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The Impact of Optimized PID Controller Based SVC on Power systems Stability Enhancement

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Abstract
The stability is the most important goal in any electrical network, and the control of this network is a part of the stability organization. This article presents application of three optimization algorithms, which are Henry Gas Solubility Optimization, Grey Wolf Optimization, and Ant Lion Optimization, to obtain the PID controller parameters for Static var compensator SVC connected to Single Machine Infinite Bus (SMIB) system. The suggested optimization techniques were used to choose the most accurate PID parameters to enhance the system stability. And then applied the proposed optimization algorithm which gives the best value of J-obj in the PID controller variables with the Static VAR Compensator's (SVC) variables to get the most suitable values for them which leads to more and faster stability than without the SVC then it compared with the Power System Stabilizer (PSS). So that the importance of installing optimized SVC based PID controller is evident.

Keywords: PID Controller; Optimization techniques; SVC; Power systems stability

NOMENCLATURE

ALO	Ant Lion Optimization
GWO	Grey Wolf Optimization
HGSO	Henry Gas Solubility Optimization
J_obj	objective function
K_c	Static VAR Compensator gain
K_d	differential gain of PID controller
K_i	integral gain of PID controller
K_p	proportional gain of PID controller
PSS	Power system stabilizer
SMIB	single machine infinite bus
SVC	Static VAR Compensator
T_c	SVC time constant

Introduction
To enhance the stability for the SMIB in the electrical networks there are a lot of devices are studied one of them is the Flexible Alternating Current Transmission System (FACTS) technology, based on modern powerful disturbances [1-7]. FACTS technology, based on modern powerful semiconductor devices, enables the transmission system to improve its efficiency by regulating the power flow, enlarging the loading capability, increasing the system security and providing greater flexibility, just to enumerate a few benefits. Particularly, FACTS compensators commanded through proficient control algorithms allow enhancing the stability and transfer capability of present and new transmission lines.

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These potentialities come from the faculty of FACTS compensators to act over the interrelated parameters that govern the operation of transmissions systems [8-15]. There are a lot of papers investigated to the performance of the optimized FACTs devices [16-17].

Dynamic Performance of the Static Var Compensator Enhancement, and many FACTs devices were investigated [18-30]. The major factors of the SVC instability analyzed and a new Automatic Gain Controller (AGC) proposed to ensure the stable operation of the SVC under various load conditions. The performance of SVC scheme connected to the 230kV grid is evaluated. Particle swarm optimization (PSO) is implemented for coordination of SVC and TCSC to control the power flow in power systems [30]. The PSO is applied to determine the accurate parameter of SVC as well as TCSC. The technique is applied to IEEE-14 bus system for examining the accuracy of the suggested optimization technique based SVC, and TCSC.

Whale optimization algorithm (WOA) is used to determine the best location of TCSC and SVC for reactive power planning [30]. On the standard IEEE30 and IEEE57 bus system the WOA is applied to find the most suitable location of TCSC by the power flow analysis method and location of SVC by the voltage collapse proximity indication (VCPI) method.

Using the optimized SVC controller by quasi-differential search for stability amelioration in solar photo voltaic (PV) integrated power system [31]. SVC is inserted with PV based power system to damp the low frequency oscillations so that at first differential search algorithm (DSA) was applied to optimize the controller's gains then quasi-oppositional learning was combined to DSA to enhance the convergence speed and get the optimal parameters of SVC_PID controller. Quasi-oppositional differential search algorithm (QODSA) was applied for designing an optimal SVC-PID based damping controller. The optimization techniques were implemented successfully for optimal allocation and FACTs devices and distributed generation for improving power systems performance [38-45].

The coordination of SVC by a hybrid Biogeography Based Optimization Differential Evolution (BBO-DE) optimization with Eigen value analysis based transient stability improvement [32]. In IEEE 39 bus test system consists of 10 generators and 19 loads with three phase fault and fault time 2 second with 2.5 seconds as clearing time the studied performance of SVC and PSS are carried out on it.

Using quasi-oppositional chemical reaction optimization (QOCRO) to optimize the location of SVC and TCSC in the optimal reactive power dispatch (ORPD) [33]. The quasi-oppositional based learning (QOBL) is combined to the conventional chemical reaction optimization (CRO) was applied on IEEE 14-bus and 30-bus to improve the quality and the convergence speed of the solution.

SVC damping controller design by Bacteria Foraging Optimization Algorithm (BFOA) to enhance the power system stability [34]. To demonstrate the superior efficiency of the proposed BFOA in tuning SVC controller the Genetic Algorithm (GA) was used with BFOA but SVC based on BFOA gives better robust damping performance over wide range of operating conditions than SVC based on GA.

Using Bacteria Foraging Optimization Algorithm (BFOA) in a multimachine power system to design the PSSs and SVC [35]. PSS designed based on BFOA, also SVC designed based on BFOA over a wide range of loading conditions and by minimizing the proposed objective function to improve the system stability performance.

SVC and TCSC optimal location and setting using Non-dominated Sorting Particle Swarm Optimization [36]. . The proposed method is validated on IEEE 30-bus and realistic Algerian 114-bus power system. The simulation results are compared with those obtained by particle swarm optimization (PSO) and non-dominated sorting genetic algorithms (NSGA-II) then the effectiveness of the proposed NSPSO was appeared.

Multi-objective VAr Planning with SVC Using Immune Algorithm (IA) and Guaranteed Convergence Particle Swarm Optimization [37]. The multi-objective VAr planning problem is solved by the fuzzy IA and the results are compared with those obtained by the fuzzy Genetic Algorithm (GA) and fuzzy Guaranteed Convergence Particle Swarm Optimization (GCPSO) to enhance the voltage stability. So that this paper will investigates the importance of the SVC in the stability of the SMIB. The SMIB studied system will be present as a time domain system with the controller system which will be the PID controller and then the optimization algorithms (HGSO, GWO, ALO) will be run in the time domain of

the SMIB with PID to evaluate the PID's gains as the variables of the optimization algorithms after that the proposed optimization algorithm will be which gives the best value for the objective function J.
The best optimization algorithm comparing with two other optimization algorithms will be used to optimize the variables of the FACTs devices (SVC) and the PID's gains together (K_p, K_i , K_d, K_c, andT_c)to compare the system with and without this device (SVC) .
after that the comparison between the controlled system by PID controller with / without the SVC and the PSS will be run ,PSS which provide supplementary feedback stabilizing signals, and they suffer a drawback of being liable to cause great variations in the voltage profile[30].
This paper presents the application of implementing different optimization techniques for PID controller parameters for static VAR compensators SVCs to enhance the power systems stability.

2. The system Modelling

The studied model is the single machine infinite bus which consists of the synchronous machine connected to the infinite bus through the transformer as shown in Fig. 1

And the following equations represent SMIB system

$$\frac{\Delta\omega_r}{\Delta t} = \frac{\Delta T_m - K_1\Delta\delta - K_D\Delta\omega_r - K_2\Delta\Psi_{fd}}{2H} \quad (1)$$

$$\frac{\Delta\delta}{\Delta t} = \omega_0\Delta\omega_r \quad (2)$$

Where $\omega_0 = 2\pi f_0$

$$\frac{\Delta\Psi_{fd}}{\Delta t} = -\frac{K_3K_4\Delta\delta + \Delta\Psi_{fd} - K_3\Delta E_{fd}}{T_3} \quad (3)$$

$$\frac{\Delta E_{fd}}{\Delta t} = -\frac{K_eK_5\Delta\delta + K_eK_6\Delta\Psi_{fd} + \Delta E_{fd}}{T_e} \quad (4)$$

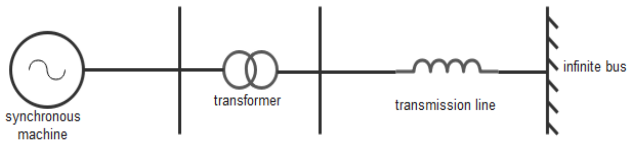


Fig. 1 Studied single machine infinite bus system [46]

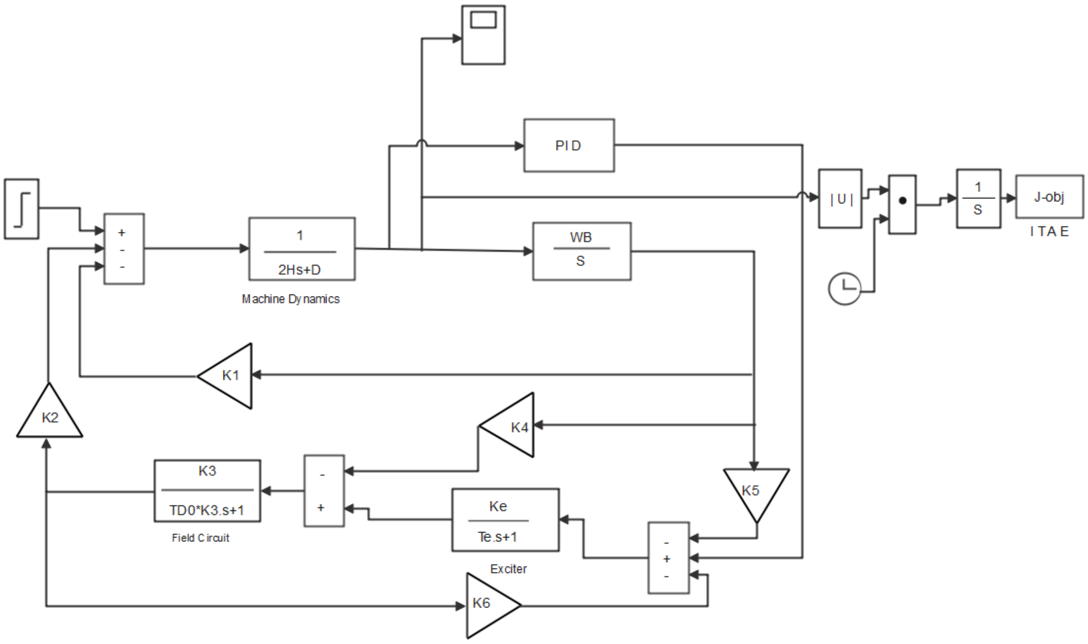


Fig. 2 the time domain of the SMIB model with PID controller

2.1 The excitation system

It is defined as the system which is used for the production of the flux by passing current in the field winding. The main requirement of an excitation system is reliability under all conditions of service, simplicity of control, ease of maintenance, stability and fast transient response and its transfer function is shown in fig.3 where (K_e =50 , T_e =0.05). The amount of excitation required depends on the load current, load power factor and speed of the machine.

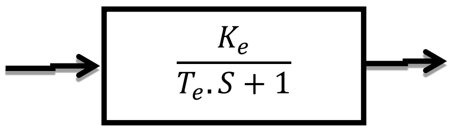


Fig. 3 The exciter block diagram [47]

2.2 PID controller

The controller was applied is PID controller, it is an acronym that stands for proportional, integral and derivative, if you need to keep something constant then this is the way to do it, it is one of the most advanced control strategies, because of its simple algorithm, good robustness and high reliability; it is widely used in the field of industrial process control.

Essentially, it uses a control loop feedback to ensure the output wanted is what you will get. The PID controller is designed to increase the damping torque of the SMIB system.

The PID controller has three parameters (K_p, K_i and K_d) as shown in Fig.4, Those three parameters not only affect the control effect, but also affect the robust performance of the controller so that the values of them are very important

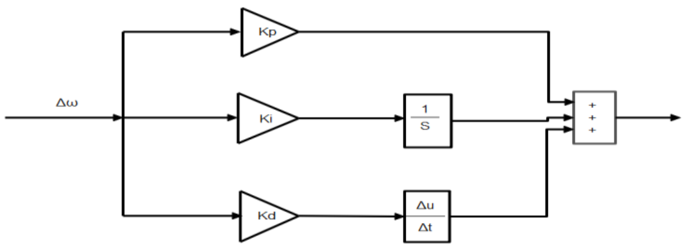


Fig. 4 PID controller

$PID(s) = K_p + \frac{K_i}{s} + \left(K_d \frac{\Delta u}{\Delta t}\right)$ (5)

K_p, K_i and K_d are the controller's gains which the optimization algorithms will apply on them.

The studied system will be a SMIB model with PID controller in it's time domain

3. The Applied Optimization Algorithms

By applying HGSO, GWO and ALO on the PID controller for the model in fig.2 to get the most suitable values for the PID gains K_d, $K_i$and K_p as the optimization algorithms variables.

3.1 GWO algorithm [48].

The GWO algorithm is modelled after the natural leadership structure and hunting mechanism of grey wolves. For replicating the leadership structure, four sorts of grey wolves are used: alpha, beta, delta, and omega. Furthermore, the three basic processes of hunting are implemented: searching for prey, encircling prey, and attacking prey.

The solution steps [49]:

–Step 1. The standard grey wolf optimizer algorithm starts by setting the initial values of the population size n, the parameter a, coefficients $\vec{A}$ and $\vec{C}$and the maximum number of iterations max_{itr}.

– Step 2. Initialize the iteration counter t.

– Step 3. The initial population n is generated randomly and each search agent $\overrightarrow{X_i}$ in the population is evaluated by calculating its fitness function $f\ (\overrightarrow{X_i})$.

– Step 4. Assign the values of the first, second and the third best solution$\overrightarrow{X_\alpha}$, $\overrightarrow{X_\beta}$ and $\overrightarrow{X_\delta}$, respectively.

– Step 5. The following steps are repeated until the termination criterion satisfied

Step 5.1. Each search agent (solution) in the population is updated as shown in Equation

$\overrightarrow{X}(t+1) = \frac{\overrightarrow{X_1}+\overrightarrow{X_2}+\overrightarrow{X_3}}{3}$ (6)

Step 5.2. Decrease the parameter a from 2 to 0.

Step 5.3. The coefficients $\vec{A}$ and $\vec{C}$ are updated as shown in Equations respectively

$\vec{A} = 2\ .\ \vec{a} + \overrightarrow{r_1}.\ \vec{a}$ (7)

$\vec{C}= 2\ .\ \overrightarrow{r_2}$ (8)

Step 5.4. Each search agent in the population is evaluated by calculating its fitness function $f\ (\overrightarrow{X_i})$.

– Step 6. The first, second and the third best solutions are updated $\overrightarrow{X_\alpha}$, $\overrightarrow{X_\beta}$ and $\overrightarrow{X_\delta}$, respectively.

– Step 7. The iteration counter is increasing t = t + 1.

– Step 8. The overall process is repeated until termination criteria satisfied.

– Step 9. Produce the best found search agent (solution) so far$\overrightarrow{X_\alpha}$.

3.2 ALO algorithm [50]

The ALO algorithm mimics the natural hunting mechanism of ant lions. The random movement of ants, building traps, trapping of ants in traps, collecting preys, and re-building traps are the five main methods for hunting prey. The ant lion is a net-winged insect belonging to the Neuro ptera order.

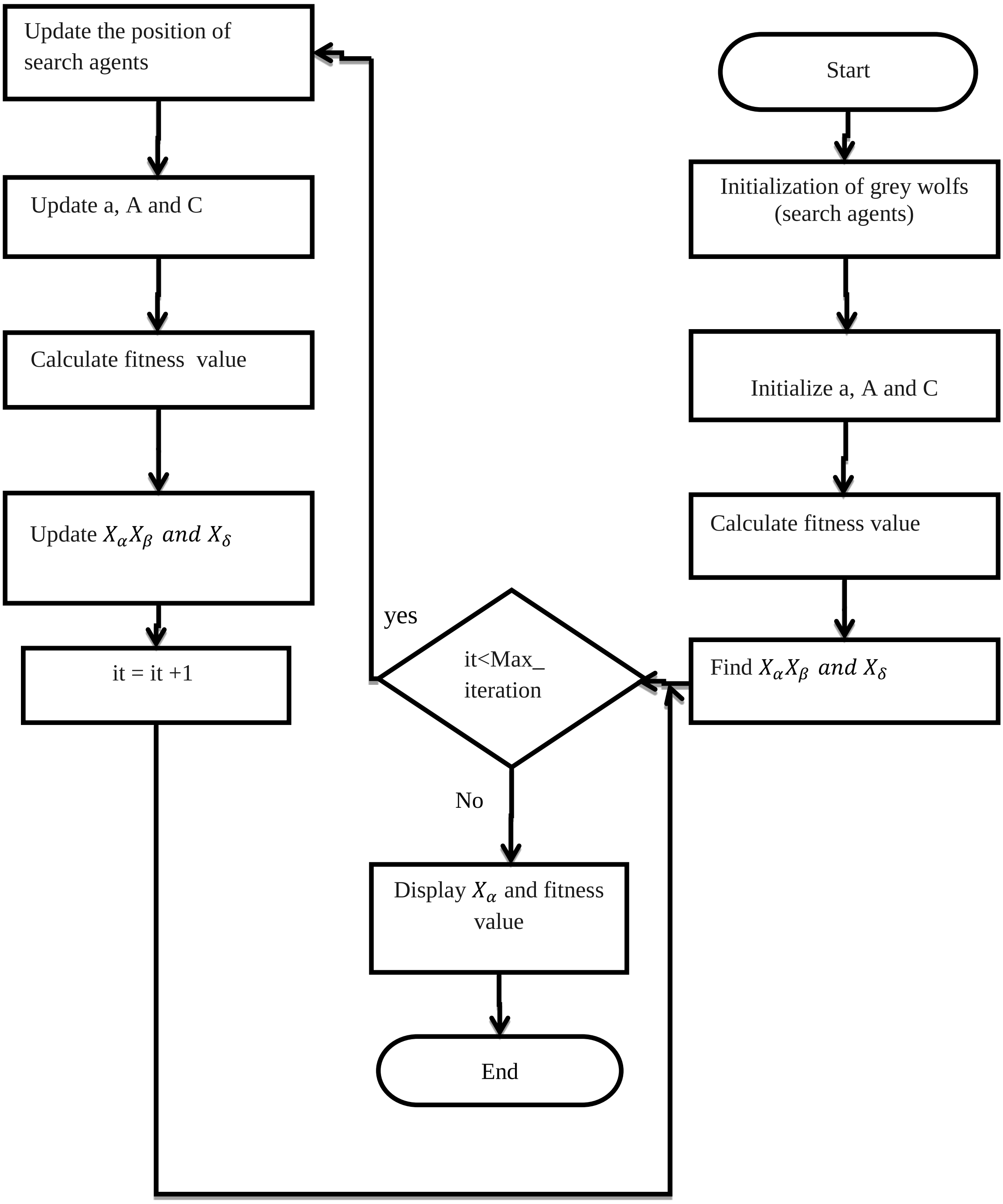


Fig. 5 GWO flow chart [49]

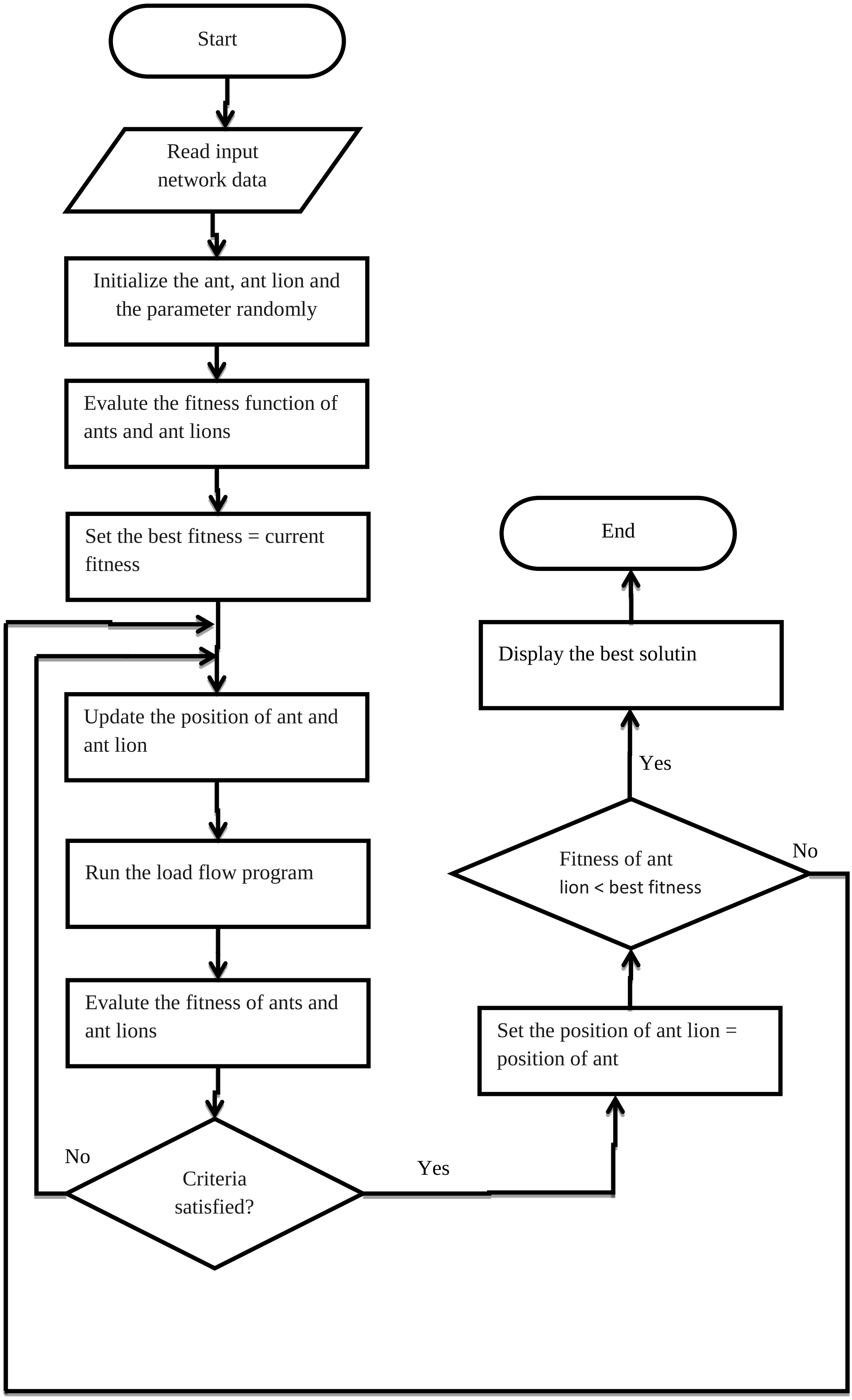


Fig. 6 the ALO algorithm flow chart [51]

The solution steps of the ALO algorithms [51].

- step 1.Randomly, the first population of ants and ant lions is distributed.
- step 2.The fitness of ants and ant lion is counted.
- step 3.Get the optimum ant lions and suppose it is the elite.
- step 4.while the final criterion is not done.
- step 5.for each ant.
- step 6.A roulette wheel is used to pick an ant lion.
- step 7.Change k and g by utilizing equation:

$$\text{U} = 10^{y}.\frac{i}{j} \quad (9)$$

- step 8.generate a random walking and apply it by utilizing equations:

$$L(s) = \begin{cases} 1, & if\ random > 0.5 \\ 0, & if\ random \leq 0.5 \end{cases} \quad (10)$$

$$K_i^t = \text{Antlion } t_i^t + k^t \quad (11)$$

$$g_i^t = \text{Antlion } t_i^t + g^t \quad (12)$$

- step 9.The place of ant is updated using equation of the objective function.
- step 10.end for.
- step 11.The fitness of all ants is counted.
- step 12.Replace an ant lion with the candidate that is calculated utilizing equation:

$$Ant_i^t = \frac{B_A^t + B_E^t}{2} \quad (13)$$

- step 13.If an ant lion is the best, the elite is changed with this ant lion.
- step 14.end while.
- step 15.Return elite.

3.3 HGSO algorithm [52].

This mimics the behavior governed by Henry's law to solve challenging optimization problems. Henry's law is an essential gas law relating the amount of a given gas that is dissolved to a given type and volume of liquid at a fixed temperature.

The proposed HGSO algorithm was implemented in MATLAB version R2016a. The numerical efficiency of HGSO was evaluated by solving 47 standard benchmark functions, CEC'17 test suite, and three engineering problems. The performance of the proposed HGSO was evaluated against seven state-of-the-art optimization algorithms.

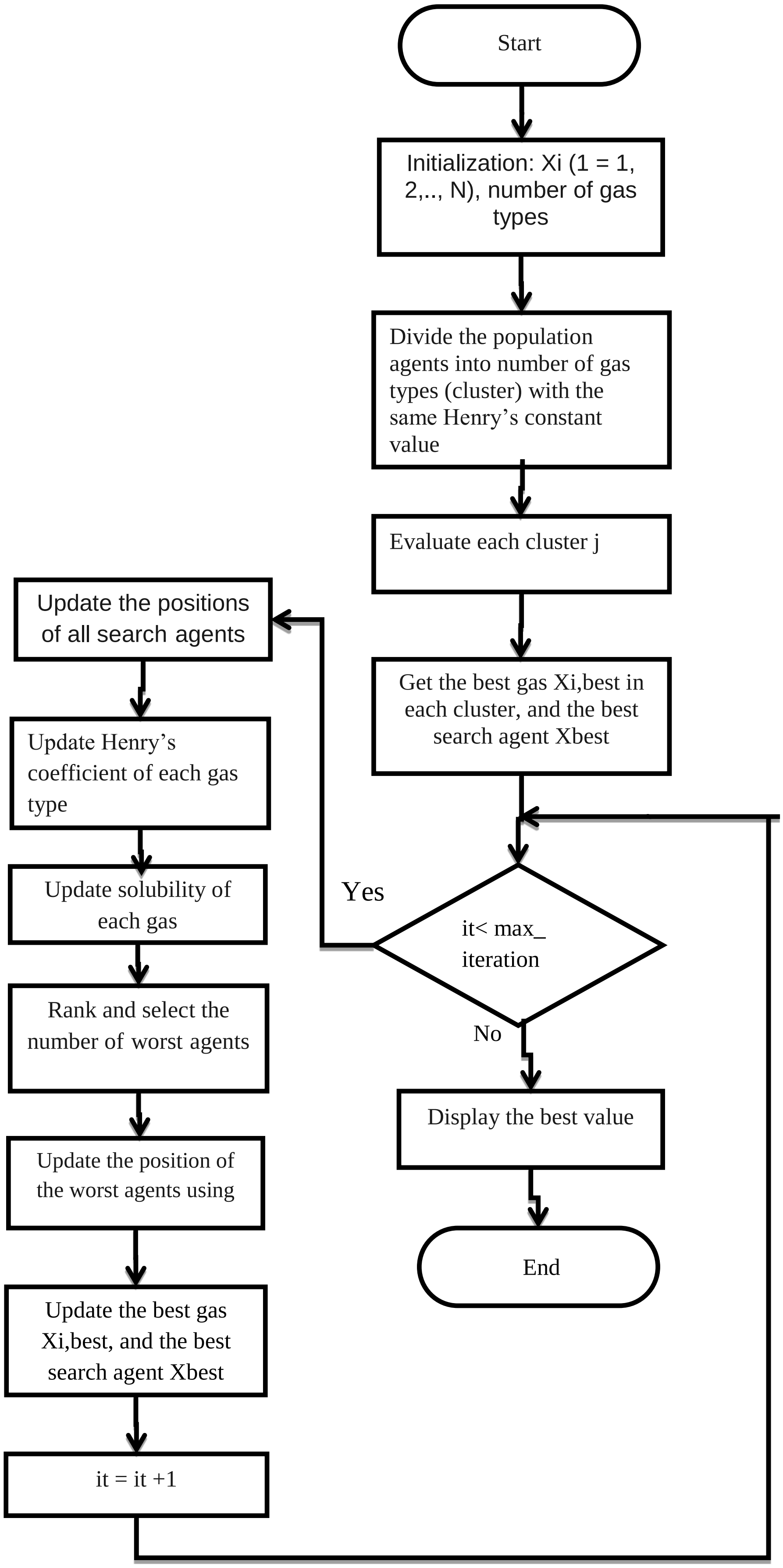


Fig. 7 HGSO flow chart [52]

The solution steps of the HGSO algorithm [52].

-Step 1: Initialization process.

The number of gases (population size N) and the positions of gases are initialized based on the following equation:

$$X_i(t+1) = X_{min} + r \times (X_{max} - X_{min}) \quad (14)$$

Where the position of the ith gas in population N is denoted by $X_{(i)}$, r is a random number between 0 and 1, and X_{max}, X_{min} are the bounds of the problem, and t is the iteration time. The number of gas i, values of Henry's constant of type j(H_j (t)), partial pressure $P_{i,j}$ of gas i in cluster j, and ∇_{sol} E/R constant value of type j(C_i) are initialized using the following Equation:

$$H_j(t) = I_1 \times \text{rand}(0,1) \quad (15)$$

$$P_{i,j} = I_2 \times \text{rand}(0,1) \quad (16)$$

$$C_j = I_3 \times \text{rand}(0,1) \quad (17)$$

Where, $I_{1,}$ I_2 and I_3 are defined as constants with values equal to (5E−02, 100, and 1E−02), respectively.

-Step 2: Clustering.

The population agents are divided into equal clusters equivalent to the number of gas types. Each cluster has similar gases and therefore has the same Henry's constant value (H_j).

-Step 3: Evaluation.

Each cluster j is evaluated to identify the best gas that achieves the highest equilibrium state from the others in its type. Then, the gases are ranked to obtain the optimal gas in the entire swarm.

-Step 4: Update Henry's coefficient.

Henry's coefficient is updated according to the following equation

$$H_j(t+1) = H_j(t) \times \exp(-C_j \times (1/T(t) - 1/T^{\theta})) \quad (18)$$

$$T(t) = exp(-t/iter) \quad (19)$$

Where H_j is the Henry's coefficient for cluster j, T is the temperature, T^{θ} is a constant and equal to 298.15 and iter is the total number of iterations.

-Step 5: Update solubility.

The solubility is updated according to the following equation:

$$S_{i,j}(t) = K \times H_j(t+1) \times P_{i,j}(t) \quad (20)$$

$$S_{i,j}(t) = K \times H_j(t+1) \times P_{i,j}(t) \quad (21)$$

Where $S_{i,j}$ is the solubility of gas i in cluster j and $P_{i,j}$ is the partial pressure on gas i in cluster j and K is a constant.

-Step 6: Update position. The position is updated as follows:

$$X_{i,j}(t+1) = X_{i,j}(t) + \text{F} \times \text{r} \times \gamma \times (X_{i,best}(t) - X_{i,j}(t)) + \text{F} \times \text{r} \times \alpha \times (S_{i,j}(t) \times X_{best}(t) - X_{i,j}(t)) \quad (22)$$

$$\gamma = \beta \times \exp\left(-F_{best}(t) + \varepsilon F_{i,j}(\text{t}) + \varepsilon\right) \quad (23)$$

$$\varepsilon = 0.05$$

Where the position of gas i in cluster j is denoted as $X_{(i,j)}$, and r and t are a random constant and the iteration time, respectively. $X_{(i,best)}$ is the best gas i in cluster j, whereas X_{best} is the best gas in the swarm. Additionally, γ is the ability of gas j in cluster i to interact with the gases in its cluster, α is the influence of other gases on gas i in cluster j and equal to 1 and β is a constant. $F_{i,j}$ is the fitness of gas i in cluster j, in contrast F_{best} is the fitness of the best gas in the entire system. F is the flag that changes the direction of the search agent and provides diversity $= \pm$.

$X_{(i,best)}$and X_{best} are the two parameters responsible for balancing the exploration and exploitation abilities. Specifically, $X_{(i,best)}$ is the best gas i in cluster j, and $X_{best}$is the best gas in the swarm.

-Step 7: Escape from local optimum.

This step is used to escape from local optimum. Rank and select number of worst agents (N_{ω}) using the following Equation:

$$N_{\omega} = N \times (\text{rand}(C_2 - C_1) + C_1) \quad (24)$$

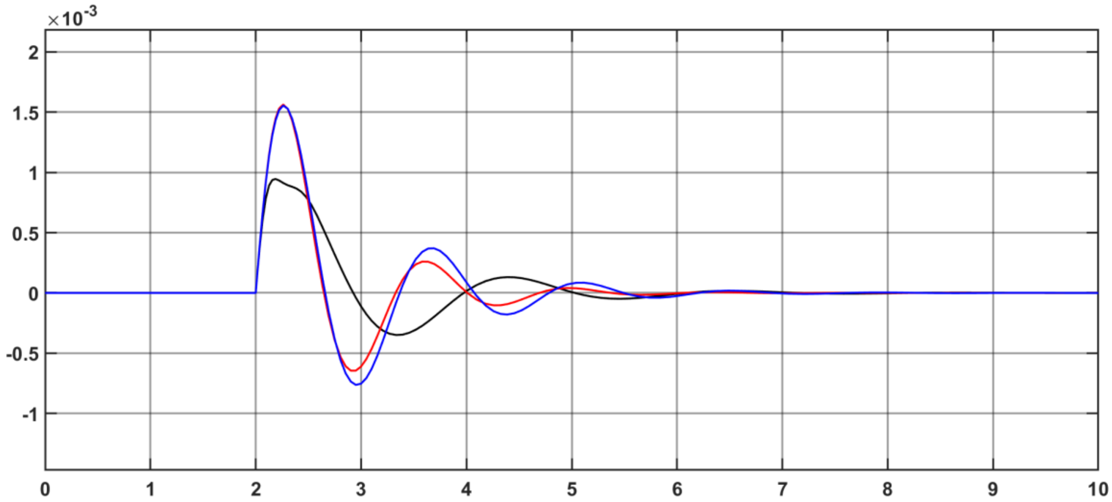
$$C_1 = 0.1, C_2 = 0.2$$

Where N is the number of search agents.

- Step 8: Update the position of the worst agents.

$$G_{(i,j)} = G_{min(i,j)} + r \times (G_{max(i,j)} - G_{min(i,j)}) \quad (25)$$

Where, $G_{(i,j)}$ is the position of gas i in cluster j, r is a random number and G_{min}, G_{max} are the bounds of the problem. Eventually, the pseudo-code of the proposed algorithm is presented in Algorithm 1, including the initial population size, population evaluation, and updating parameters.



______Based on Henry ______Based on GWO ______Based on ALO

Fig. 8 Dynamic Performance of SVC based PID controller using HGSO, GWO and ALO

4. Results and Discussion

Table 1 shows the values of the PID gains for each applied optimization algorithms with lower bound (lb=0) and upper bound (ub=15).

Table 1 PID controller parameters based HGSO, GWO and ALO optimizer

variables	HGSO	GWO	ALO
Kp	15	15	10
Ki	15	0	8.8901
Kd	15	3.4207	3.976
J-obj.	0.0028	0.003	0.0038

From the table it was obtained that the best optimization method is HGSO which present low value of J-obj. and its results are better than the others methods (GWO and ALO).

J-obj is the "Integral Time Absolute Error"

$$\text{J-obj} = \int_0^t |\omega| . \text{t}. \text{dt} \quad (26)$$

When the optimization was running between the three methods at time t=10 second the results show that the HGSO optimization is better than GWO and ALO, as shown in Fig. 8. So that the coming graph will show that difference clearly.

So that the proposed optimization algorithm Henry Gas Solubility Optimization (HGSO) provide better performance.

4. 1 PID with SVC

SVCs are part of the Flexible AC Transmission System devices (FACTS) family which regulating voltage, power factor, harmonics and the system stability. It is a set of electrical devices for providing fast-acting reactive power on high-voltage electricity transmission networks which are connected in shunt with the system. Although designed to support bus voltage by controlling reactive power, SVC is also capable of improving the angle stability of the system.
Static Var Compensator (SVC) is one of FACTS devices that in this part the SVC will be applied with the PID controller as shown in fig.4 to enhance the stability for the SMIB and optimize the PID's gains with the SVC's parameters (K_p, K_i, K_d, $K_c$and T_c) by using the HGSO algorithm to obtain the most suitable values for them with best J-obj value.

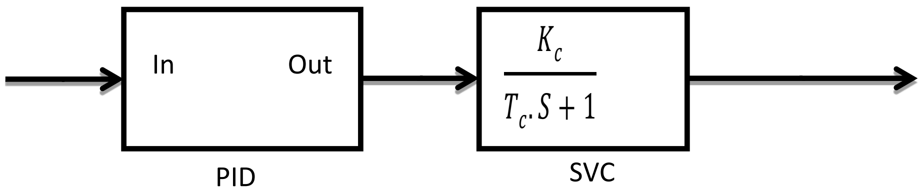


Fig.9 PID controller with the SVC modeling [53]

Table 2 show the results from the optimization for all variables together by HGSO algorithm with lower bound (lb=0) and upper bound (ub=15) and 100 iteration

Table 2 Optimized PID controller parameters with SVC parameters

Variables / controller	K_p	K_i	K_d	K_c	T_c	J-obj
PID	15	15	15	______	______	0.0028
PID with SVC	9.2144	14.4086	0.8612	12.6046	0.0254	8.4794 e^{-4}

Using the suggested optimized parameters and comparing them it is seen that the PID controller with SVC, it is evident that they provide more stability than the PID only.

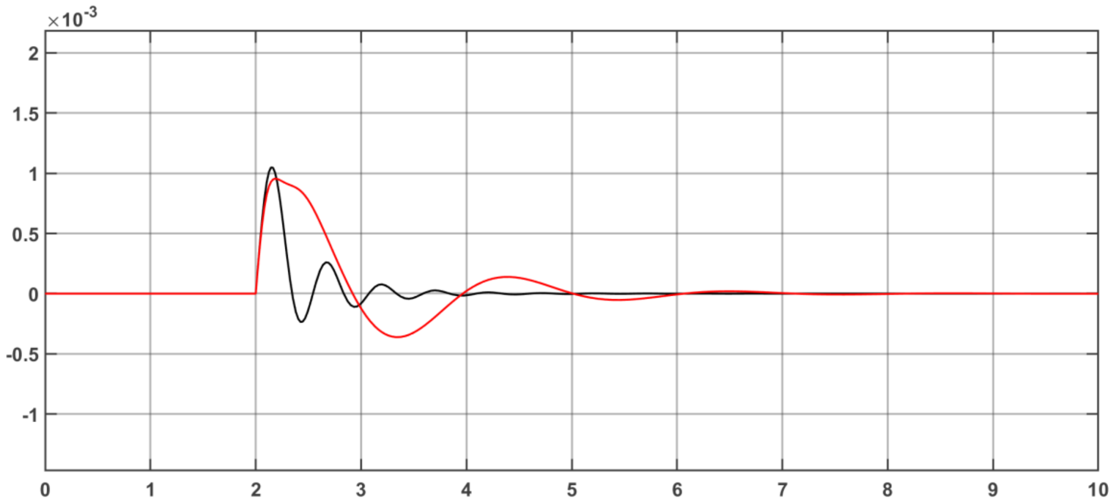
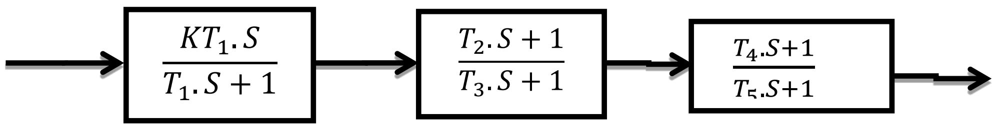


Fig. 9 SMIB Dynamic performance of with different opt. technique based SVC with S.C. fault

__________PID with SVC based on Henry ________PID based on Henry

It is clear that implementing the optimized parameters in compared with conventional value, the optimized provide better response. .

The main objective of the PSS is to provide an additional damping torque in order to improve the stability of the power system. In fact, the PSS must produce an electrical torque component in phase with the variation of rotor speed. In this way, it allows to improve and expand the limits of the system stability by reducing the variations of power introduced by the generator rotor speed oscillations. It is clear from Fig. 9 that, the PID controller with SVC gives more stability than the PID only or PSS. Table 3 shows the PSS parameters.

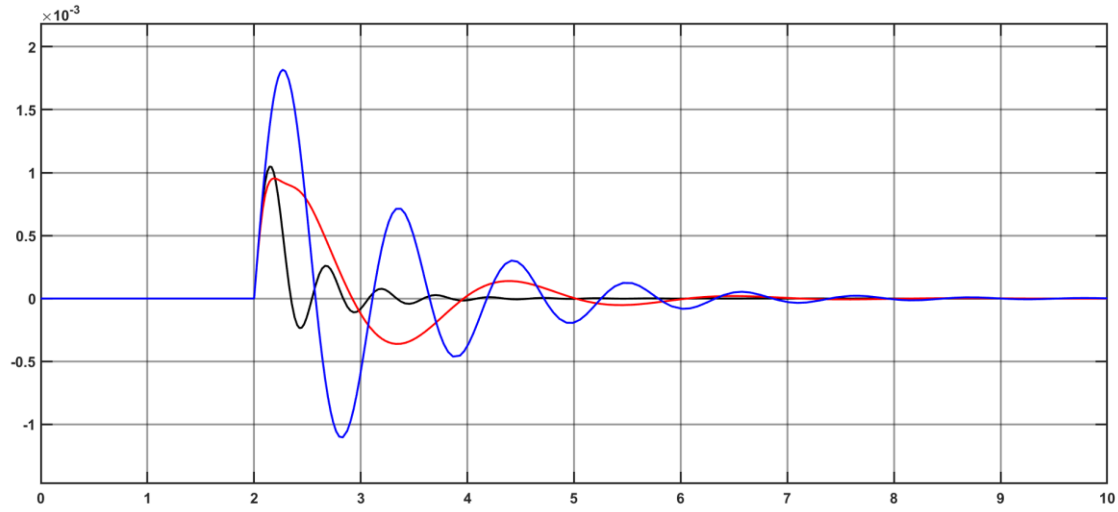


Power System Stabilizer

Fig.10 Power system stabilizer in time domain [54]

Table 3 PSS parameters

parameter	K	T1	T2	T3	T4	T5
value	20	10	0.15	0.05	0.05	0.15



PID &SVC PID PSS

Fig. 10 Dynamic response of SMIB with Optimized PID based SVC, PSS, and conventional PSS

From Fig. 10 it is clear that the HGSO algorithm is better than the other optimization algorithms (GWO &ALO) which gives the best value of J-obj. It is clearly that the performance of the PID with SVC is more stable than the performance of the PID controller only and that is the goal of using the FACTs devices.

6. The conclusions

In this paper the major aim is to get the effect of the FACTs devices (SVC) in the stability of the SMIB system so at first we compare between three optimization algorithms (HGSO &GWO &ALO) on the PID controller only and then we applied the best one (from the results) which was HGSO in the PID's with the SVC's variables together(K_p, K_i, K_d, $K_c$and T_c) to obtain the best values for them with the smallest J-obj value which means more and faster stability than without the SVC and here the importance of applying the FACTS devices (SVC) appeared . After that the comparison between PID with and without SVC and PSS was done.
So the most stability was obtained by PID with SVC and all the above graphs showed that.

The values of the model's parameters are

parameter	value	parameter	value
D	4.4000	T_{D0}	7.6700
H	4.6300	ω_b	377
K_1	0.5758	X_D	0.9730
K_2	0.9738	X_{D1}	0.1900
K_3	0.6584	X_e	0.9970
K_4	0.5266	X_Q	0.5500
K_5	-0.0494		
K_6	0.8450		

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