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Optimal Tuning of SVC-PI Controller using Whale Optimization Algorithm for Angle Stability Improvement

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Article Info	ABSTRACT
	This paper proposed a new swarm-based optimization technique for tuning conventional proportional-integral (PI) controller parameters of a static var compensator (SVC) which controls a synchronous generator in a single machine infinite bus (SMIB) system. As one of the Flexible Alternating Current Transmission Systems (FACTS) devices, SVC is designed and implemented to improve the damping of a synchronous generator. In this study, two parameters of PI controller namely proportional gain, KP and integral gain, KI are tuned with a new optimization method called Whale Optimization Algorithm (WOA). This technique mimics the social behavior of humpback whales which is characterized by their bubble-net hunting strategy in order to enhance the quality of the solution. Validation with respect to damping ratio and eigenvalues determination confirmed that the proposed technique is more efficient than Evolutionary Programming (EP) and Artificial Immune System (AIS) in improving the angle stability of the system. Comparison between WOA, EP and AIS optimization techniques showed that the proposed computation approach gives better solution and faster computation time.

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1. INTRODUCTION

The excitation control of generators is among the important topics in the field of power system. Flexible Alternating Current Transmission Systems (FACTS) technologies have been used widely for power systems applications [1, 2], by providing better power control and improving system flexibility and performances. Static Var Compensator (SVC) is one of FACTS devices that is connected in shunt with the system. It is a combination of a delta connected Thyristor Controlled Reactor (TCR) along with a fixed capacitor (TCRFC) in parallel with the load through a regulating transformer for controlling the bus voltage across the bus [3]. It provides a smooth, fast and precise regulation of terminal voltage. Over the last decades, many techniques have been proposed for the damping controllers for SVC to improve the damping of synchronous machines oscillations mode, by means of the lead lag controllers [4], proportional-integral (PI) controllers [5] and proportional-integral-derivative (PID) controllers [6]. In this study, PI which is one of the leading types of controllers is selected. PI calculates the error between the measured and the desired variables and tries to minimize the error by adjusting the input parameter. With the combination of SVC and PI controllers (SVC-PI), it can serve as an alternative equipment to improve angle stability and the damping performance for the power systems. For tuning the SVC-PI, two variables: proportional gain, K_P and interval gain, K_I are need to be optimized.

Optimization approaches are frequently chosen to tune variables of devices in solving power system stability problems. Among them are Evolutionary Programming (EP) [7] and Artificial Immune System (AIS) [8]. EP used biological evolution process in searching for an optimal solution. On the other hand, AIS tries to benefit from the characteristics of a human immune system. A new nature-inspired meta-heuristic optimization algorithm called Whale Optimization Algorithm (WOA) is proposed [9]. This method mimics the social behavior of humpback whales which is characterized by their unique method of hunting known as the bubble-net feeding method. It brought better performance than EP and AIS in calculating the optimal solution.

This paper presents an efficient technique to determine the optimal parameters of SVC-PI damping controller in solving angle stability problems. Both K_P and K_I variables are determined using WOA and it was compared with EP and AIS optimization methods. The objective is to produce the most stabilized technique in the shortest time.

2. PROBLEM FORMULATION

In this study, the Phillips-Heffron block diagram model for the single machine infinite bus (SMIB) system that equipped with SVC and PI controller (SVC-PI) is considered. The concept of SMIB is equivalent with one synchronous machine connected to one big bus with infinite load. The input of SVC-PI is fed from the speed deviation $\Delta\omega_r$ and the output then channelled to $\Delta\sigma$. The block diagram model of SMIB with SVC-PI is shown in Figure 1.
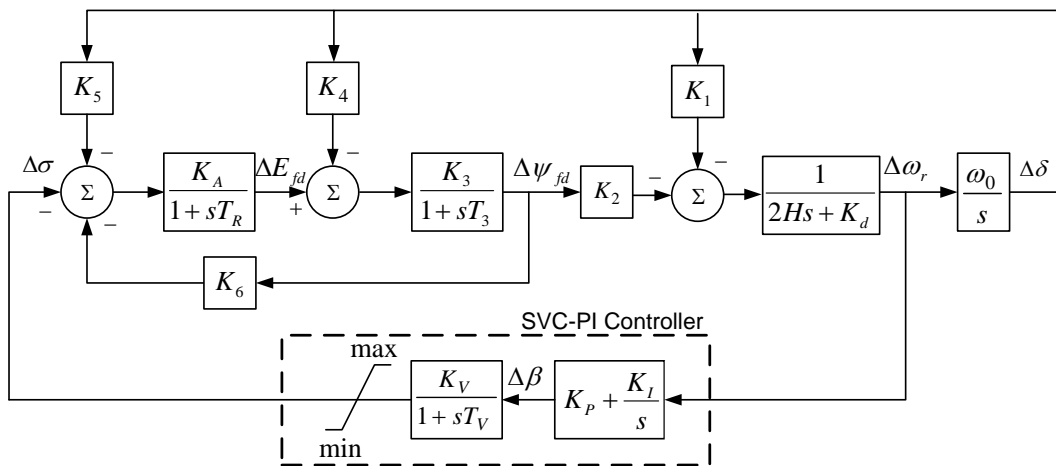

Figure 1. The block diagram model of SMIB with SVC-PI

SVC-PI can be segregated to SVC component and PI component. SVC component consists of circuit and time constant, K_V and T_V. The PI component is derived from proportional and integral gain of the PI controller which simplified respectively as K_P and K_I.

The equations represent SMIB system installed with SVC-PI are as followed:

$$\frac{\Delta\omega_r}{\Delta t} = \frac{\Delta T_m - K_1\Delta\delta - K_d\Delta\omega_r - K_2\Delta E_q}{2H} \tag{1}$$

$$\frac{\Delta\delta}{\Delta t} = \omega_0\Delta\omega_r \tag{2}$$

$$\frac{\Delta E_q}{\Delta t} = -\frac{K_3 K_4\Delta\delta + \Delta E_q - K_3\Delta v_f}{T_K} \tag{3}$$

$$\frac{\Delta v_f}{\Delta t} = -\frac{K_R K_5\Delta\delta + K_R K_6\Delta E_q + \Delta v_f}{T_R} \tag{4}$$

$$\frac{\Delta\sigma}{\Delta t} = -\frac{\Delta\sigma - K_V\Delta\beta}{T_V} \tag{5}$$

$$\frac{\Delta \beta}{\Delta t} = \left(K_1 + \frac{K_d K_P}{2H}\right)\Delta\omega_r - \frac{K_1 K_P}{2H}\Delta\delta + \frac{K_2 K_P}{2H}\Delta E_q \tag{6}$$

H is the inertia constant, T_m is the mechanical torque, K_D is the damping torque coefficient, K_R and T_R are the circuit constant and time constant of the exciter oscillation system, respectively. ω_0 is equal to $2\pi f_0$. The K constants i.e. K_1, K_2, K_3, K_4, K_5, K_6 and T_K are represented the dynamic characteristics of the system model. Detail calculation of parameters K_1, K_2, K_3, K_4, K_5 and K_6 can be found in [10].

The equation (1) – (6) are then combined to create a matrix form as followed:

$$\dot{X}_{SVC} = A_{SVC} \cdot X_{SVC} + B_{SVC} \cdot U \tag{7}$$

Where

$$X_{SVC} = [\Delta\omega_r \quad \Delta\delta \quad \Delta E_q \quad \Delta v_f \quad \Delta\sigma \quad \Delta\beta]^T \tag{8}$$

$$A_{SVC} = \begin{bmatrix} -K_d/2H & -K_1/2H & -K_2/2H & 0 & 0 & 0 \\ \omega_0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -K_3 K_4/T_K & -1/T_K & K_3/T_K & 0 & 0 \\ 0 & -K_R K_5/T_R & -K_R K_6/T_R & -1/T_R & 0 & 0 \\ 0 & 0 & 0 & 0 & -1/T_V & -K_V/T_V \\ K_I - K_P K_d/2H & -K_P K_1/2H & -K_P K_2/2H & 0 & 0 & 0 \end{bmatrix} \tag{9}$$

$$B_{SVC} = [1/2H \quad 0 \quad 0 \quad 0 \quad 0 \quad 0]^T \tag{10}$$

$$U = [\Delta T_m] \tag{11}$$

Here, A and B are matrices of real constants and variables with appropriate dimensions. X and U are the state vector and input signal vectors, respectively.

In this paper, the value of proportional gain, K_P and integral gain K_I of the PI controller are kept within specified limits. The WOA algorithm is proposed to calculate the optimal value of these two SVC-PI parameters. The SMIB systems parameters are shown in Table 1.

Table 1. The Parameters for SMIB and SVC System.

Components	List of Parameters
Generator	$H = 2.0$, $T_{d0}^{'} = 8.0$, $X_d = 1.81$, $X_q = 1.76$, $X_d^{'} = 0.30$, $R_a = 0.003$, $K_{sd} = K_{sq} = 0.8491$, $E_t = 1.0 \angle$ -36°
Transmission Line	$R_e = 0.0$, $X_e = 0.65$, $X_L = 0.16$
Exciter and SVC	$K_A = 100$, $T_A = 0.05$, $K_V = 10$, $T_V = 0.05$

3.   COMPUTATIONAL INTELLIGENCE METHODS

Lately, the use of Artificial Intelligence (AI) technology is synonymous in solving power system problems. AI techniques utilize the logic and knowledge representations of expert systems, artificial neural network (ANN) [11] and evolutionary computation (EC). The EC field includes Particle Swarm Optimization (PSO) [12], Evolutionary Programming (EP) [7], Artificial Immune Systems (AIS) [8] and Firefly Algorithm (FA) [13]. In this study, the proposed WOA is compared with EP and AIS in order to highlight their merit. The algorithms for all methods are discussed below.

3.1 Whale Optimization Algorithm

Whale Optimization Algorithm (WOA) is a novel nature-inspired meta-heuristic optimization algorithm proposed by Seyedali Mirjalili and Andrew Lewis in 2016, which mimics the social behavior of humpback whales. The humpback whales dive deeply, create bubbles in a spiral shape around the prey, and swim to the surface during the manoeuvre. They usually attack the small fishes close to the surface. Based on this behavior, the modelling of WOA can be divided into three operators: the search for prey (exploration phase), the encircling prey, and the bubble-net foraging (exploitation phase). In this paper, the WOA works as follows:

a) Step 1 (Initialization): The whale position x_i of *N solution* ($i=1,...,N$) are randomly created to form initial whale population. Each whale is evaluated using the objective function *J*. In this initialization process, J_i

is set as personal best objective function $J_{i,p}$ for ith whale. The maximum objective function of all whales J_{max} is set as best objective function J_{best} and the whale position at J_{best} is set as best position x_{best}.

b) Step 2 (Update positions): x_i is updated when the following conditions are met:

   1) If $p < 0.5$ and $|A| < 1$, update the current whale position x_i by the following equation:

$$x_i(j) = x_{best} + A \cdot \left(C \cdot x_{best} - x_i(j-1) \right) \tag{12}$$

   where A is the inertia weight, p and C are both random functions in the range [0,1]. This phase is called encircling prey. In this phase, WOA assumes that the current best position x_{best} is the target prey or close to the optimum.

   2) If $p < 0.5$ and $|A| > 1$, search random position for the current whale position x_i by the following equation:

$$x_i(j) = x_{rand} + A \cdot \left(C \cdot x_{rand} - x_i(j-1) \right) \tag{13}$$

   This phase is called exploration phase. In this phase, the search agents are forced to move far away from the best whale position.

   3) If $p > 0.5$, update the current whale position xi by the following equation:

$$x_i(j) = x_{best} + e^{bl} \cdot cos(2\pi l) \cdot \left(C \cdot x_{best} - x_i(j-1) \right) \tag{14}$$

   *where b is a constant, l is a random number in $[-1,1]$. This phase is called exploitation phase. This equation is created between the position of whale and prey to mimic the helix-shaped movement of humpback whales.

c) Step 3 (Calculate objective functions): The new J, J_{max} and the minimum objective function of all whales J_{min} are calculated.

d) Step 4 (Stopping criteria): The search process will be terminated if it reaches the maximum number of iterations or the value of (J_{max} - J_{min}) is very close to 0. If the process is not terminated, the iteration will be set to $j=j+1$ and algorithm will start again from Step 2.

     The overall process of WOA algorithm is illustrated in the form of flowchart, as shown in Figure 2.
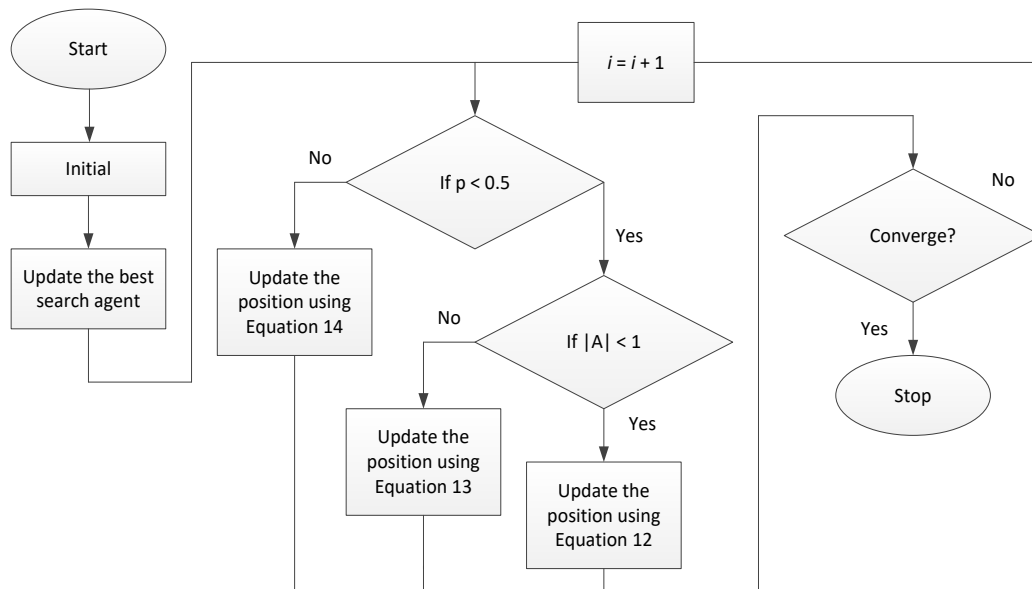

Figure 2. Flowchart for the Whale Optimization Algorithm (WOA)

3.2 Evolutionary Programming

     The Evolutionary Programming (EP) uses the model of biological evolutionary process to determine the solution for nonlinear engineering problems. This searching process of desirable solution is based on the

natural biological evolution. The process of EP algorithm includes initialization, statistical evaluation, fitness calculation, mutation, combination and selection. Further details about this technique can be found in [7].

3.3 Artificial Immune System

Artificial Immune System (AIS) and EP share many common aspects of optimization techniques. EP is based on the natural evolution model, while AIS tries to benefit from the characteristics of a human immune system. Basic algorithm for AIS-based optimization is called the Clonal Selection Algorithm (CSA). The algorithm of AIS that involved are initialization, statistical evaluation, fitness calculation, mutation, combination, selection and one extra component, namely cloning. The flow chart which represents AIS algorithm can be found in [8].

3.4 Fitness Equation

The implementation of SVC-PI in the SMIB system is capable to improve the oscillations damping and minimize the power angle deviation after a disturbance. In this paper, a fitness equation based on the minimum damping ratio ξ_{min} is proposed as follows [14]:

$$J = \xi_{min} = min\left(-\frac{\sigma_i}{\sqrt{\sigma_i^2 + \omega_i^2}}\right), \ \xi_i \in \xi_{EM} \tag{15}$$

where, ξ_i is the damping ratio of the ith electromechanical modes of oscillation, respectively. ξ_{EM} is the set of damping ratios of the electromechanical modes of oscillation. σ_i and ω_i are the real and imaginary part of the ith eigenvalue at the loading condition, respectively.

With the optimization of ξ_{min}, the system poles are consistently pushed further left of the imaginary ($j\omega$) axis. Also, the decreasing value of imaginary part of the eigenvalue ω will shift eigenvalue region towards the real axis. The area of eigenvalues on the phase plan for comparison case between system with and without proposed approach is shown in Figure 3. The area bounded by this effect can be shown as a trapezoid-shaped sector on the phase plan.
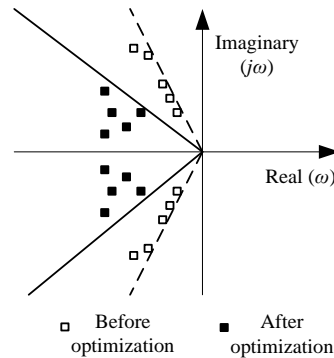

Figure 3. Comparison of eigenvalue areas on the complex s-plane (with and without J).

Therefore, the design problem can be formulated as:

Maximize J

This is subject to:

$$K_P{}^{max} \leq K_P \leq K_P{}^{min},$$

$$K_I{}^{max} \leq K_I \leq K_I{}^{min}$$

Here, K_P and K_I are optimized by EP, AIS and WOA approach. The fitness values and parameters involved in these three techniques are tabulated in Table 2.

Table 2. The Parameters for AIS, EP and WOA Algorithms

Methods	AIS	EP	WOA
List of Parameters	β_{ais}=0.05	β_{ep}=0.05	$A = 0.9, b = 1$

4.   RESULTS AND DISCUSSION

In this paper, simulation studies of SVC-PI based SMIB power system are carried out in MATLAB environment. Two parameters: proportional gain K_P and integral gain K_I are optimized until maximum value of the fitness equation J is defined.

In this study, the performance of system with conventional SVC-PI system (C-PI) is compared to SVC-PI system optimized by WOA (WOA-PI), SVC-PI system optimized by EP (EP-PI) and SVC-PI system optimized by AIS (AIS-PI). Following two different loading conditions are simulated:
a)   Case 1 (P = 0.35 p.u., Q = 0.7 p.u.)
b)   Case 2 (P = 0.15 p.u., Q = 0.3 p.u.)

The response of speed deviation for Case 1 is shown in Figure 4. The system with C-PI is poorly damped and becomes stable for more than 3 seconds. For EP-PI, AIS-PI and WOA-PI, all three systems are improving the damping capability. From the speed response, its shows that WOA-PI manage to deliver the fastest and smoothest damping performance, followed by EP-PI and AIS-PI.
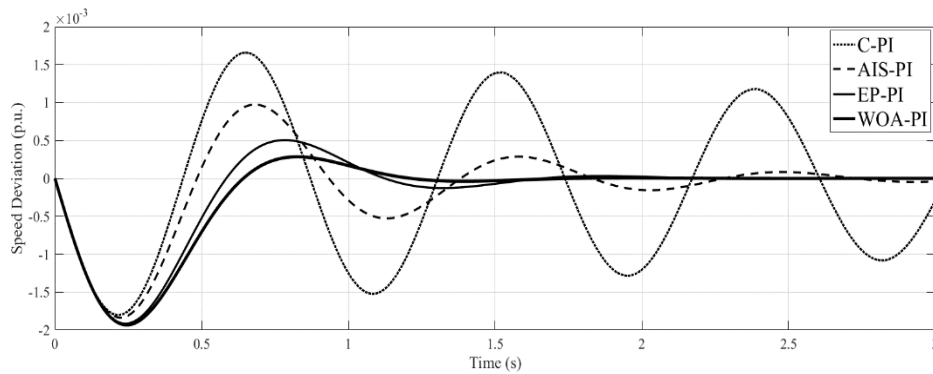

Figure 4. Speed response for Case 1

The regions of eigenvalues location in complex s-plane for all four techniques in Case 1 are shown in Figure 5. It indicates that WOA method is more capable to improve the stability of the system by pushing the eigenvalues location far further to the left-hand side of the complex s-plane and closer to the real, σ axis. It also shows that C-PI have two eigenvalues that place near to the left-hand side of the $j\omega$ axis, indicate that the system is the most less stable.
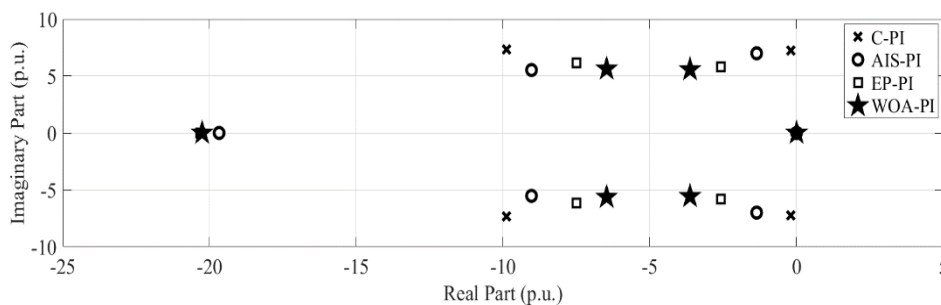

Figure 5. Complex s-plane for Case 1

The results of fitness profiles (which based on minimum damping ratio ξ_{min}), number of iteration N_i and computation time using C-PI, AIS-PI, EP-PI and WOA-PI for Case 1 are tabulated in Table 3. From the results, WOA-PI optimized the highest value of J followed by EP-PI, AIS-PI and C-PI. From the iteration

perspective, AIS is terminated in the shortest iteration, which is 4 iterations, followed by WOA with 12 iterations, while the EP was stopped at iteration 22. This shows that AIS give the shortest computation time compared to WOA and EP. Even though slower than AIS in computation time, WOA still the best approach, as it gives far more good result in improving damping capability of the system.

Table 3. Comparison of C-PI, AIS-PI, EP-PI and WOA-PI System for Case 1

Type	K_P	K_I	$J (\xi_{min})$	N_i
C-PI	0.5	3.0	0.0272	-
AIS-PI	0.6121	16.8865	0.1908	4
EP-PI	1.5090	25.1941	0.4031	14
WOA-PI	1.6003	28.0343	0.5462	12

The response of speed deviation for Case 2 is shown in Figure 6. Here also, the proposed WOA-PI system shows lower oscillation and better damping compared to other four techniques. The regions of eigenvalues location in complex s-plane for Case 2 as shown in Figure 7. From the results, WOA is the most sufficient approach in shifting the eigenvalues towards σ axis, as well as further to the left-hand side of $j\omega$ axis at the loading condition compared to other three techniques. Table 4 tabulates the results for comparative studies using C-PI, AIS-PI, EP-PI and WOA-PI for Case 2. Results obtained shows that WOA-PI achieve higher fitness compared to other three techniques.
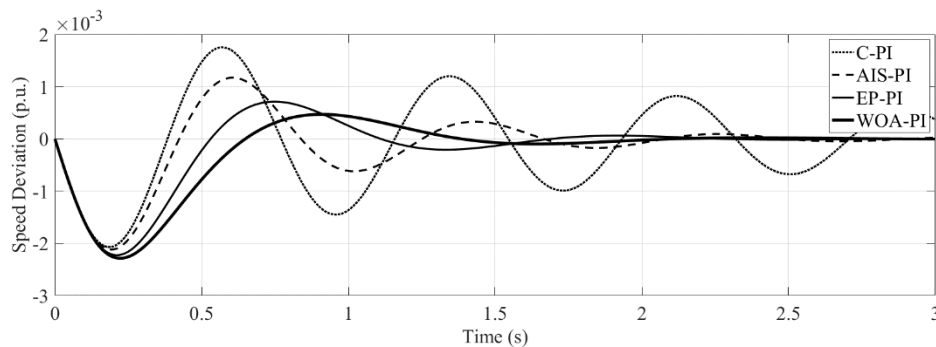

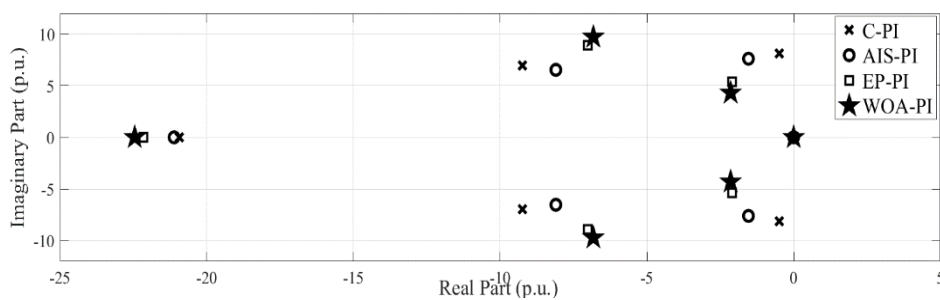Figure 6. Speed response for Case 2

Figure 7. Complex s-plane for Case 2

Table 4. Comparison of C-PI, AIS-PI, EP-PI and WOA-PI System for Case 2

Type	K_P	K_I	$J (\xi_{min})$	N_i
C-PI	0.5	3.0	0.0604	-
AIS-PI	0.8119	7.8797	0.1987	5
EP-PI	1.5673	12.1472	0.3629	15
WOA-PI	1.8573	14.472	0.4472	10

5.   CONCLUSION

This paper proposed a new optimization approach for tuning SVC with PI controller. Three methods based on AIS, EP and WOA computation intelligence methods for optimizing K_P and K_I of PI controller have

been developed. Results obtained from the study show that WOA outperformed EP and AIS in terms of giving better damping and lower oscillation. The performances are validated with respect to speed deviation response as well as minimum damping ratio ξ_{min} and eigenvalues.

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