power system is addressed by using an optimal fractional order PID controller optimized by, i.e., Salp swarm algorithm (SSA) introduced by Mirjalili et al. in [8].

Further, the present work has been structured as follows; Sect. 2 deals with mathematical linearized model of system under investigation, i.e., a two-area IEPS system with GRC and GDB for LFC issues. In Sect. 3, brief introduction of fractional order controller, SSA as an optimization algorithm and selection criterion of objective function for LFC issue have been discussed. Section 4 focuses on simulation results and associated discussions. At last, concluding remarks are made in Sect. 5.

2 Dynamic Model of the Interconnected Power System

IEPS is a composite dynamical system with numerous generator and loads. Typically, IEPS investigated for LFC performance are subjected to very small load variations in contrast with their rated capacity. Therefore, a linearized model is usually utilized for the present investigation. A realistic IEPS with GRC and GDB nonlinearities incorporated simultaneously has been presented in Fig. 1. The extensively used two-area

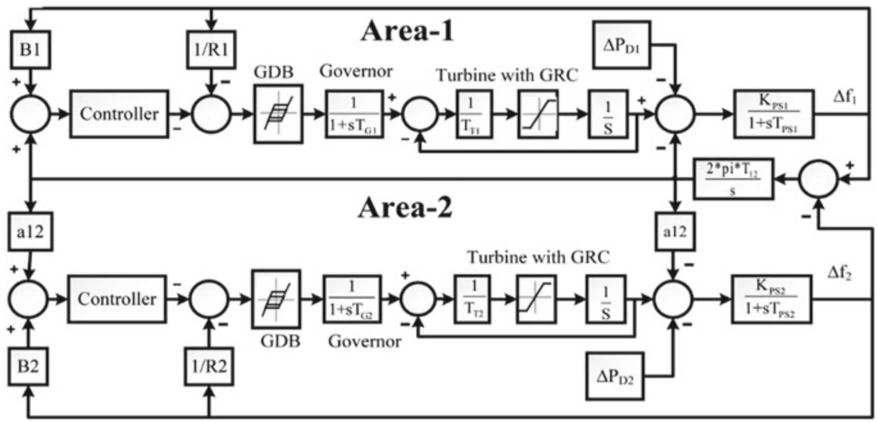

Fig. 1 Block diagram of the investigated IEPS, i.e., Non-reheated thermal-thermal two-area interconnected electric power system incorporating GDB and GRC

non-reheated IEPS for the investigation of the LFC performance under nominal operating condition adopted power from [9, 14]. The investigated IEPS for the presented work has been represented in Fig. 1. The system nominal parameters under investigation have been adopted from [9, 14] and presented in Appendix 1. Further in subsequent section, the control structure for the investigated LFC and its optimal controller parameters utilizing optimization algorithm has been presented to obtain the anticipated control objectives.

3 Load Frequency Controller Structure and Parameter Tuning

The fractional calculus offers the freedom to the operator for implementation of the non-integer or differential order operator, which can have a superior level of performance in terms of robustness when compared with integer order. In the literature, several approximation methods are proposed. Some simplified continuous-time domain approximations are 'Crone or Oustaloup approximation,' 'Carlson approximation,' 'Matsuda approximation,' etc. Present articles utilize the 'Oustaloup approximation' for approximating the fractional-order integrator and differentiator, because of its very decent fitting to fractional-order elements. This approximation technique performs the fractional-order integral and differential operators via a higher-order analog filter having an order of '$2N + 1$' within a specified frequency bound [ω_L, ω_H] [16]. The value of 'N' and frequency bound [ω_L, ω_H] for present work has been considered as 5 and [10^{-3}, 10^{3}] respectively, and well accepted in the LFC application. For the sake of brevity, the details of implementation of fractional-order operator have been omitted here and can be found in [16, 18]. The fractional-order

PID controller can represent ($PI^{\lambda}D^{\mu}$) as:

$$\mathrm{Gc(s)} = K_{\mathrm{P}} + K_{\mathrm{I}}S^{-\lambda} + K_{\mathrm{D}}S^{\mu} \tag{1}$$

To obtain the desired control objective, the controller parameters must be accustomed. In the last decade, evolutionary computing and swarm intelligence based methods have grown substantial consideration from researchers around the world. Soft computing techniques have been used extensively for tuning the LFC parameter to achieve superior dynamic system performances [19]. Various popular optimization algorithms used for finding the optimal controller parameters to solve the LFC problem effectively have been presented in Table 1. Out of these algorithms, SSA has appeared as a robust optimization algorithm with only one tunable factor, rapid convergence to optimal solutions with the tendency to avoid local optimum points.

Like other optimization algorithms, a *n*-dimensional search space is created to represent the positions of salps, where *n* is the number of decision variable for a given problem. A two-dimensional matrix denoted by '*x*' is used for storing the positions of salps. The food source '*S*' has been assigned as the swarm's target in the search space. Equation (2) is used for the updating for the swarm positions in the search space as follows:

$$x_i^1 = \left\{ \begin{array}{l} S_i + A_1((ul_i - ll_i)A_2 + lbl \text{ for } A_3 \geq 0.5 \\ S_i - A_1((ul_i - ll_i)A_2 + ll_i \text{ for } A_3 < 0.5 \end{array} \right\} \tag{2}$$

$$A_1 = 2\mathrm{e}^{-\{4l/\mathrm{Max\_\ iter}\}^{\ 2}} \tag{3}$$

where 'S_i' represents *i*th dimension the position of the food source, 'ul_i' designates the *i*th dimension of upper limit, 'll_i' designates the *i*th dimension of lower bound of, x_i^1 represents the *i*th dimension position of the first salp and the uniformly distributed random numbers in interval [0, 1] represents the A_2 and A_3. "*l*" is current iteration.

The follower's (k^{th}) positions in the search space (in i^{th} dimension) modified utilizing the newton law of motion and given by the following equation considering initial speed (v_0) to be zero.

$$x_i^k = \frac{1}{2}\alpha t^2 + v_0 t \tag{4}$$

The '*i*' will always be greater than or equals to two, further, $\alpha = \frac{v_{\mathrm{final}}}{v_0}$, $v = \frac{x - x_0}{t}$ and '*t*' the time taken for completing one iteration of optimization. Hence Eq. (4), can be restructured as

$$x_i^k = \frac{1}{2}\left[x_i^k + x_i^{k-1}\right] \tag{5}$$

Further, SSA algorithm outline [8] can be present as follows.

Set population of salp x_i (i=1, 2,..n), subjected to 'ul' and 'll'
***while** (end condition is not fulfilled)*
Fitness of individual salp is calculated and allocate it as 'F' as best that individual salp
Calculate and modify 'A_1' by Eq.3
    ***for** each individual salp (x_i)*
      ***if** (i==1)*
      By utilizing the Eq. 2 modify the leader salp position
        else
      Utilizing the Eq. 5 modify the follower salp position
        end
    On the basis of 'll' and 'ul' variables, modify the salps variables
      end
      Return S

3.1 Load Frequency Controller Design

It needs to mention here that various studies have been presented in the literature for LFC design, but very few of these have pertained attention to the existing actuator nonlinearities in the power system while focusing on the LFC design. In the current work, integral time absoluter error (ITAE) is used as an objective function for obtaining the PID/FOPID controller because the ITAE-optimized controllers have lesser settling time as well overshoot as compared with others. Equation (6) represents the expression for the considered objective function.

$$J = \text{Objective Function (ITAE)} = \int_0^{t_{sim}} (|\Delta f_1| + |\Delta f_2| + |\Delta P_{\text{tie12}}|) t \, dt \tag{6}$$

where, $|\Delta f_1|$, $|\Delta f_2|$,$|\Delta P_{\text{tie12}}|$ and 't_{sim}' are the absolute values of deviation of frequency in control area-1, 2, tie-line power deviation, and simulation time, respectively. Figure 2a and b shows the convergence of the objective function for the PID and FOPID controller achieved by PSO and SSA for the design of LFC for a two-area IEPS. It may be noted that the convergence of SSA is more rapid in comparison with PSO for integer as well as fractional order PID controller. It also provided a better (lesser) value of the considered objective function (ITAE), i.e., a mere value of 3.928 and 3.203 in with SSA for PID and FOPID controller, respectively. Clearly, with reference to Fig. 3, the SSA-tuned FOPID (SSAFOPID) controller was a true winner under nominal conditions in comparison with PSO tuned FOPID. The optimized controller parameters of all the controllers under consideration are listed in Table 2.

The parameters of each controller employed in individual areas are considered as same to due identical structure of both control areas. Further, the frequency and tie-line power deviation suppression in both the areas for optimized controllers, under

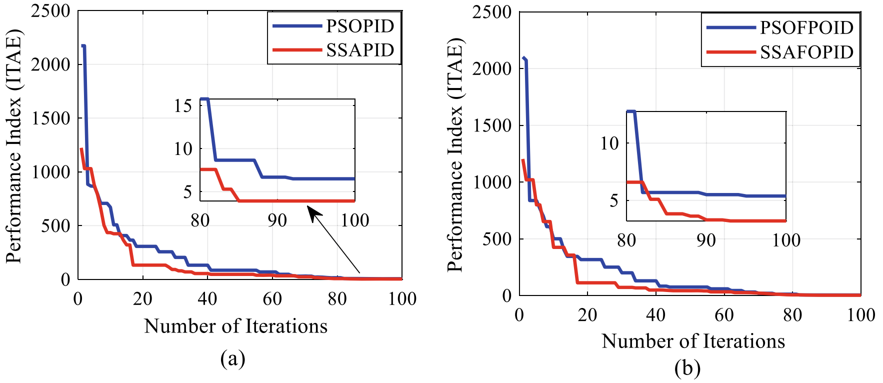

Fig. 2 Comparative convergence curves for PSO and SSA (**a**) PID controller (**b**) FOPID controller

Fig. 3 Values of '*J*' for different controllers under nominal system parameters for realistic two-area interconnected power system

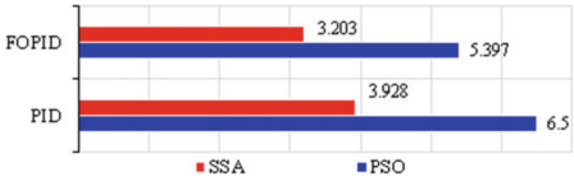

Table 2 Optimized controller parameters for realistic two-area interconnected power system with GRC and GDB

Parameter	PID		FOPID	
	PSO	SSA	PSO	SSA
Kp	13.085	8.9178	4.580	12.161
Ki	0.169	0.0374	7.0372	0.069
Kd	13.29	14.657	12.032	14.75
λ	–	–	0.024	0.951
μ	–	–	1.144	1.1912

nominal conditions, are shown in Fig. 4. Figure 4 shows the variation of frequency in control area-1, 2 and tie-line power exchange with PID controller structure. It may be noted from the above results that the SSA-tuned PID controller (SSAPID) provides minimal deviation in frequency deviations in comparison with PSO-tuned PID controller (PSOPID). However, this performance can be further enhanced with the use of fractional-order PID controllers, which provide more flexibility in the controller design. As can be seen from Fig. 5, the deviation of frequency in area-1, area-2 and tie-line power exchange, shows lesser deviations with FOPID controller as compared PID.

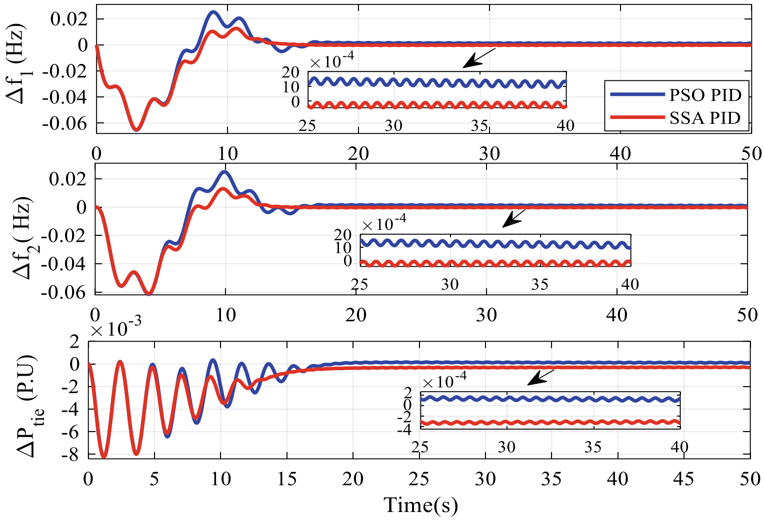

Fig. 4 Variation in Δf_1, Δf_2 and ΔP_{tie}, under step load perturbation (SLP of 0.01 pu in area1 with nominal parameters for PID controllers

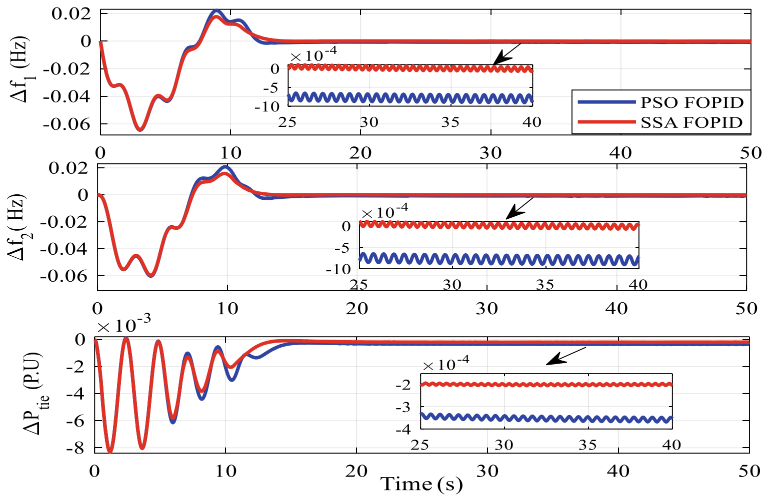

Fig. 5 Variation in Δf_1, Δf_2 and ΔP_{tie}, under step load perturbation (SLP) of 0.01 pu in area1 with nominal parameters for FOPID controllers

4 Simulation Result and Discussion

This work presents a study on the use of optimally tuned fractional order controllers for the efficient design of LFC for system under investigation. As mentioned earlier,

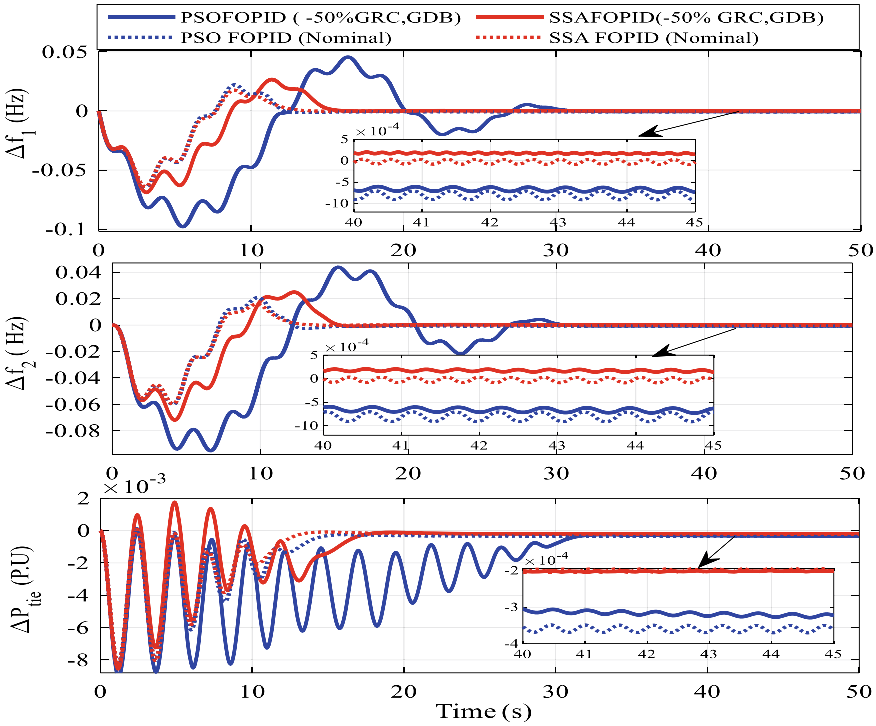

Fig. 6 The 'Δf' suppression in area-1, 2 and 'ΔP_{tie}' for −50% deviations in GRC and GDB from their nominal values

the presence of nonlinearities in the system can significantly affect the control performance.

4.1 LFC Performance Analysis with Uncertainty in GRC and GDB

This work is quite probable that the measurements of different nonlinear components characteristics be uncertain, and their actual values may be different from the one which is estimated by some means. This variation in parameter values can further bring a significant degradation of control performance or in some cases even instability. The variation of GRC and GDB has been recognized in the steps of 10% from their nominal values up to a maximum deviation of 50%. Negative deviations are considered in this study since GRC is a crucial parameter that specifies the control performance and a decrement in GRC will seriously affect the instant disturbance rejection capabilities of the system.

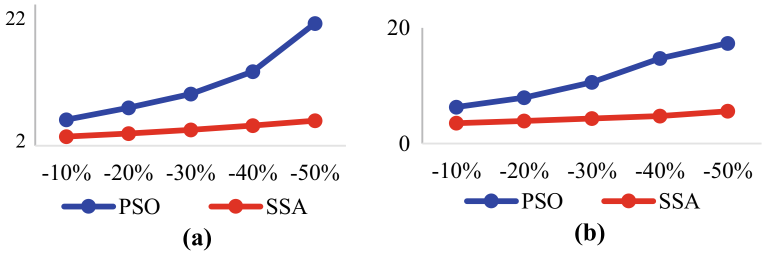

Fig. 7 Variation in 'J' values for parametric uncertainty in (**a**) GRC and GDB, (**b**) GRC, GDB and time constant values with different FOPID controllers

Figure 6 shows the variation in Δf_1, Δf_2 and tie-line power exchange for a limiting case where a deviation of -50% is considered in GRC as well as GDB. This study proves the supremacy of the SSAFOPID controller for the robustness requirement, where a significant deviation in nonlinear component parameters can appear in the control loop. Further, a pictorial depiction of variation in cost function (J) is also presented in Fig. 7 for better interpretation of the control performance improvement achieved by SSAFOPID in comparison with PSOFOPID controller.

5 Conclusion

In the present work, a robust fractional order controller optimized via of PSO and salp swarm algorithm (SSA) has been explored for an enhanced load frequency control in nonlinear interconnected electrical power system (IEPS). The investigated IEPS is nonlinear in the sense, as we incorporated the nonlinear generation rate constraint (GRC) and governor deadband (GDB) in control loop. Comparative analyses based on simulation studies under nominal as well as against magnitude variation of nonlinearities, i.e. GRG and GDB show that SSA optimized FOPID controller is able to control the mitigate the any limit cycles originated due to governor deadband as well as reduces the settling time as well in comparison with PSO FOPID controller.

Appendix 1

The system nominal parameters under investigation are represented as follows [9, 14, 18] $P_{R1} = P_{R2} = 2000$ MW (rating), $PL_1 = PL_2 = 1000$ MW (nominal loading), $f = 60$, $T_{PS1} = T_{PS2} = 20$ s; $T_{T1} = T_{T2} = 0.3$ s; $2 * \text{pi} * T_{12} = 0.545$ pu; $T_{G1} = T_{G2} = 0.08$ s; $K_{PS1} = K_{PS2} = 120$ Hz/pu MW; $a_{12} = -1$; $R_1 = R_2 = 2.4$ Hz/pu MW; $B_1 = B_2 = 0.425$ pu MW/Hz, GDB $= 0.06$ pu and GRC $= 10\%$ puMW/min.

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