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Research paper

Application of Hybrid Optimization Technique for Static Var Compensator Installation

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Abstract

Nowadays, the demand for electricity in power system network increased rapidly, influencing the expansion and urbanization of the network. This process results in inefficient system and may lead to unstable power system, high transmission line losses and many more. To alleviate these problems, Flexible Alternating Current Transmission System (FACTS) such as Static Var Compensator (SVC) can be used. An optimally-sized SVC must be placed at an optimal location. In order to find the optimal size of the SVC devices, a hybrid optimization technique called Immune Evolutionary Programming (IEP) is proposed in this paper. The proposed hybrid optimization technique was tested on the IEEE 26-Bus Reliability Test System (RTS) to minimize total voltage deviation index, to reduce transmission line losses and to improve voltage profile. The results of IEP have been compared with the two existing optimization techniques, which are Evolutionary Programming (EP) and Artificial Immune System (AIS). From this comparison, it is found that the proposed IEP method gives better optimization solution in terms of minimized transmission line losses, improved the voltage profile and reduced total voltage deviation compared to the other two techniques.

Keywords: *Static Var Compensator; Immune Evolutionary Programming; Evolutionary Programming; Artificial Immune System.*

1. Introduction

The demand for electrical energy has increased rapidly year by year. The effect of increasing power demand may stress the power system network, causing problem such as high transmission line losses, unbalance voltage profile and high voltage deviation. These problems can be solved by generating more power and expanding the transmission line. However, environmental and economic aspects needs to be considered before taking such approaches. Luckily, without generating more power, the power system could also be improved by installing some power electronic devices to increase the power system transfer capability.

In this paper, power electronic device from Flexible Alternating Current Transmission System (FACTS) family will be installed to improve the power system by compensating the reactive power. FACTS devices can be divided into four different types such as series, shunt, combination of series-series and combination of series-shunt. Shunt FACTS controllers, such as Static Var Compensator (SVC) and Static Synchronous Compensator (STATCOM) are capable to improve the power system network. But, SVC is more popular due to its lower cost as compared to STATCOM [1]. SVC is chosen as the compensation device to improve the power system stability because of its ability to inject and absorb the reactive power into the system as well as providing voltage support and reducing power losses [2].

Since the FACTS controllers are costly, its installation must be carefully planned. Optimization techniques like Evolutionary Programming (EP) and Artificial Immune System (AIS) are widely used to determine the optimal SVC size and location. In this paper, a hybrid optimization technique is used to solve the SVC installation problem. The hybrid technique is a combination of two optimization techniques, which are EP and AIS. The proposed optimization technique is called Immune Evolutionary Programming (IEP). The optimization results of EP, AIS and IEP will be compared at the end of this paper.

The IEEE 26-bus Reliability Test System (RTS) is used to investigate the performance of the proposed IEP technique. The RTS has twenty load buses, one slack bus and five generator buses. The single line diagram of the bus system is shown in Figure 1.

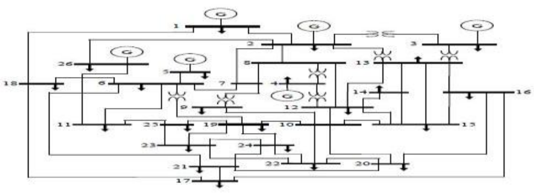

Fig.1: Single line diagram of IEEE 26-bus system [3].

2. Optimization technique for SVC installation

The function of SVC can be maximized when it is appropriately installed at suitable location with optimal size. Therefore, optimization technique is required to find the optimal location and size of the SVC with the objectives to improve voltage profile and to minimize both transmission line losses and voltage deviation index. For this research, EP and AIS are hybridized to form an optimization technique named IEP. This IEP is applied on 26-bus test system to solve its SVC installation problem.

2.1. Static Var Compensator (SVC)

Static Var Compensator (SVC) is a controller under the family of Flexible Alternating Current Transmission System (FACTS). SVC is made up of a Thyristor Controlled Reactor (TCR) connected with Thyristor Switched Capacitor (TSC) in a parallel connection [4]. SVC operates by setting up the thyristor firing angle (α) to regulate the reactive power output of the SVC.

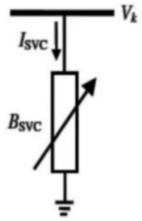

Fig. 2: SVC modelling [5].

Mathematically, SVC can be explained as a function of the firing angle (α), shown in equation (1) while the reactive power generated by SVC is calculated in equation (2) [6].

$$B_{SVC} = \frac{X_L - \frac{X_C}{\pi}[2(\pi - \alpha) + \sin 2\alpha]}{X_L X_C} \tag{1}$$

Where:

X_C = *Inductive reactance*

X_L = *Capacitive reactance*

$$Q_{SVC} = -V_i^2 \times B_{SVC} \tag{2}$$

Equation 3 shows the range of reactive power that SVC capable to inject and absorb [7].

$$\boldsymbol{-100MVar \le Q_{SVC} \le 100MVar} \tag{3}$$

The value of $\boldsymbol{Q_{SVC}}$ can be in positive and negative number. Positive value of $\boldsymbol{Q_{SVC}}$ represents the injection of the reactive power to the system while negative value represents the reactive power absorption from the system.

2.2. Evolutionary programming

Evolutionary programming (EP) is a technique in the field of evolutionary computation and it was developed by Fogel in 1960 [8]. EP will find the optimal solution according to the objective function. The first working principle of EP optimization technique is generating an initial population called parents, randomly. The fitness of the parents are calculated such that only the fit parents will be selected during this initialization process. All of the selected fitness value will be mutated using Gaussian mutation operator to generate a new population called offspring. The mutation of generating offspring occurs in mutation process. Mutation process is important to improve the convergence rate [9]. Equation (4) represents the formula of Gaussian mutation operator [10]:

$$x_{i+m,j} = x_{i,j} + N\left(0, \beta\left(x_{jmax}\, x_{jmin}\right)\left(\frac{f_i}{f_{max}}\right)\right) \tag{4}$$

Where:

$x_{i+m,j}$ = *mutated parent (offspring)*
$x_{i,j}$ = *parent*
N = *Gaussian random variable with* μ *and variance* γ^2
β = *mutation scale,* $0 < \beta < 1$
x_{jmax} = *maximum random number for each variable*
x_{jmin} = *minimum random number for each variable*
f_i = *fitness for the i random number*
f_{max} = *maximum fitness*

Next, the offspring population will be combined with the parents population during combination process. After that, the process continue with ranking and selection. In ranking process the individuals of the combined population will be sorted ascendingly before the best twenty are selected based on the objective function. The flowchart of EP is shown in Figure 3.

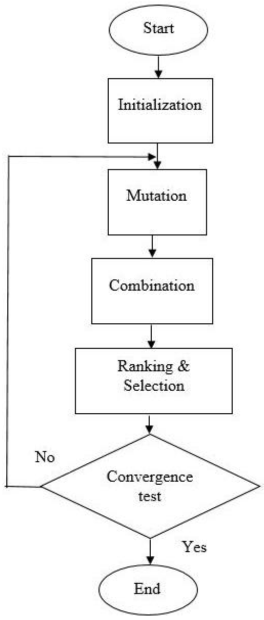

Fig. 3: General flowchart of EP [11].

2.3. Artificial immune system

Artificial Immune System (AIS) was inspired by the concept of the human immune system to solve computational problems [12]. AIS methods have some similarities with the EP methods such as initialization and mutation. In AIS, there is no combination process, which EP does. But AIS has cloning process which EP does not have. Cloning is the process in which the control variable are copied in order to increase the size of population [12]. During the cloning process, the individuals will be multiplied by ten. After that, the cloned individuals will be mutated by using Gaussian mutation, producing offspring. The mutation process will mutate the cloned population to find better individuals for the optimal solution [13]. After the mutation process, the fittest cloned population will be selected during the ranking and selection process. The flowchart of AIS is shown in Figure 4.

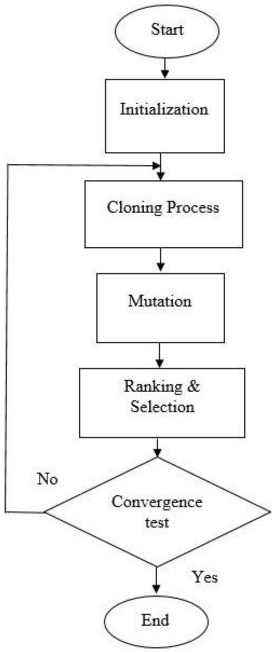

Fig. 4: General flowchart of AIS [14].

2.4. The proposed immune evolutionary programming

The proposed Immune Evolutionary Programming (IEP) technique is a hybrid optimization technique that combines two existing optimization techniques, which are EP and AIS. The main optimizer of this algorithm is EP while cloning process of AIS is added into the EP process. The IEP algorithm has several processes, which are initialization, cloning, mutation, combination and ranking & selection.

Initialization process of IEP will randomly generate twenty individuals that satisfying the objective function. After initialization process, the 20 individuals are cloned by multiplying them 10 times to become two hundreds individuals. The product of cloning process is called parents. Subsequently, the two hundreds individuals are mutated using Gaussian mutation operator and the product is called offspring. Combination process will accordingly combine the offspring and the parents matrices. After combination process, all the combined individuals are ranked according to their fitness value and then the first twenty fittest individuals will be selected as the possible optimal solution of the objective function. The flowchart of IEP algorithm is as shown in Figure 5.

3. Cases of study

The effectiveness of IEP technique can be only justified by testing it with different loading conditions. The loading conditions are represented by case studies. There are three cases, which are base case, light-loading and heavy-loading. In the base case condition, the power system is operating normally without making any changes on the parameters of the system. In light-loading condition, the value of parameter for reactive power load demand at bus 9 is reduced to 10 MVar from 50 MVar. In heavy-load condition, the reactive power demand at bus 16 is increased to 80 MVar from 27 MVar. These buses are selected because they have the existing demand of reactive power in the power system.
For the all three cases, the optimization technique was executed ten times in order to observe any significant variation of the results. The results for these three cases are divided into three categories referring to the objective functions, which are to improve voltage profile, to minimize total voltage deviation index and to minimize transmission line losses.

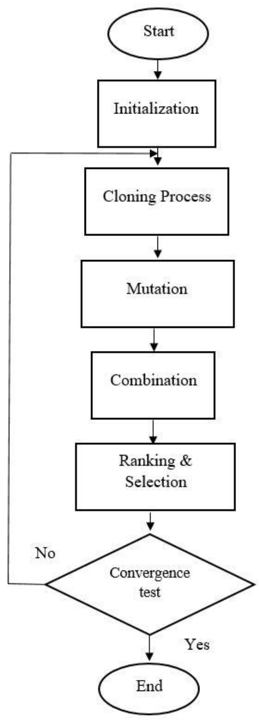

Fig. 5: Flowchart of IEP.

SVC devices are decided to be installed at three load buses that have the highest value of voltage deviation index, which found from load flow solution. Voltage deviation index is the difference between the voltages in nodes with respect to the nominal voltage. The smaller the deviation index, the better the voltage condition of the system. Equation (5) states how the VDI is calculated [3]. Table 1 shows the values of voltage deviation index of each bus for base case condition. From Table 1, it can be seen that buses 23, 24 and 25 are the three buses that experienced highest voltage deviation. Therefore, SVC devices are installed at the three buses.

$$Vdi = \sum_{i=1}^{k} \left(\frac{Vref - Vi}{Vref} \right)^2 \qquad (5)$$

Where:
$Vref$ = *reference voltage*
Vi = *bus voltage*
i = *number of bus*

3.1. Reducing total voltage deviation index

For this research, reducing total VDI is made as one of the objective functions. The total VDI is the summation of VDI for all load buses. The results of SVC installation for total VDI minimization as objective function with three cases are tabulated in Table 2.
Table 2 illustrates that, the values of total VDI changed according to the different optimization techniques. The value of total VDI of pre-optimized for base case condition is 0.0049. And EP produced value of 0.019 while AIS and IEP produced values of 0.0029 and 0.0017

respectively. For light-loading condition, it can be seen that AIS and IEP produced the same value of total VDI which is better than EP. It also can be seen that IEP managed to outperform EP and AIS in most cases. Figure 6 reveals the comparison of results of total VDI produced by all three optimization techniques for all cases.

Table 1: Value of voltage deviation index of each bus for base case condition

Bus	Voltage Deviation Index
1 (slack bus)	0.0006
2 (voltage-controlled bus)	0.0004
3 (voltage-controlled bus)	0.0012
4 (voltage-controlled bus)	0.0025
5 (voltage-controlled bus)	0.0020
6 (load bus)	0.0000
7 (load bus)	0.0000
8 (load bus)	0.0000
9 (load bus)	0.0001
10 (load bus)	0.0001
11 (load bus)	0.0000
12 (load bus)	0.0001
13 (load bus)	0.0002
14 (load bus)	0.0000
15 (load bus)	0.0001
16 (load bus)	0.0003
17 (load bus)	0.0002
18 (load bus)	0.0001
19 (load bus)	0.0000
20 (load bus)	0.0004
21 (load bus)	0.0005
22 (load bus)	0.0005
23 (load bus)	0.0006
24 (load bus)	0.0010
25 (load bus)	0.0007
26 (voltage-controlled bus)	0.0002

Table 2: Total Voltage Deviation Index of 26-bus system

Condition	Pre-optimized	Post-optimized		
		EP	AIS	IEP
Base case	0.0049	0.0019	0.0029	0.0017
Light-loading	0.0042	0.0025	0.0022	0.0022
Heavy-loading	0.0079	0.0035	0.0028	0.0025

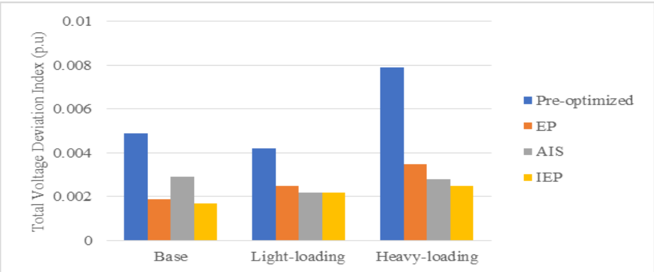

Fig. 6: Total voltage deviation index reduction.

From Figure 6, it can be seen that in base case condition, IEP can reduce the total VDI by 65.31%, whereas 61.22% for EP and 40.82% for AIS. In light-loading condition, AIS and IEP give the same percentage value of 47.62%, while EP can only minimize to 40.48%. The percentage difference for heavy-loading condition of EP is 55.70%, while AIS and IEP reduced the total VDI by 64.56% and 68.35% respectively.
Calculation example of Total VDI reduction percentage for IEP in base case condition:

$$\%Total\ VDI\ reduction = \frac{Total\ VDI_{pre-optimized} - Total\ VDI_{post-optimized}}{Total\ VDI_{pre-optimized}} = \frac{0.0049 - 0.0017}{0.0049} \times 100\% = 65.31\%$$

Table 3: Size of SVC devices to minimize total voltage deviation index

Bus	Condition		
	Base case (MVar)	Light-loading (MVar)	Heavy-loading (MVar)
Bus 23	-4.4398	-5.7488	-1.7509
Bus 24	-8.5685	1.1902	-20.9094
Bus 25	3.9969	20.0779	-8.3403

Table 3 indicates the optimal size of SVC devices in order to minimize the total VDI. By using IEP technique, performance of SVC devices can be known, whether it needs to inject reactive power to the system or absorb the reactive power from the power system.
In order to minimize the total VDI by 65.31 % from pre-optimized value in base case condition, 4.4398 MVar need to be absorbed at bus 23. At bus 24 and bus 25, 8.5685 MVar need to be absorbed and 3.9966 MVar need to be injected respectively. In light-loading condition, 47.62 % of total VDI can be reduced from the pre-optimized by ensuring SVC device at bus 23 absorb 5.7488 MVar and SVC devices at bus 24 and bus 25 inject 1.1902 MVar and 20.0779 MVar respectively. All the SVC devices need to absorb the reactive power with the aim to reduce total VDI by 68.35 % in heavy-loading condition. The size of SVC device that need to be installed at bus 23 is 1.7509 MVar, while 20.9094 MVar and 8.3403 MVar at bus 24 and bus 25 respectively.

3.2. Minimize transmission line losses

Transmission lines in a power system are used to transfer the electrical energy from generation part to the demand or load. As most of the transmission lines are long distance, hence there are electrical power losses in during transmitting the energy. Therefore, it is important to consider the transmission line losses in solving this SVC installation problem. The total generated power is equal to combination of power consumed by the load and power loss at transmission lines in the system, which can be expressed in equation (6) [15]. The results of SVC installation for transmission line losses minimization as objective function with three cases are tabulated in Table 4.

$$\sum_{i=1}^{ngen} P^{Gi} = \sum_{k=1}^{nload} P_{Dk} + \sum_{n=1}^{nline} Loss_n \tag{6}$$

Where:
P^{Gi} = *real power from generator i*
P_{Dk} = *real power consumed by demand load k*
$Loss_n$ = *line loss at line n*

Table 4: Transmission line losses of 26-bus system

Condition	Pre-optimized (MW)	Post-optimized (MW)		
		EP	AIS	IEP
Base case	15.5341	15.0049	14.8029	14.6711
Light-loading	15.2812	14.8766	14.5421	14.4743
Heavy-loading	16.3308	15.9818	15.4231	15.3742

In base case condition, the transmission line losses for pre-optimized is 15.5341 MW, while 15.2812 MW and 16.3308 MW for light-loading and heavy-loading respectively. From the results, IEP can be considered as the best technique since it gives lowest transmission losses for all three cases compared to the other two optimization techniques.

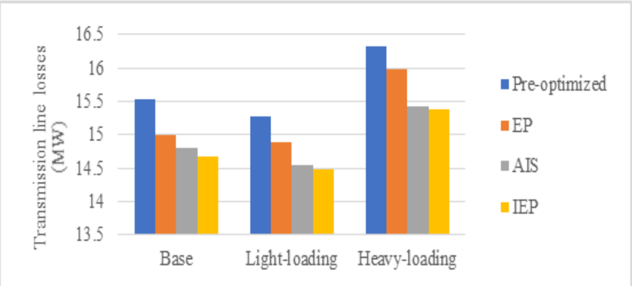

Fig. 7: Transmission line losses minimization.

Figure 7 illustrates the performance of the three optimization techniques in minimizing transmission line losses for all three cases. With EP technique, the loss for base case condition has been reduced by 3.41 %, light-loading condition by 2.65 % and heavy-loading condition by 2.14 %. Both AIS and EP optimization techniques show better performance as compared to EP. For base case condition, the loss reduction percentage with the AIS is 4.71 % while with IEP is 5.56 %.
For light-loading condition, 4.84 % has been reduced by using AIS techniques while by using IEP, it can be reduced by 5.28 %. However, for heavy-loading condition, AIS and IEP showed a much greater percentage of loss reduction compared to EP. The AIS and IEP can minimize the losses with reduction of 5.56 % and 5.86 % respectively.

Table 5: Size of SVC devices to minimize transmission line losses

Bus	Condition		
	Base case (MVar)	Light-loading (MVar)	Heavy-loading (MVar)
Bus 23	-6.4526	-4.4415	-12.2006
Bus 24	-34.1895	-8.5705	-45.4225
Bus 25	-10.8142	3.9960	-6.9744

Table 5 shows the optimal size of the SVC devices that need to be installed for transmission line losses as objective function. For base case condition and heavy-loading condition, the reactive power are absorbed from the power system to minimize the transmission line losses. However, for the light-loading condition, bus 23 and bus 24 absorbed the reactive power by 4.4415 MVar and 8.5705 MVar, respectively while bus 25 injected 3.9960 MVar.

3.3. Improving voltage profile

The third objective of this SVC installation problem is to improve the voltage profile of the power system. The voltage profile at each bus must be within the permissible range to ensure the stability of the system. Some devices may not be functioning if the voltage profile is out of acceptable range, making it important to be maintained within the allowable range. By installing SVC devices at optimal location with optimal size will improve the stability of the system's voltages. The voltage magnitude of each bus in the system must be within ±5 % of its nominal value as shown in equation (7). It was ensured that as the load of the system increased, the IEP will make sure the minimum voltage magnitude is above 0.95 p.u and improved from the pre-optimized's value. [15]. The results of SVC installation for voltage profile improvement as objective function with three cases are tabulated in Table 6.

$$0.95 \leq V_i \leq 1.05 \tag{7}$$

Table 6: Minimum voltage magnitude of 26-bus system

Condition	Pre-optimized (p.u)	Post-optimized (p.u)		
		EP	AIS	IEP
Base case	0.9682	0.9703	0.9741	0.9772
Light-loading	0.9709	0.9739	0.9801	0.9820
Heavy-loading	0.9636	0.9641	0.9718	0.9725

From Table 6, it can be seen the minimum voltage magnitude before installing SVC devices for base case, light-loading and heavy-loading are 0.9682 p.u, 0.9709 p.u and 0.9636 p.u, respectively. After SVC devices are installed, the minimum voltage magnitude has improved for all three techniques. IEP gives better improvement of voltage magnitude compared to the other two techniques for all three cases.

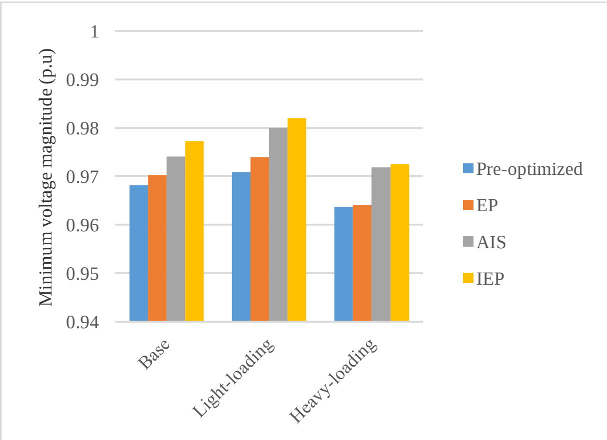

Fig. 8: Minimum voltage magnitude improvement.

According to Figure 8, the highest minimum voltage magnitudes of 26-bus system for all three cases are produced by IEP since the values are closer to 1.0 p.u compared to EP and AIS.

Table 7: Size of SVC devices to improve voltage profile

Bus	Condition		
	Base case (MVar)	Light-loading (MVar)	Heavy-loading (MVar)
Bus 23	-29.7398	-45.3532	-4.1071
Bus 24	22.8222	6.2815	-8.4977
Bus 25	21.5204	39.7097	-4.9201

Table 7 shows the size of SVC devices that need to be installed at the test system to improve the voltage profile of the entire system. At base case condition, buses 23 and 24 need to absorb the reactive power by 29.7398 MVar and 22.8222 MVar respectively, while bus 25 needs to be injected with 21.5204 MVar.
In light-loading condition, only bus 23 needs to absorb 45.3532 MVar while bus 24 and bus 25 need to inject 6.2815 MVar and 39.7097 MVar respectively. In heavy-loading condition, all the SVC devices need to absorb the reactive power. And, in heavy-loading condition, bus 23 absorbed 4.1071 MVar, 8.4977 MVar at bus 24 and 4.9201 MVar at bus 25.

4. Conclusions

In the nutshell, this paper has presented the application of hybrid optimization technique termed as Immune Evolutionary Programming (IEP) and Voltage Stability Index (VDI) for the installation of SVC devices in power system network. And it has been proven that the proposed IEP technique is superior than AIS and EP techniques in giving optimal solution of SVC installation problem for all three objective functions which are minimizing voltage stability index, minimizing transmission line losses and improving voltage profile of power system. This would be a great interest for power utility companies as it can increase the stability of their power systems and would decrease the operation cost of their power systems.

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