NIPES
Journal of Materials Engineering, Structures and Computation
Journal homepage: www.nipesjournals.org.ng

Development of an Optimal Frequency and Terminal Voltage Control of Two-Source Two-Area System Using Optimized Pid Controller

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ARTICLE INFORMATION

Article history:
Received 3 July 2023
Revised 27 July 2023
Accepted 29 July 2023
Available online 29 August 2023

Keywords:
Load frequency control, Automatic voltage regulation, SCA, SA, PID controller

https://doi.org/ 10.5281/zenodo.8298121

ABSTRACT

The frequency and voltage challenges when subjected to load disturbance in an interconnected power system has a negative impact on power system stability. This research work is to develop an optimal secondary controller for combined load frequency control and automatic voltage regulation in two area interconnected power system with thermal-hydro power plant in each area. In this work, a proportional integral derivative (PID) controller used for proper control of frequency, tie-line power and voltage when subjected to the load disturbance instead of speed governor alone (which is a primary controller). Then, one of the soft computing techniques called sine-cosine algorithm (SCA) proposed to be used in this study to optimized the PID controller gains and ensure that the frequency, voltage and tie-line errors are minimized to the optimal level. The optimized SCA-PID control scheme was implemented on LFC-AVR model of two area interconnected power system. The stability analysis carried out on frequency, tie line power, voltage deviations and peak undershoot, peak-overshoot and settling time were used as performance metrics. The result reveals that the SCA optimized PID controller has achieved reduced frequency undershoot and settling time of -0.28Hz and -0.29Hz, signifying 60.86% and 61.7% and settling time differences are -2.77 second and -2.37 second, signifying 56.76% and 54.48%, in area 1 & 2 respectively, over SA-tuned PID controller, with little improvement in voltage reduced overshoot in both area 1 & 2. Similarly, the tie-line power deviations settling time found to be -0.51 second when the SCA- tuned PID controller is applied. This also indicate 8.39% reduction in tie-line power deviations settling time compared to SA-tuned PID control technique. The results indicated that proposed Sine-Cosine Algorithm outperformed the SA reported in the literature. The proposed research work, show up an improvement in minimization of the frequency, tie-line power and voltage deviations.

1. Introduction

The number of utilities in interconnected power system forms a large complex network possess the dynamic behavior [1] When the end consumers' demand changes both the frequency and voltage following the load is subjected to violate its limits [2]. In interconnected power system, frequency controlling is taken care by the LFC loop and terminal voltage is controlled by AVR loop [1]. The mismatch between the load and generation leads system frequency to oscillates, if the generation is more than demand frequency over shoot from the specified value and other for vice-versa [1]. The power system exchange between utilities is done through tie-lines (Chandrakala & Balamurugan, 2016). Now a day continuous electric supply of constant frequency and terminal voltage is desired in order to maintain the stability and efficiency of the system [3] In the power system any sudden load perturbations cause the deviation of tie line exchange and frequency fluctuations, their variations are weighted together by a linear combination to a single variable called the area control error (ACE) [4]. The smaller the deviation of the bus voltage from nominal voltage the better the voltage conditions of the system. The power system should be maintained by regulating frequency and the system voltage in order to stabilize the system [1].

Both the frequency and voltage may deviate subject to load disturbances, depending on the nature of the load. As the constancy in frequency is among the important factors in determining the quality of power supply, the constancy in voltage is also equally important factor in determining the quality of power supply. The variation in terminal voltage is controlled by varying the generator field excitation current prior to reactive power burden on the system [1]. For efficient and reliable operation of power system voltage has to be maintain at the scheduled value. The automatic voltage regulation (AVR) loop is the key approach of controlling the voltage of a generating unit [5]. A change in real power demand affects essentially the frequency whereas the change in reactive power affects essentially the voltage magnitude [6]. So, voltage deviation (especially, terminal voltage) has to be considered (investigated and analyzed) together with system frequency. A lot of literatures are available on LFC and AVR individually [1]. Recently, researchers came up with the idea of investigating and analyzing frequency and voltage response in a combine LFC-AVR loop on subjection to load disturbance, which helps in attaining better results in terms of reduced settling time, peak over shoot and under shoot compared to dealing with LFC loop or AVR loop individually. The literatures of combined LFC-AVR scheme brings simultaneous control over frequency and voltage variations [1]. Load frequency control (LFC) balances the power exchange by controlling the frequency and automatic voltage regulator (AVR) balances the machine power out by controlling the voltage [2]. This study considered minimization of frequency, tie line power and voltage deviation in two area interconnected power system on subjection to load perturbation.

In a related area several researchers have conducted studies on load frequency control and system voltage control independently. For decades, researchers focus on simultaneous control action of frequency and terminal voltage in a combined model of LFC-AVR in a single area, due to its significant role in power system stability of interconnected power system. Recently, problems in multi-source multi-area system dealing with LFC & AVR presented by [2]. Many other research works have been conducted on different load frequency control techniques with the aim of minimizing area control error while minimizing frequency deviation in an interconnected power system [4, 7]. At the same time many researchers conducting researches on different voltage control techniques right from the generator terminal up to the distribution level [8][9]. Many research work has been carried out on load frequency and terminal voltage control considering combined model of LFC-AVR of an interconnected power system [10, 11, 12]. In an interconnected power system, frequency controlling is taken care by the LFC loop and terminal voltage is controlled by AVR loop (Kalyan & Rao, 2020). The effect of frequency and voltage on LCF-AVR scheme investigated and analyzed in a single area power system by [13], analysis was further carried out in an interconnected system with two area considering conventional power source of thermal units but without taking care of nonlinearities like GRC by [14]. The multi area system having hybrid source of combined Diesel-Wind-Solar PV and HVDC was presented for the analysis of combined effect of frequency and voltage in LFC-AVR scheme, considering GRC where DE-AEFA employed in stabilizing the frequency and system voltage deviation simultaneously [1].

A lot of secondary controllers using different soft computing techniques had been developed in various form in searching for optimal control of LFC and AVR system. Fractional order (FO) controllers such as FOPID and FOPI were used in LFC scheme [14,15,16,17,18, 19]. In paper [20], the authors use secondary controller such as PID controller used to fine tune the frequency of the system. The Algorithms is use to determine the most suitable or best parameter gains of the PID controller by minimizing the error in frequency, tie-line power and terminal voltage. However, the performance of these algorithms is limited due to the uncertainty in their parameter selection, trapping in to local minima in high dimensional space and suffer low convergence [3]. The major setback on this algorithm includes the time consuming toward performing the control action, as such it may result in a delay while entering an unstable region of the operation [3].

1. Proposed Approach

The following are the procedures adopted for the developed LFC-AVR control model:

1. Adoption of the two area interconnected power systems
   - i. Simulation of the governor, turbine and generator, exciter, amplifier, sensor, generator field for a thermal-hydro, power system with nonlinearity features using MATLAB/Simulink.
     - a. Simulation of the components of the thermal turbine power plant with GDB, GRC and time delay.
     - b. Simulation of the components of the hydro turbine power plant with GDB, GRC and time delay.
     - c. Connection of the different power generating units with tie-line.
   - ii. Development of the LFC-AVR model for the selection of the governor, turbine and generator for a thermal-hydro, power system with nonlinearity features using MATLAB/Simulink, used for the simulation and analysis of any of the listed combinations (thermal-hydro and hydro-thermal) as in (i) and hydro-thermal from (Chandrakala & Balamurugan, 2016) for such metrics as ISE, ITSE & ITAE.

2. Implementation of SCA technique in (1) and optimized the gains (K_P, K_I, K_D) of PID controller through simulation in MATLAB/Simulink environment, the following step were followed:

- i. Initializing the set of search agents (control gains X)
- ii. Evaluating the value of each of the search agents by objective function subject to its constraints.
- iii. Saved the best solution obtained at moment, assigns it as final tip ($p=X^*$) then update the other solutions with respect to it
- iv. Also update the sine and cosine function ranges r_1, r_2, r_3 and r_4 to emphasize search space development while iteration progresses
- v. Observe the termination criteria: in this work SCA stops the optimization process when the iteration counter is higher than upper limit number of iterations, best solutions are obtained if condition satisfied
- vi. Otherwise update the status of search agents using equation (1) and return to step (ii)

3. Compared the results obtained from the research finding with the work of (Chandrakala and Balamurugan, 2016) which is the based paper using ISE, ITSE & ITAE as performance metric.

2.1. Modeling of Combined LFC-AVR in Two-Source Two-Area System

Modeling of a combined LFC-AVR scheme in two area power system with two source of thermal and hydro units. Figure 1 present LFC-AVR combined model for single area system with thermal-hydro unit the combine LFC-AVR loop, consist of thermal-hydro combined power generating units in both area 1 and 2 as shown in figure 2, the first area comprises of thermal-hydro generating units the second area comprises of hydro-thermal generating units and each area has its PID controller connected accordingly. The system depicted in Figure 2 was developed in MATLAB/Simulink environment. In figure 2 the thermal power plant consists of speed governor, governor dead band, hydraulic amplifier, boiler system, non-reheat steam turbine. When there is load perturbation, the primary control system that is, speed governor control the steam input turbine according to the demand by adjusting the position of the control valve. Connected next to the speed governor is the dead band, which occurred as a result of valves overlap in the hydraulic relays, backlash effects and coulomb friction caused in different governor linkages. Followed by dead band is hydraulic amplifier which its output is an input to the boiler, used to control the boiler input (boiler valve power ΔP_V) with respect to steam flow $\Delta P_{R,}$ connected between the amplifier and the turbine is boiler which is the input to the turbine to control its valve power ΔP_V with respect to steam flow $\Delta P_{R,}$ the turbine mechanical power output ΔP_T drives the generator which in turns produces an electrical power to the power system.

Also the hydro power plant consists of speed governor and hydro turbine, between the speed governor and turbine is a transient droop compensation system for stable speed control performance and turbine output power drives the generator which in turns produces an electrical power to the system.

The change in load demand causes a mismatch between the generation and the demand is sensed indirectly as change in voltage by the automatic voltage regulator which control the generator terminal voltage by adjusting the excitation current and change in frequency by the governor which control the water input to the turbine by adjusting the gate position.

Considering a Cohn control strategy, the system area 1 and 2 are interconnected through tie-line which shares the active power within limits.

In the case of AVR, the effect of small voltage changes on real power ‘ΔP_{Real}’ is given as:

$$\Delta P_{Real} = P_S \, \Delta\delta + K_1 V_F \qquad (1)$$

So the change in the generator terminal voltage including the small effect of power angle ‘δ’ is given as

$$\Delta V_t = K_2 \, \Delta\delta + K_3 \, V_F \qquad (2)$$

The AVR model consist of amplifier in which its output is an input to the exciter which control the current of the generator field in returns regulating the generator terminal voltage

The Figure 3, depicted a flowchart used in modeling of combined LCF-AVR scheme with two-source (thermal-hydro) two-area interconnected system. The parameter used was adopted in (Chandrakala and Balamurugan, 2016). Figure 4 present MATLAB/Simulink environment modeled LFC-AVR scheme of thermal-hydro with two area system.

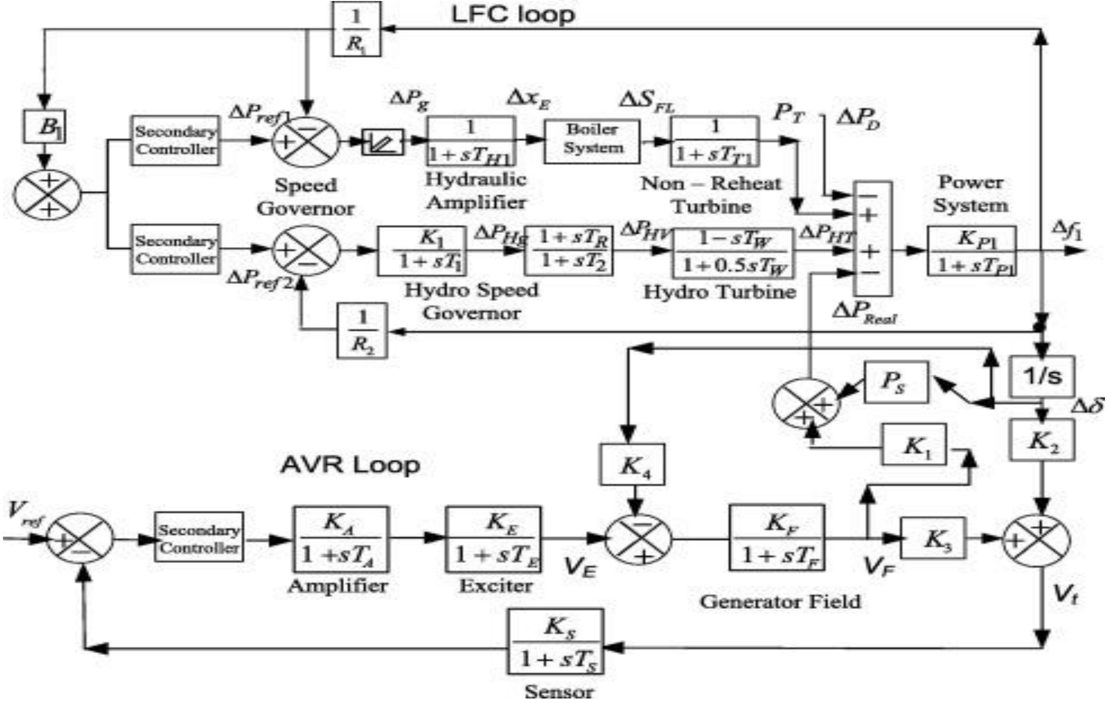

Figure 1. LFC-AVR combined model for single area system with thermal-hydro units.

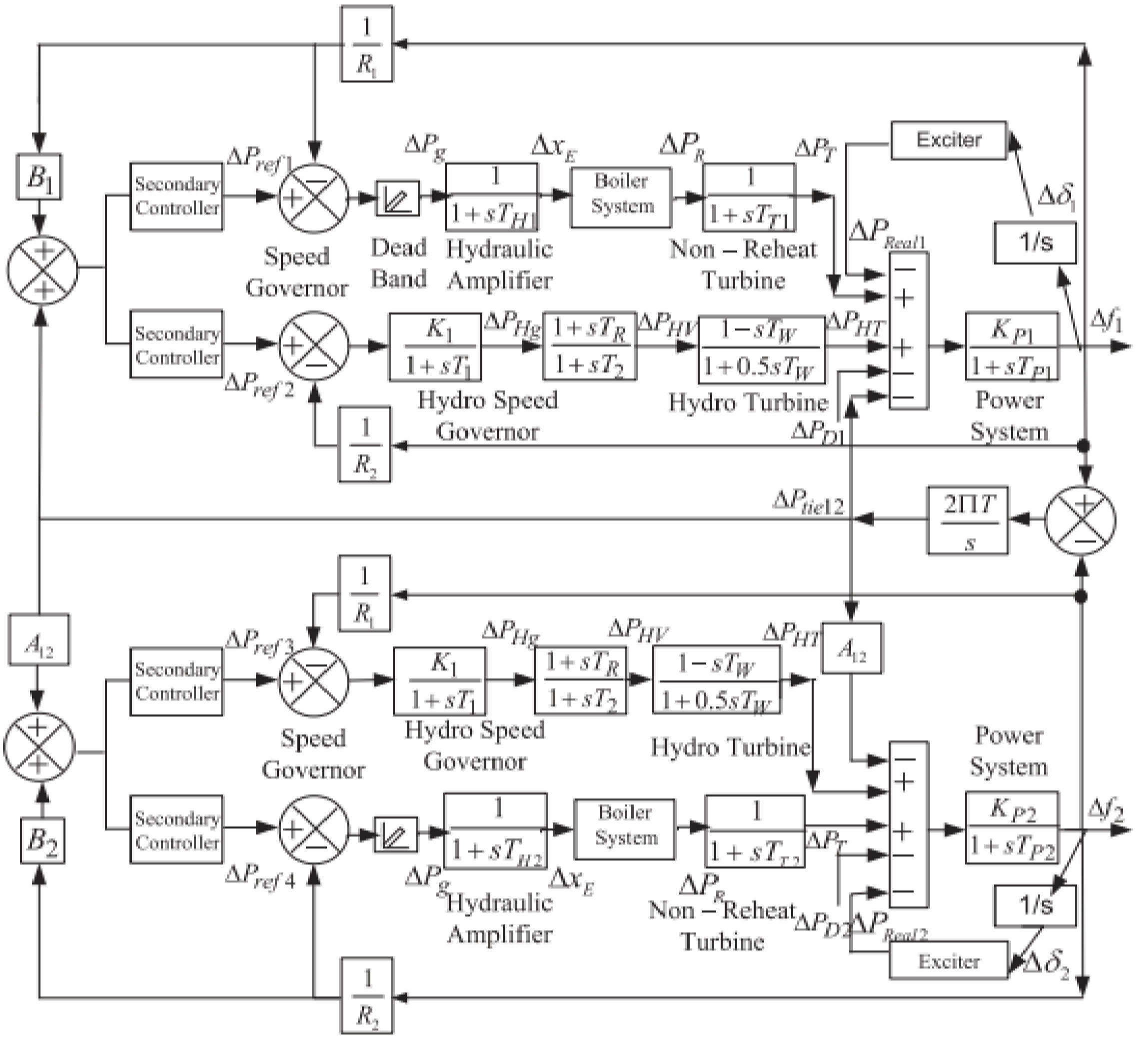

Figure 2. LFC-AVR combined model for two area system with thermal-hydro units.

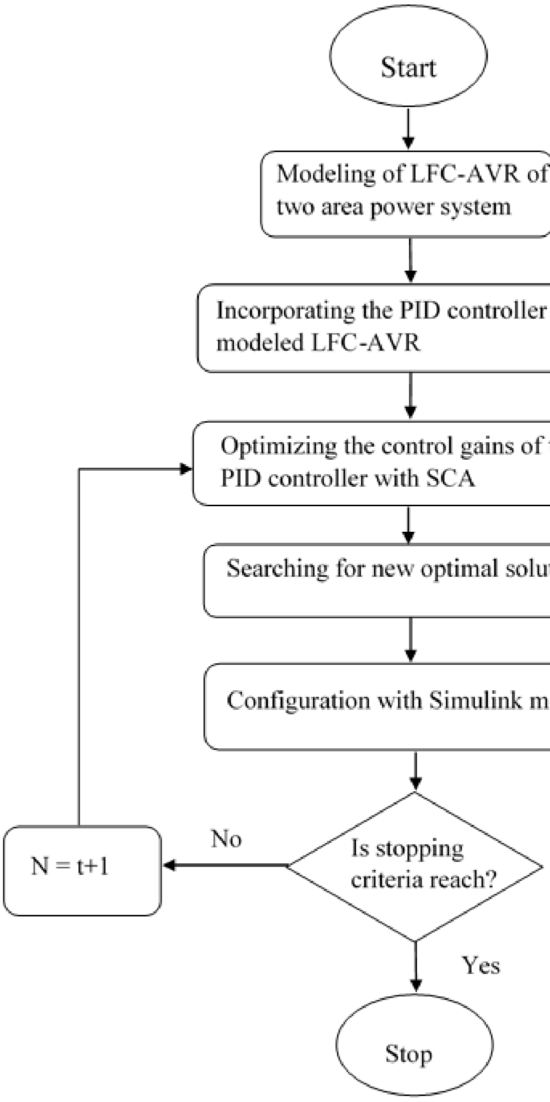

Figure 3. Flowchart for modeling LFC-AVR scheme.

The simulation parameters in Table 1 were used in determining the performance of the efficacy of the PID controller using ISE, ITSE and ITAE to minimize the frequency, tie line and voltage deviations.

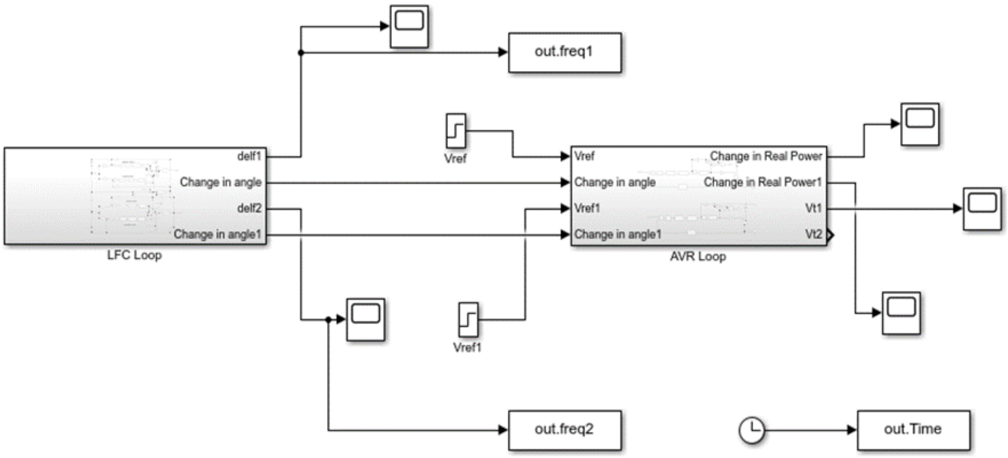

Figure 4. modeled LFC-AVR scheme of thermal-hydro, with two area system on the MATLAB/Simulink environment

2. Simulation Result and Discussion

In this section results obtained from the developed LFC-AVR scheme using optimized PID controller is presented and discussed. The results obtained were validated with (Chandrakala & Balamurugan, 2016). The SCA optimization was applied to opitimize the control gains of the PID controller. In restoring the frequency, tie line power and terminal voltage to the nominal value after excursion, the optimized PID controller performed that task. This was achieved by sending the frequency, tie line power and voltage values of the objective function from Simulink model to the MATLAB workspace continuously at specified time interval while SCA optimizes the objective function in line with the new values. The stability analysis was carried out on the modeled LFC-AVR scheme in the MATLAB Simulink environment using frequency, tie line power and voltage deviations, overshoot, undershoot and settling time as performance metrics. The performance of the SCA technique presented in this paper was compared with the SA technique established in the literature by analyzing the simulation results. The optimal parameter gains of PID controller for thermal-hydro combination are depicted in Table 1

Table 1: The optimal parameter gains of PID controller for thermal-hydro combination.

SECONDARY CONTROLLER *****	THERMAL			HYDRO		
	K_P	K_I	K_D	K_P	K_I	K_D
Area 1						
SCA	5.4653	5.5899	4.8934	5.1178	8.4630	4.2009
SA	5.1000	9.0999	4.1000	5.0025	8.9003	4.0995
Area 2						
SCA	5.1858	9.9928	3.5591	4.4549	9.0683	4.3127
SA	5.0098	9.0725	3.9220	4.9008	9.0994	4.0870

From Table 1, K_P, K_I & K_D are the proportional gain, integral gain and derivative gain of the PID controller respectively. The result shows that the SCA tuned PID controller in the combined LFC-AVR model has better compared to that of SA technique used in Chandrakala & Balamurugan, (2016)

3.1 Simulated result from the combined model of LFC-AVR of two-source, two-area network

This section shows the simulated results of frequency, tie line power and voltage deviation from the combined scheme of LFC-AVR loops of thermal and hydro power generating units of two area system. Figures 5 and 6 shows the frequency deviation of area 1 and 2 respectively. Figure 6 shows the tie line power exchange between area 1 and 2

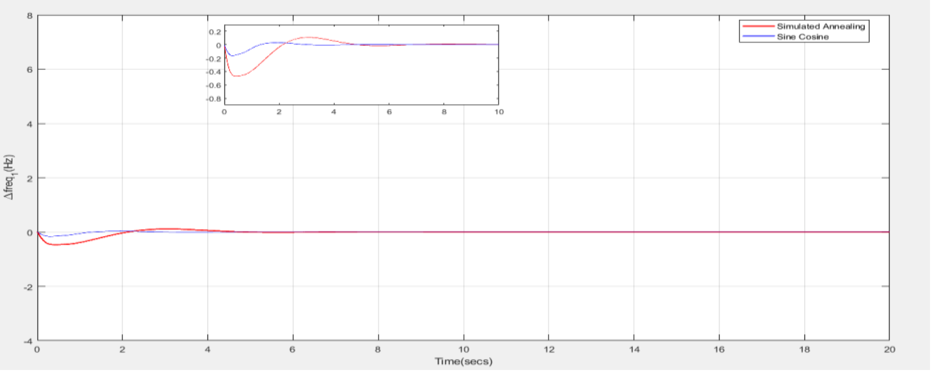

Figure 5. The frequency deviation in area 1

Figure 5 depicts the frequency graph of the area 1, it shows the frequency response for area 1. From the graph Red line represent frequency response of the work of Chandrakala & Balamurugan, (2016) using SA technique while Blue line represent the frequency response of the proposed work using sine cosine algorithm (SCA). The plant was subjected to 1% SLP only in area 1, for SA the frequency in area 1 deviated and reached the peak undershoot to -46×10^{-2} then, peak overshoot to 10×10^{-2} and 4.88 second for the settling time, while for SCA peak undershoot value was -18×10^{-2} and 2.11 second for the settling time. The SCA has reduced undershoot, zero overshoot and has short settling time in area 1, compared to SA technique.

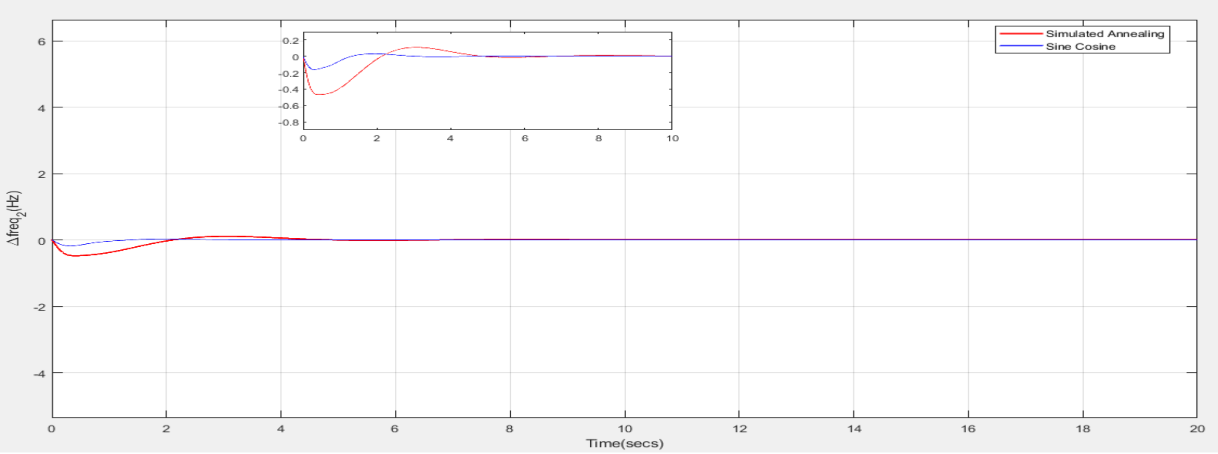

Figure 6. the frequency deviation in area 2.

Figure 6 show the frequency response for area 2 of interconnected power system with combined LFC-AVR scheme. From the Figure 6, it shows the frequency response in area 2 of the combined LFC-AVR scheme. From the Figure 6, the red line represent the frequency response of the work of Chandrakala & Balamurugan, (2016) which used SA technique while Blue line represent the frequency response of the proposed work which used sine cosine algorithm (SCA). The plant was subjected to 1% SLP only in area 1, and considering the SA, the system frequency of area 2 deviated with peak undershoot to -47×10^{-2} then, peak overshoot to 10×10^{-2} with 4.35 second settling time, while for SCA, peak undershoot value was -18×10^{-2} with 1.98 second settling time. The SCA has reduced undershoot, zero overshoot and also has short settling time compared to SA technique.

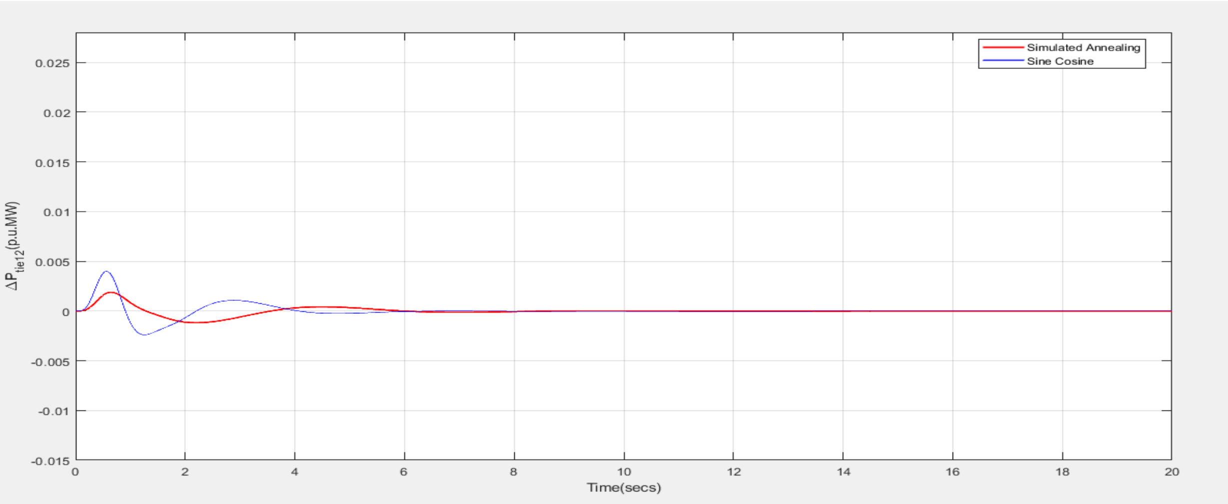

Figure 7 the tie-line power deviation between area 1 & 2

Figure 7 shows the tie-line power deviation between area 1 & 2 for two area interconnected system. From the From the Figure 7, the red line represent the frequency response of the work of Chandrakala & Balamurugan, (2016) which used SA technique while Blue line represent the frequency response of the proposed work which used sine cosine algorithm (SCA).). After the plant was subjected to 1% SLP only in area 1, for SA, the frequency deviated and has peak undershoot of, -1.8×10^{-3} , with peak overshoot of 2.05×10^{-3} and 6.08 second settling time, while for SCA peak undershoot value was -2.51×10^{-3} with peak overshoot of 4.11×10^{-3} with 5.57 second settling time. The SA has reduced undershoot, overshoot but has high settling time compared to SCA.

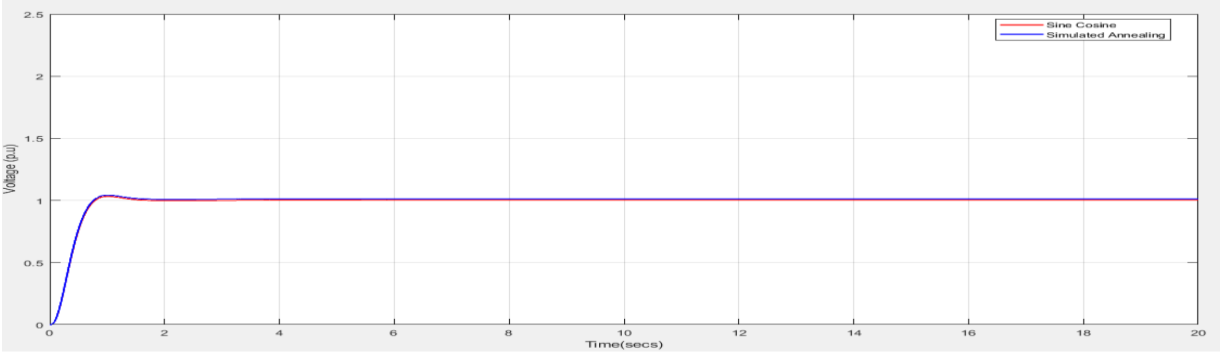

Figure 8 the voltage deviation in area 1

Figure 8 shows the voltage response in area 1 of the two area interconnected power system. From the From the Figure 8, the red line represent the frequency response of the work of Chandrakala & Balamurugan, (2016) which used SA technique while Blue line represent the frequency response of the proposed work which used sine cosine algorithm (SCA). After the plant was subjected to 1% SLP only in area 1, for SA, the voltage deviated and reached peak overshoot of 1.0417 and 1.4808 second settling time, while for SCA the peak overshoot was 1.0411 and has 1.4808 second settling time. The SCA has slightly reduced overshoot and both the SCA and SA has the same settling time but the result for SA, ripples appear after even 2 seconds.

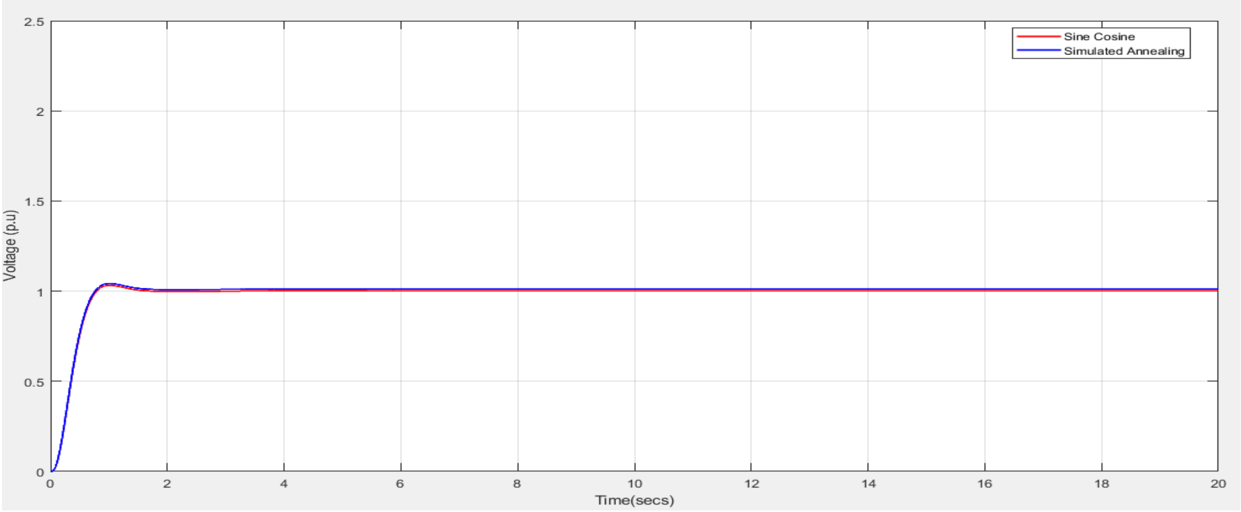

Figure 9. The voltage deviation in area 2

Figure 9 shows the voltage deviation in area 2 of the two area interconnected power system. From the From the Figure 9, the red line represent the frequency response of the work of Chandrakala & Balamurugan, (2016) which used SA technique while Blue line represent the frequency response of the proposed work which used sine cosine algorithm (SCA). After the plant was subjected to 1% SLP only in area 1, for SA, the voltage deviated and reached peak overshoot of 1.0417 and 1.4808 second settling time, while for SCA the peak overshoot was 1.0411 and has 1.4808 second settling time. The SCA has slightly reduced overshoot and both the SCA and SA has the same settling time but the result for SA, ripples appear after even 2 seconds.

3.2 Comparison of the Proposed Results with Chandrakala & Balamurugan, (2016)

The results obtained from the proposed work compared with that obtained from the work of (Chandrakala & Balamurugan, 2016), considering different scenarios such as settling time (T_s), peak undershoot (U_p) and peak overshoot (O_p). Figures 5 and 6 shows the comparison of Chandrakala & Balamurugan, (2016) and the proposed work for the frequency deviation response for area one and two respectively. Figure 7 shows the tie line power deviation between area 1 and 2, while Figures 8 and 9 were area 1 and 2 voltage deviation response of the proposed work and that of Chandrakala & Balamurugan, (2016).

By the given results and observations figures 5-7 of the LFC loop, it is clear that the SCA optimized PID controller performed better than SA technique in term of settling time and reduced peak undershoot at the same time the SCA tuned PID controller in AVR loop also slightly improved the terminal voltage profile of the generating units in both the two areas.

There was huge improvement in minimization of frequency, tie-line power and voltage deviation using SCA tuned PID controller in two-source, two-area LFC-AVR scheme.

3. Conclusion

The designed interconnected two-area power system with two-source (thermal-hydro plant) in each area for the combined LFC-AVR scheme using MATLAB/Simulink was subjected to a unit step load disturbance in area 1 only. The PID controller was optimized using Sine Cosine Algorithm (SCA) and minimized the error signal. The SCA- PID controllers in LFC loop and AVR loop of the combined scheme of two-source, two area system helped the system governor and the generator field excitation system to restored the system frequency, tie-line power and terminal voltage to their desired values at a faster rate on subjection to load perturbation. The stability of the optimized SCA-PID controller and response of frequency, tie-line power and voltage to deviation, were analyzed and compared with that of Chandrakala & Balamurugan, (2016). For the proposed work, the settling time of frequency are within 2.11 and 1.98 seconds for area 1 and 2 respectively. The tie-line power settling time is within 5.57 seconds and the voltage deviation settling time is within 1.48 seconds in both area 1 & 2. The system restored back faster in term of settling time and less under shoot compared to the work of Chandrakala & Balamurugan, (2016). Thus, the frequency and voltage profile improved in both area 1 and 2. However, in term of terminal voltage response both in area 1 and 2 there were no significant improvement in the proposed work in term of error minimization (such as settling time and reduced overshoot) compared to Chandrakala & Balamurugan, (2016). This clearly show that in the combined scheme of LFC-AVR, the SCA tuned PID controller performed better than the SA tune PID controller presented in Chandrakala & Balamurugan, (2016) in term of reduced peak overshoot and settling time. The SCA tuned PID controller emerged as the best (optimal) Secondary controller.

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