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Chaos Embedded Symbiotic Organisms Search Technique for Optimal FACTS Device Allocation for Voltage Profile and Security Improvement

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Abstract

Due to the ever-increasing energy demand, power system operators have attempted to cope with these demands while keeping the power system remain operable. Economic constraints have forced the power system operator to abandon their effort in expanding the power system. The increased load demand can cause the power system to suffer from voltage instability and voltage collapse, especially during contingency condition. Hence, a strategy is required to maintain the steady state operation of a power system. Various research has been conducted to tackle this problem. Therefore, this paper presents the implementation of Chaos Embedded Symbiotic Organisms Search technique to solve optimal FACTS device allocation problem in power transmission system. Various practical constraints are also considered in the optimisation process to emulate the real-life constraints in power system. The optimisation process is conducted on a 26-bus IEEE RTS has validated that the results obtained has not violated the power system stability. The results provided by the proposed optimisation technique has successfully improved the voltage profile and voltage security in the system. Comparative studies are also conducted involving Particle Swarm Optimization and Evolutionary Programming technique resulting good results agreement and superiority of the proposed technique. Results obtained from this study would be beneficial to the power system operators regarding optimisation in power system operation for the implementation in real power transmission network.

***Keywords**: Chaos Embedded Symbiotic Organisms Search, Static VAr Compensator, Thyristor Controlled Series Compensator, Voltage Deviation Index, Fast Voltage Stability Index*

1. Introduction

In recent years, power system operator has implemented various methods to keep the power system stable and secure. However, power systems are constantly at risk of instability due to various reasons such as load demand changes and contingency conditions. An increase in load demand can cause the voltage to reduce until it reaches its voltage collapse point. A voltage collapse is defined as reduction of voltage in a power system due to heavy loading which then causes blackout. Voltage collapse then causes disturbance of electrical power transmission and threat to the power system security. Overloading of a transmission line in a power system can also pose a threat on the security of power system. High loading of transmission lines can cause heating which increases the power losses as well as risk of damage to the line [1]. To cope with the increasing load demand, power system operator can opt to increase the power generation capacity by installing more generation unit in a power system or expand the network by installing more transmission lines. However, installing more generation unit or transmission lines are not favoured by the power system operator due to high investment cost and location restrictions [2]. Installation of compensation device can provide support to a power system, hence improving the stability and security of the power system.

Flexible AC Transmission System (FACTS) devices have been widely installed as compensation devices in power system operation. Static VAr Compensator (SVC) and Thyristor Controlled Series Compensator (TCSC) are some examples of FACTS devices which can be installed in a power system to provide support and compensation to the system. Conventionally,

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capacitor banks are used to provide reactive power support. On the other hand, SVC is capable to supply or draw reactive power discretely; while, TCSC allows the power system operator to control the power flow of a transmission line since it can modify the reactance of a transmission line by acting as an inductive or capacitive compensation device [3]. Various studies have been conducted on optimal placement of FACTS devices in a power system to achieve various goals such as minimizing the total power loss in a power system, improvement of voltage profile, optimal power flow, maximization of available transfer capacity. Particle Swarm Optimization (PSO) technique has been widely implemented to solve problems on optimal FACTS devices placement such power loss reduction [4], voltage profile improvement [5], maximisation of loading margin and combinations of all problems [6]. Various other techniques have been implemented to solve optimal FACTS device allocation such as Genetic Algorithm (GA) [7], Teaching Learning Based Optimization (TLBO) [8], Harmony Search (HS) Algorithm [9], Evolutionary Programming (EP) [10], Differential Evolution (DE) [11] and Cat Swarm Optimization (CSO) [12].

Despite of the implementation of various optimisation techniques, each of the technique imposes serious drawbacks which reduces the quality of the final solution. To overcome the problem, this paper presents the application of Chaos Embedded Symbiotic Organisms Search (CSOS) technique to solve optimal FACTS devices allocation in a transmission system to improve the voltage profile and voltage security in the system. The voltage profile in the system is observed through the value of total voltage deviation index in the system while the voltage security is observed using a voltage stability index known as Fast Voltage Stability Index (FVSI). The main objective of this research is to improve the voltage profile through minimization of voltage deviation index and improvement of voltage security via minimization of the worst FVSI value. Comparative studies are also conducted with EP and PSO, highlighting the superiority of CSOS in term of solution quality provided by the optimisation algorithm.

2. Research Method

To solve the problems stated as in section 1, CSOS technique is applied to obtain the optimal FACTS device allocation which are SVC sizing and TCSC compensation ratio to be implemented in a power system. The detail of the problems related to the optimisation process such as objective function and the constraints imposed are discussed in section 2.1 while brief explanation about the CSOS technique is discussed in section 2.2.

2.1. Problem Formulation

The goal of this research is to implement CSOS technique for solving the optimal SVC and TCSC allocation in a transmission system. The objective of the optimisation technique is to solve minimization of multi-objective problems related to voltage profile and voltage security issue. The first objective of the optimisation is to improve the voltage profile of the system by minimising the total voltage deviation index (VDI) of the system. The fitness function of VDI is represented by:

$$f_1 = VDI = \sum_{i=1}^{N_b} \left(\frac{V_{ref,i} - V_i}{V_{ref,i}} \right)^2 \quad (1)$$

Where *VDI* is the total voltage deviation index of the buses in the system. In [13], *VDI* is only considered at load buses. Therefore, voltage deviation at buses other than load buses are excluded from the total *VDI*. Reference value of bus voltage in the system is set to unity. In this study, the reference value of load buses is set to 1.00 p.u. while reference value of slack bus and generator buses are set at their voltage setpoint as in the power flow algorithm.

The second objective of the optimisation process is to improve the voltage security of the system. To assess the voltage security of the power system, voltage stability index can be implemented. In this research, the voltage stability index used is Fast Voltage Stability Index (*FVSI*) developed by Musirin *et al*. [14]. To improve the voltage stability, the value of worst *FVSI* should be minimised. The worst refers to the highest *FVSI* value. Therefore, the fitness function for the second optimisation objective can be expressed by:

$$f_2 = FVSI_{max} = max\left(\frac{4Z^2Q_r}{V_s^2X}\right) \quad (2)$$

In this study, there are 2 optimisation objectives which needs to be considered. Normally, an optimisation process will cater only 1 objective. To cater all the stated objectives, multi-objective optimisation mode should be implemented. To solve multi-objective optimisation problem, weighted sum method is employed by combining all fitness functions and weighted using weighing factor. Therefore, the overall objective function can be represented as:

$$OF = min\big((w_1 \times f_1) + (w_2 \times f_2)\big) \quad (3)$$

In weighted sum method, sum of all weighing factor used should be equal to 1. Therefore, the sum of weighing factors is expressed as:

$$w_1 + w_2 = 1 \quad (4)$$

SVC is a device which is capable of feeding or drawing reactive power from a power system. In this paper, the SVC is modelled as an ideal negative reactive power load. Positive value of SVC rating indicates the reactive power being injected from SVC into the system while negative value of SVC rating indicated the reactive power drawn from the system. The sizing of SVC is limited by the capacity of the SVC and represented by:

$$Q_{SVC}^{min} \leq Q_{SVC} \leq Q_{SVC}^{max} \quad (5)$$

TCSC is a device which can modify its reactance to modify the reactance of the transmission line. In this paper, TCSC is modelled as the compensation ratio. Various literature has suggested that the value of TCSC compensation ratio should be maintained in the range of -0.8 up to 0.2 to avoid overcompensation problem. The range of TCSC compensation ratio can be expressed as:

$$\gamma_{TCSC}^{min} \leq \gamma_{TCSC} \leq \gamma_{TCSC}^{max} \quad (6)$$

To maintain acceptable voltage profile, all bus voltage should be maintained in between the permissible minimum and maximum voltage value. Under-voltage and over-voltage condition should be avoided since both conditions can cause harm to the power system. The permissible range of bus voltage value is represented as follows:

$$V_i^{min} \leq V_i \leq V_i^{max} \quad (7)$$

Various references have reported that the allowed deviation of bus voltage should be kept in the range at 10% above and below the rated bus voltage [13]. Therefore, the permissible bus voltage range used in this paper is 0.90 p.u. and 1.10 p.u.

2.2. Chaos Embedded Symbiotic Organisms Search

To solve optimal FACTS device allocation in a transmission system for voltage profile and voltage security improvement, CSOS has been implemented to obtain the optimal solution to the problem. CSOS was developed by S. Saha and V. Mukherjee in 2016 [15] to solve optimal placement and sizing of distributed generators in a radial distribution system. CSOS is developed based on novel SOS algorithm, which emulates the interaction of organism's reliance on other species in an ecosystem for its survival and sustenance. The detail process of CSOS in searching the optimal FACTS device allocation is summarized as follows:

Step 1: Initialization phase. In this phase, a set of variables consists of SVC sizing and TCSC compensation ratio are randomly generated as stated in (5) and (6). The generated value should allow the power flow solution to converge and yield lower fitness value compared to fitness value without the FACTS devices. In this study, 20 accepted organisms are considered as 1 ecosystem and used for the optimisation process.

Step 2: Best organism identification phase. During this phase, an organism with the minimal fitness value is chosen to be the best organism. Set *i* equal to 1.

Step 3: Mutualism phase. In this phase, i^{th} set of FACTS device rating X_i is chosen. Then, j^{th} set of FACTS device rating X_j is chosen randomly from the ecosystem where $j \neq i$. Both sets of the device rating are then modified based on their mutual relationship. Both modified FACTS device ratings are compared to their original FACTS device respectively in terms of their fitness value. Modified FACTS device rating replaces their original ratings if they have a better fitness value. The mutual relationship of the organisms is expressed as:

$$X_{i,new} = X_i + rand(0,1) \times (X_{best} - MV \times BF1) \quad (8)$$

$$X_{j,new} = X_j + rand(0,1) \times (X_{best} - MV \times BF2) \quad (9)$$

$$MV = \frac{X_i + X_j}{2} \quad (10)$$

where MV is the mutual vector, $X_{i,new}$ and $X_{j,new}$ are the new set of SVC sizing and TCSC compensation ratio produced from the mutual relationship. The *rand(0,1)* is defined as a random number ranged from 0 to 1, X_{best} is the best set of SVC sizing and TCSC compensation ratio which yield the best fitness value. *BF1* and *BF2* are the benefit factor which is an integer random number either 1 or 2.

Step 4: Commensalism phase. During this phase, i^{th} set of FACTS device rating X_i is chosen. Then, j^{th} set of FACTS device rating X_j is randomly chosen from the ecosystem which $j \neq i$. Then, X_i is then modified with the assistance of X_j using commensal symbiosis relationship. The modified X_i replaces the original X_i if the modified X_i provides better fitness value compared to the original X_i. Mathematical expression used to model the production of new X_i is stated as follow:

$$X_{i,new} = X_i + rand(-1,1) \times \left(X_{best} - X_j\right) \quad (11)$$

where $X_{i,new}$ is the modified set of FACTS device rating, *rand(-1,1)* is a random number in the range of -1 to 1, X_{best} is the best set of FACTS device rating which yield the best fitness value.

Step 5: Parasitism phase. In parasitism phase, i^{th} set of FACTS device rating X_i is chosen. Then, j^{th} set of FACTS device rating X_j is then randomly chosen from the ecosystem where $j \neq i$. Then, a parasite vector is created by duplicating X_i. Later, random dimension of the parasite is modified using random value of SVC sizing and/or TCSC compensation ratio. The fitness value of the parasite is then evaluated. If the parasite has a better fitness value X_j, then the parasite replaces X_j.

Step 6: Best organism identification. At this phase, the set of FACTS device rating with the best fitness value is chosen as the best organism. If all organisms have undergone step 3 until step 6, then proceed to step 7. Otherwise, increase *i* by 1 and go back to step 3.

Step 7: Chaotic local search phase. At this phase, chaotic local search (CLS) is initiated. To start CLS, a counter for CLS iteration counter is initialized and a chaotic variable is generated from a random number in the range of 0 to 1. It can be expressed as:

$$k = 1 \quad (12)$$

$$cu_k = rand(0,1) \quad (13)$$

Step 8: Chaotic variable update phase. During this phase, the chaotic variable is updated using Piecewise Linear Chaotic Map (PLCM). A control parameter *p* controls the updating process. Reference [16] suggested that the value of *p* can be chosen in the interval of $p \in [0,0.5]$. The PLCM can be mathematically expressed as:

$$cu_{k+1} = \begin{cases} \dfrac{cu_k}{p} & cu_k \in (0,p) \\ \dfrac{(1-cu_k)}{(1-p)} & cu_k \in (p,1) \end{cases} \quad (14)$$

Step 9: Chaotic variable mapping phase. The chaotic variable generated at step 8 is then mapped back to the best organism obtained from step 6. After the variable has been mapped, fitness value of the mapped variable is then computed. The variable mapping can be mathematically expressed as:

$$u_{k+1} = X_{best} + r(2cu_{k+1} - 1) \quad (15)$$

Step 10: If the mapped variable has a better fitness value compared to the fitness value of the best organism obtained from step 6, then replace the best organism with the mapped variable and go to next step. Otherwise, go back to step 8 until maximum CLS iteration counter is reached.

Step 11: Reduce the chaotic search space radius by a factor of random number in the range from 0 to 1, and it can be expressed as:

$$r = \delta \times r \quad (16)$$

$$\delta = rand(0,1) \quad (17)$$

Step 12: Convergence test. Check if the optimisation process has reached its maximum iteration. If not, go back to step 3. Otherwise, halt the optimisation process.

3. Results and Analysis

In this research, the proposed CSOS is tested on IEEE 26-bus Reliability Test System (RTS) to solve optimal FACTS device allocation problem in the effort to improve the voltage profile and voltage security of the test system. The test system comprises 6 generation units and 17 load centres. During the optimisation process, the number of organisms are set to 20 while the number of SVC and TCSC installed in the test system is set at 3 units. The maximum iteration of the optimisation process is limited at 100 iterations. To test the robustness of the optimisation technique, the optimisation problem is subjected to different case studies in effort to test whether the optimisation technique can successfully provide optimal solution in various power system operation conditions. Case studies considered in this research are listed as follows:

Case 1 : In this scenario, the power system is operating at its nominal condition. The test system is not subjected to any changes. This condition is known as base case condition.

Case 2 : In this scenario, the reactive power load at bus 18 is reduced to 10MVAr while keeping other parameters of the test system as in its base case condition. This condition is known as light-loading condition.

Case 3 : In this scenario, the reactive power load at bus 17 is increased to 100MVAr while keeping other parameters of the test system as in its base case condition. This condition is known as heavy-loading condition.

To observe the variation of results produced by the optimisation algorithm, each case study is executed for 20 times. Upon the completion of the execution, results are analysed. The analysed data consist of the fitness value which comprises the total voltage deviation index in the test system and the worst FVSI value in the system. To illustrate the effectiveness of CSOS in solving this problem, the problem is solved using PSO and EP with the similar case studies and the results obtained is compared with CSOS.

3.1. Base Case Condition

During this condition, the power system is operates at its nominal condition and no changes has been subjected to the power system. During this condition, SVC is installed at bus 24, 25 and 23 and the TCSCs are installed at transmission lines which connect bus 4 to bus 12, bus 4 to bus 8, and bus 3 to 13. The results obtained from the optimisation algorithm is then analysed and tabulated as in Table 1.

Table 1. Optimisation results during base case condition

Parameters	Technique	Results		
		Total V_{di}	Worst FVSI	Fitness value
Pre-optimized		0.00483	0.35376	0.17929
Best post-optimized	CSOS	0.00222	0.33861	**0.17042**
	PSO	0.00282	0.33896	0.17089
	EP	0.00196	0.34112	0.17154
Worst post-optimized	CSOS	0.00179	0.34040	**0.17109**
	PSO	0.00197	0.34219	0.17208
	EP	0.00199	0.34208	0.17203

Referring to Table 1, it can be observed that CSOS, PSO and EP were managing to solve the FACTS device allocation problem with CSOS providing higher solution quality compared to PSO and EP. After 20 executions of the optimisation process, the best results produced revealed that CSOS has performed better in solving the objective function compared to PSO and EP. However, while EP has achieved the lowest total V_{di}, it also yielded the highest worst FVSI value which indicates it can produce results which significantly improve the voltage profile of the system at the cost of its voltage stability index. The worst results yielded by the optimisation process indicates that CSOS has managed to produce better results compared to PSO and EP in terms of fitness value, total V_{di} and worst FVSI value. CSOS can improve the voltage profile and voltage stability better than other techniques although at is worst.

3.2. Light-Loading Condition

In this condition, the reactive power load at bus 18 of the test system is reduced to 10MVAr while maintaining other parameters as in its base case condition. The locations of SVC to be installed are bus 24, bus 25, and bus 23. At the same time, TCSCs were installed on transmission lines connecting bus 4 to bus 12, bus 4 to bus 8 and bus 3 to bus 13. The results obtained from the optimisation process are tabulated as in Table 2.

Table 2. Optimisation results during light-loading condition

Parameters	Technique	Results		
		Total V_{di}	Worst FVSI	Fitness value
Pre-optimized		0.00445	0.35258	0.17851
Best post-optimized	CSOS	0.00182	0.33945	**0.17064**
	PSO	0.00189	0.34024	0.17107
	EP	0.00289	0.34198	0.17244
Worst post-optimized	CSOS	0.00252	0.33975	**0.17113**
	PSO	0.00375	0.34137	0.17256
	EP	0.00289	0.34198	0.17244

Table 2 illustrates the results of the optimisation process during light-loading condition. From the results obtained, even though CSOS, PSO and EP can solve the optimal FACTS device allocation problem, CSOS has proven its superiority over PSO and EP in providing the best optimisation results by achieving the lowest fitness value with minimal total V_{di} and lowest worst FVSI value. The same scenario can be observed in the worst optimisation results yielded by the optimisation algorithms. Therefore, CSOS performs better than PSO and EP in solving optimal FACTS device allocation problem during light-loading condition.

3.3. Heavy-Loading Condition

During this case, the reactive power load at bus 17 was increased to 100MVAr while maintaining other parameters as in its base case condition. SVC is proposed to be installed at bus 17, bus 24, and bus 25. The TCSCs are installed at transmission lines connecting bus 4 to bus 12, bus 4 to bus 8 and bus 16 to bus 17. The optimisation results are tabulated as in Table 3.

Table 3. Optimisation results during heavy-loading condition

Parameters	Technique	Results		
		Total V_{di}	Worst FVSI	Fitness value
Pre-optimized		0.00772	0.35731	0.18251
Best post-optimized	CSOS	0.00154	0.33959	**0.17057**
	PSO	0.00170	0.34095	0.17132
	EP	0.00355	0.34176	0.17266
Worst post-optimized	CSOS	0.00168	0.34004	**0.17086**
	PSO	0.00330	0.34380	0.17355
	EP	0.00355	0.34176	0.17266

As seen in Table 3, CSOS managed to provide the highest quality solution among the best post-optimized results provided by CSOS, PSO and EP. CSOS has significantly improve the voltage profile of the system while improving the voltage stability by providing reactive power support on the heavily loaded bus. CSOS also managed to provide a better solution quality among the worst post-optimised results by having the lowest fitness value among other optimisation techniques. Therefore, CSOS capability to solve optimal FACTS device allocation problem for voltage profile and security improvement in a heavily loaded power system has been proved.

4. Conclusion

The implementation of Chaos Embedded Symbiotic Organisms Search technique in solving optimal FACTS device allocation for voltage profile and security improvement problem has been presented in this paper. A good voltage profile indicates a healthy power system while an improvement in voltage security can ensure that the power system is able to retain its operation even in contingency condition without exceeding its stability limits. To achieve this, optimal allocation of FACTS devices should be exercised to avoid under-compensation and over-compensation issues. From the case studies conducted in this paper, the proposed optimisation technique is capable of solving optimal FACTS device allocation problem. The success of the optimisation technique to reduce the fitness value, which reflects the voltage deviation index and FVSI value indicates the improvement of the voltage profile and the voltage security in the system. Comparative studies with other techniques discussed in the paper has revealed the superiority of CSOS compared to PSO and EP by providing better performance in terms of solution quality in solving the problem.

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