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Static VAR Compensator for Minimising Transmission Loss and Installation Cost Calculation

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Abstract: The increment of load variation in a power transmission system can lead to potential failure on the entire system. This is due to the fact that the system has to work under a stressed condition. Therefore an attempt to increase reactive power support should be conducted. Flexible AC Transmission System (FACTS) can be one of the means to alleviate this problem. This paper presents Evolutionary Programming (EP) technique for transmission loss minimisation and calculation of static VAR compensator (SVC) in power transmission system. The objective of the study is to employ EP optimization technique for loss minimisation along with installation cost calculation and voltage profile monitoring. The optimizations are made on two parameters namely the location of the devices and it sizes. The SVC devices are installed in the system in order to enhance the system security; performed on the IEEE 30-bus RTS for several loading conditions. The simulations results are compared with those obtained from the Artificial Immune System (AIS) technique in the attempt to highlight its merit.

Key words: Evolutionary Programming, Artificial Immune System, Static Var Compensator (SVC), Loss Minimisation, Cost Installation, Static Voltage Stability Index

INTRODUCTION

Voltage stability improvement in power system is an important consideration in power system operation when involving heavily stressed system with large amount of real and reactive power demand and low voltage condition. The electrical energy demand increases continuously from time to time. This increase should be monitored or observed because few problems could appear with the power flows through the existing electric transmission networks. If this situation fails to be controlled, some lines located on the particular paths might become overloaded (Kazemi, A., S. Jamali, 2006). Due to the overloaded conditions of the transmission lines, the system will have to be driven close to or even beyond their transfer capacities.

Building a new transmission line will not be an efficient way to solve the problems since it is quite complicated which is due to the environmental and political reasons (Glanzmann, G. and G. Andersson, 2005). Therefore the only way to overcome this major problem is by developing a new way of transmitting more efficient and economical supply using the existing transmission lines. There are few other methods available in solving the problems. In couple of years, the electromechanical equipments were used. Those equipments were switched inductors or capacitors bank and phase-shifting transformer. However all this equipments are not reliable or not efficient enough due to the problems related to this equipments. They are not only relatively slow but they also cannot be switched frequently because they tend to wear out quickly (Kazemi, A., S. Jamali, 2006). Due to the improvements in the semiconductor technology, Flexible AC Transmission Systems (FACTS) devices are used. It opens up new opportunities for controlling the power, decreasing the losses and enhancing the unstable capacity of existing transmission lines (Kazemi, A., S. Jamali, 2006). However not all can be provided by FACTS devices and it is important to select the type of devices in order to achieve the purpose. Static Var Compensator (SVC) is one of the suitable approaches to be chosen according to the purpose. These devices have been commonly used in electric power systems for reactive power (VAR) support and voltage stability enhancement (Ishak, S., A.F. Abidin, 2004). This requires optimization techniques. In last few years,

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many researchers have proposed optimization techniques incorporating with FACTS device such as Genetic Algorithms (GAs), Tabu Search (TS) and Simulated Annealing (SA) (Chung, T.S., Y.Z. Li, 2001; Bhasaputra, P., W. Ongsakul, 2002). An evolutionary programming approach to determine the optimal allocation of multi-type FACTS devices (Ongskul, W. and P. Jirapong, 2005; Wang, K.P., 2003), Genetic Algorithm technique which proposed for solving the optimal location of FACTS (Ippolito, L. and P. Siano, 2004; Radu, D. and Y. Besanger, 2006) and particle swarm technique for optimal location of FACTS devices (Saravanan, M., S.M.R. Slochanal, 2005; Shaheen, H.I., G.I. Rashed, 2007). Preedavichit and Srivastava (1998) proposed a loss sensitivity approach for placement of series capacitors, phase shifters and static VAR compensators.

In this study, Evolutionary Programming (EP) technique was used as one of the optimization technique. By using EP technique to optimize the size of SVCs, the loss can be minimized and voltage profile can be improved. Therefore the recovered supply can be used to support the increasing electrical energy demand in the system. EP is optimisation technique implemented in solving power optimisation problems. This method has been thoroughly discussed since its introduction by Fogel in 1960 (Wei, G., 2004). It has also been successfully applied to various areas of power systems to solve the optimisation problem related to unit commitment (Uyar, A.S. and B. Turkay, 2008), optimal reactive power dispatch (Uyar, A.S. and B. Turkay, 2008), reactive power planning (Musirin, I. and T.K.A. Rahman, 2005; Lai, L.L. and J.T. Ma, 1996), and optimal power flow problems (Yuryevich, J. and K.P. Wang, 1999). Another technique which can address optimization technique is Artificial Immune System (AIS).

The fundamental mechanics of AIS technique can be found in (Castro, L.N.D. and F.J.V. Zuben, 1998). AIS is a new branch of Artificial Intelligence (AI) used for computational models and problem solving methods (Yuryevich, J. and K.P. Wang, 1999). It has been defined as a computational system inspired by the principles and process extracted from the immune system (Dasgupta, D., Z. Ji, 2003). Dasgupta *et al*. (2003) review the application of this method to solve all kinds of application such as feature extraction, pattern recognition, learning, and memory.

This paper presents static VAR compensator installation for minimizing transmission loss and installation cost calculation. The study involved the development of EP engine to implement the optimization of SVC sizing. Placement of the SVC is conducted through the sensitive line in the system deduced from a voltage stability index. The proposed technique implemented on the IEEE 30-Bus RTS has indicated promising results as compared to AIS.

MATERIAL AND METHODS

Flexible AC transmission system (FACTS) devices have several types namely, static VAR compensator (SVC), thyristor controlled static compensator (TCSC), static compensator (STATCOM), Thyristor Controlled Phase Angle Regulator (TCPAR) and unified power flow controller (UPFC). The optimization of SVCs for solving reactive power control problem involve several equation and constraint; equality constraint and inequality constraint. The equality constraints are the nodal power balance equations, while the inequality constraints are the limits of all control or state variables. The objective function is optimisation of real power losses in power system.

Static VAR Compensator (SVC) Design:

SVC can provide a fast-acting reactive support in power system. The SVC can be operated as both inductive and capacitive compensation which can control bus voltage by absorbing or injecting reactive power (Saravanan, M., S.M.R. Slochanal, 2005). The SVC is modelled as a shunt variable susceptance added at both ends of the line. The model of SVC considered in this study is shown in Figure 1.

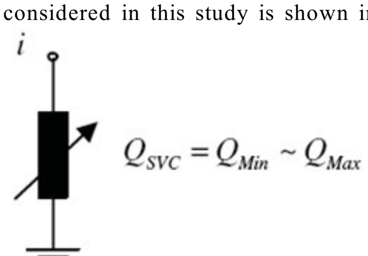

Fig. 1: Block diagram of the considered SVC devices

Hence, it is modelled as ideal reactive power injections to perform the steady-state condition at bus *i*, as shown in Figure 2 (Cai, L.J. and I. Erlich, 2003). The injected power at bus *i* is:

$$\Delta Q_{is} = Q_{svc} \tag{1}$$

where,

Q_{is} = reactive power injections at bus i
Q_{svc} = reactive power injected by the SVC

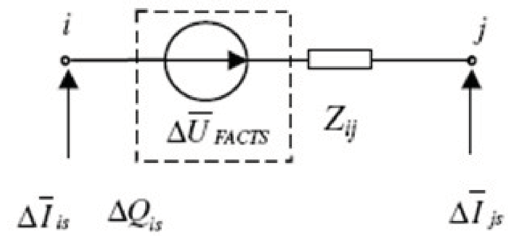

Fig. 2: Mathematical models of the FACTS device

Static Var Compensator Location:

First, the location of the devices in the network must be determined and then, the setting of the control parameters of SVC is optimized by controlling the device parameters. Locations of FACTS devices in the power system are obtained based on the performance using the voltage stability index measured for each line. SVCs are installed at the weakest buses and heavily loaded areas to reduce stressed condition in the system. The Static Voltage Stability Index (SVSI) technique was applied as the tool to indicate the SVCs location into the network. When the load flow program was run, stability indices are calculated for SVC; placed in every line one at a time for the same operating conditions and the system identified five line buses with the highest SVSI for the purpose of installing the SVC. The EP optimization technique is then used to determine the suitable value of the SVC. The concept of the SVSI is demonstrated through a simple two-bus system model. For a given value of V_j, the power flow into the receiving end bus *j* from the sending end bus *i* can be written as:

$$S_{ji} = V_j I_{ji}^* = V_j \left(\frac{V_i - V_j}{Z_{ji}} \right)^* = V_j \left(\frac{V_i^* - V_j^*}{R_{ji} - jX_{ji}} \right) = \frac{V_j V_i^* - |V_j|^2}{R_{ji} - jX_{ji}} = \frac{|V_j||V_i|\left(\cos\delta_{ji} + j\sin\delta_{ji}\right) - |V_j|^2}{R_{ji} - jX_{ji}} \tag{2}$$

where $\delta_{ji} = \delta_i - \delta_j$

The above equation can be derived as follows:

$$|V_j|^2 \left(\frac{X_{ji}}{R_{ji}} + \frac{R_{ji}}{X_{ji}} \right) - |V_j||V_i| \left(\frac{R_{ji}}{X_{ji}} \cos\delta_{ji} + \frac{X_{ji}}{R_{ji}} \cos\delta_{ji} \right) + \left(X_{ji} + \frac{R_{ji}^2}{X_{ji}} \right) \frac{X_{ji}}{R_{ji}} Q_{ji} + \left(R_{ji} + \frac{X_{ji}^2}{R_{ji}} \right) \frac{R_{ji}}{X_{ji}} P_{ji} = 0 \tag{3}$$

The mathematical formulation for SVSI (Qi, L., 2004) is given as in equation (4):-

$$SVSI_{ji} = \frac{2\sqrt{\left(X_{ji}^2 + R_{ji}^2\right)\left(P_{ji}^2 + Q_{ji}^2\right)}}{\left| |V_i|^2 - 2X_{ji}Q_{ji} - 2R_{ji}P_{ji} \right|} \tag{4}$$

where,
i = the sending bus
j = the receiving bus
R_{ji} = the line resistance
X_{ji} = the line reactance
P_{ji} = the real power at the receiving end
Q_{ji} = the reactive power at the receiving end
V_i = the sending end voltage.SVSI has a value between 0 and 1, in which 0 represents the no-load condition and 1 represents unstable condition. Therefore, to obtain stability in the system, SVSI has to be maintained far below 1.

Cost of Installation:

The cost of installation of SVC devices has been mathematically formulated and given by (Saravanan, M., S.M.R. Slochanal, 2005);

$$IC = C_{SVC} \times S \times 1000 \tag{5}$$

where IC is the installation cost of SVC devices in US$ and C_{SVC} is the cost of SVC devices in US$/KVAR.

Installation cost includes the sum of installation cost of all the devices and it can be calculated using the cost function given by (Saravanan, M., S.M.R. Slochanal, 2005);

$$C_{SVC} = 0.0003S^2 - 0.3051S + 127.38(US\$ / KVAR) \tag{6}$$

$$S = |Q_2 - Q_1| \tag{7}$$

where,
S = operating range of SVC in MVAR
Q_1 = reactive power flow through the branch before SVC installation
Q_2 = reactive power flow through the branch after SVC installation
Hence, the SVC device constraint limit is given by,

$$-200MVAR \le Q_{SVC} \le 200MVAR \tag{8}$$

where Q_{SVC} is the reactive power injected by the SVC placed bus in MVAR

IEEE 30-Bus Reliability Test System:

The IEEE 30-bus RTS was chosen to investigate the effectiveness of the proposed technique. The system has 5 voltage control buses, 24 load buses, 1 slack bus, 41 interconnected lines and 4 transformer tap changers. The base apparent power is 100MVA. The one line diagram of the system is illustrated in Figure 3.

Evolutionary Programming:

Evolutionary Programming (EP) technique is a sub-division under the Evolutionary Computation. It is a global search technique based on natural selection (Wei, G., 2004). They always produce high quality solutions and, therefore, they are excellent methods for searching optimal solution in a complex problem. The EP start with random generation of initial population and then the mutation and selection are preceded until the best population is found. The procedure for EP is represented in flowchart as shown in Figure 4. Several inequality constraints are set in this study so as to achieve the optimal solution.

In the initialization process, the number of SVC devices to be used is declared and five initial variables i.e. x_1, x_2, x_3, x_4 and x_5 are generated randomly. Tests are performed at several loading conditions. These values will be the size of SVCs to be installed and utilised into the load flow programme for evaluating the total losses. In this case, loading factor, λ is set from 2 to 3.5 which means that the load bus is increased in p.u.. λ is a loading factor based on their base case value. The initial population is generated randomly within their feasible range to generate parent individual, x_i as denoted below:

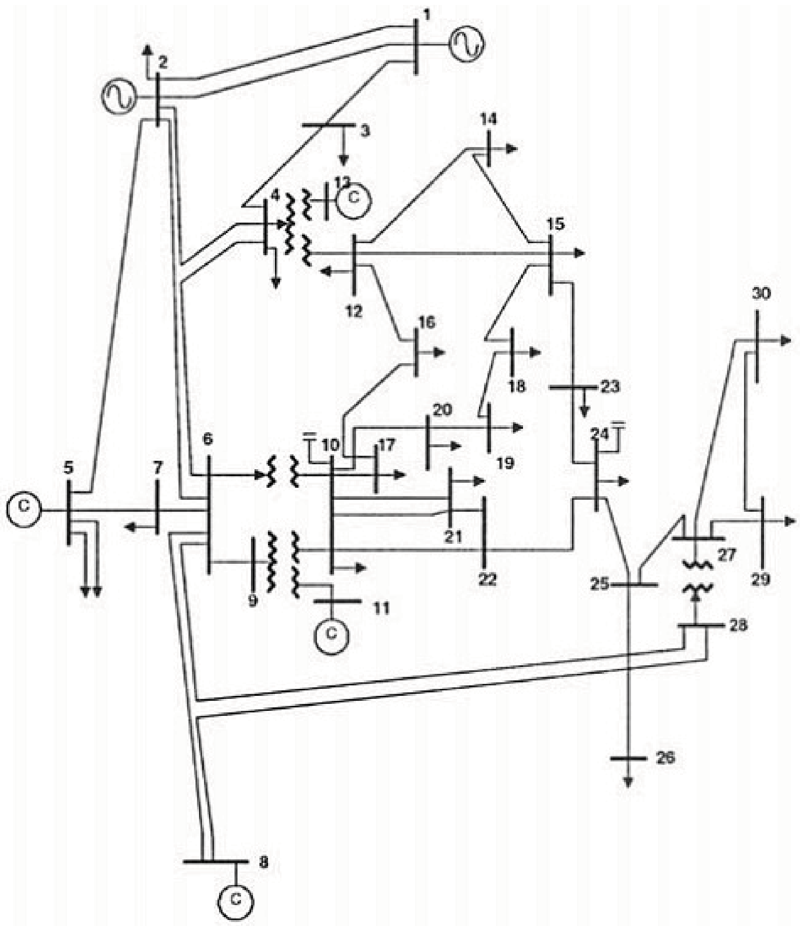

Fig. 3: IEEE 30-bus Reliability Test System

$$x_{im} = [Q_{svc_{(y_1)i}}, Q_{svc_{(y_2)i}}, Q_{svc_{(y_3)i}}, Q_{svc_{(y_4)i}}, Q_{svc_{(y_5)i}}] \tag{9}$$

where $i = 1,2,3,4,\ldots m$. The variable, m indicates the population size from a set of random distributions ranging from Q_{svc}^{min} to Q_{svc}^{max}. The variables y_1 until y_5 indicate the five buses at the sensitive line. The initial parent should satisfy the constraints specified in the beginning. Subsequently, after initialisation, an offspring is produced by mutating the parents. A new population is evolved from an existing population through the use of a Gaussian mutation as express below;

$$x_{i+m,j} = x_{i,j} + N\left(0, \sigma_{i,j}^2\right) \tag{10}$$

where $x_{i+m,j}$ and $x_{i,j}$ are the value of j^{th} element in the new individual, p_j' produced from old individual p_i respectively and $N\left(0, \sigma_{i,j}^2\right)$ is Gaussian random number with a mean of zero and a standard deviation of $\sigma_{i,j}$. The standard deviation decides the features of offspring produced related to its parent. The expression for $\sigma_{i,j}$ is given by:-

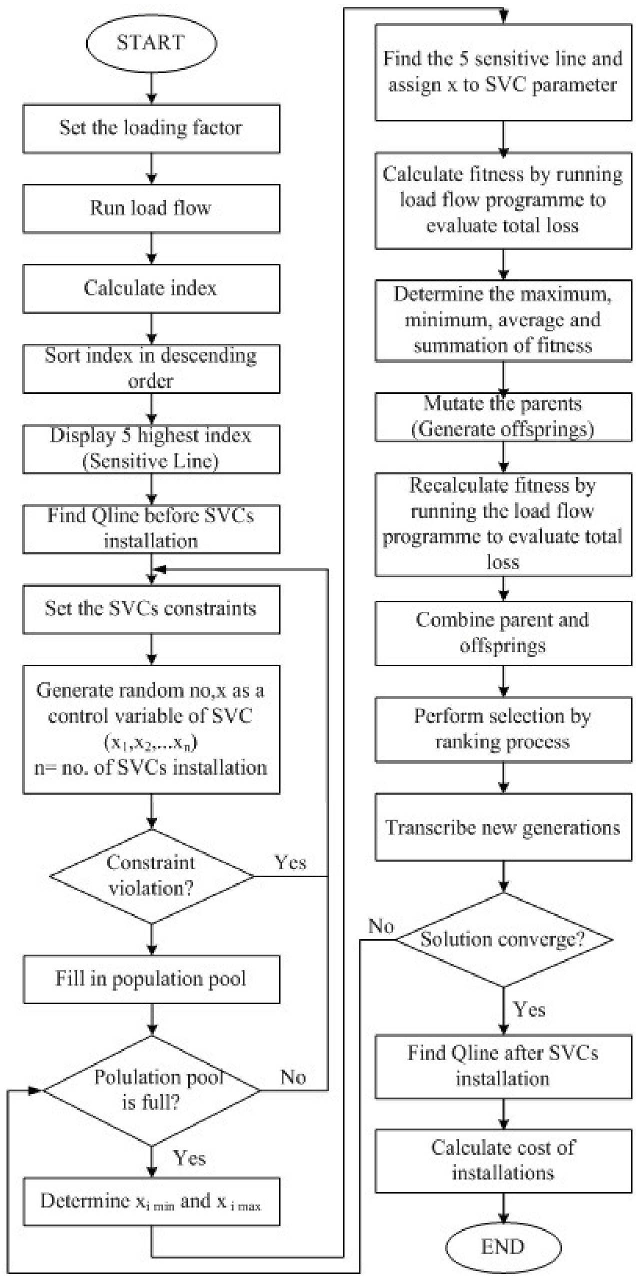

Fig. 4: Flow of developed EPs optimization algorithms for SVC parameters

$$\sigma_{i,j} = \beta\left(x_{j\max} - x_{j\min}\right)\left(\frac{f_i}{f_{\max}}\right) \tag{11}$$

where f_i is the fitness of individual *i*; f_{max} is the maximum fitness within the population, $x_{j\max}$, $x_{j\min}$ denote the maximum and minimum random number of variable *j* and β is the mutation scale ($0<\beta<1$). The mutation scale β can be manually adjusted to achieve better convergence. The lower value of β, leads to fast convergence of EP is expected to occur more quickly and vice versa (Musirin, I. and T.K.A. Rahman, 2005).

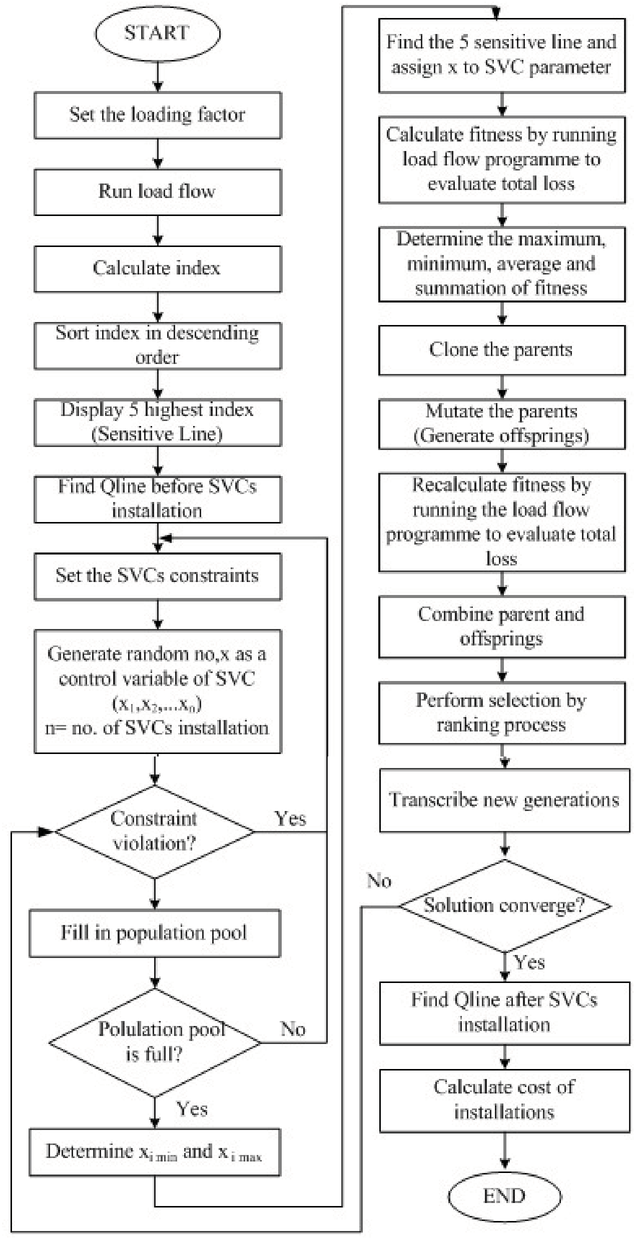

Fig. 5: Flow of developed AIS optimization algorithms for SVC parameters

After that, in the tournament selection process, the tournaments among the individuals are accomplished and the winner of a tournament with the highest fitness will be transcribed into the next generation. An individual is randomly selected from the set of parents and offsprings population. The populations of individuals with better fitness function are sorted in ascending order. The first half or the population would be retained as the new individuals or parent to the next generation and the others will be removed from the pools. The process is continued until a stopping criterion is reached. The stopping criterion is given by:

$$Total\ Loss_{max} - Total\ Loss_{min} \leq 0.0001 \qquad (12)$$

Artificial Immune System:

The procedure for AIS is represented in flowchart as shown in Figure 4. Artificial Immune System (AIS) methods involve several operators which have similarities with the EP methods such as fitness function, initialization and mutation. However in the mutation process, the combination between offsprings and parents do not occur in this process. In addition, the major dissimilarity between EP and AIS is the application of cloning process over the parents. Cloning is the process in which the control variables were copied in order to increase the population. During cloning, the size of each parent is expanded for producing offspring. This creates the same number of clones for each individual. The basic immune models and algorithm in AIS are; Bone Marrow models, negative selection algorithm, clonal selection algorithm and immune network models.

RESULTS AND DISCUSSION

Implementation of SVC installation to minimize transmission loss, along with computation of installation cost is conducted in the IEEE RTS. There are two constraints assigned before the SVCs sizing is optimised. The constraints are; total loss to be less than the *loss_set* and voltage at the loaded bus higher than *V_set*. The *loss_set* and *V_set* are the total loss and voltage at the loaded bus before the optimisation process was conducted. Results for loss minimisation and voltage profile improvement at bus 29 are tabulated in Table I. From the table, bus 29 was subjected to variation of loading conditions. Loading factor, λ is increased gradually in order to observe the effect of total losses with the installation of SVCs in the system. The loading factor, λ was increased up to 3.5 p.u.. The five locations of SVCs installation in the network are also identified by using SVSI technique and shown in the table. Different loading condition shows a different location for SVCs placement in the system as it depends on which line are the weakest subjected to loading factor variation. The application for minimisation of losses as the objective function using EP has significantly reduced the losses and increased the voltage profile value at the loaded bus; hence improving the voltage stability in the system.

By referring to Table 1, Figure 6 and Figure 7, it is observed that the value of total losses value decreased accordingly and the voltage profiles for post-SVC are higher with the increment in loading factor. This implies that with the implementation of SVC optimization, voltage has been improved, while total losses have been reduced indicating voltage stability improvement. The improvement demonstrates that total loss decreases from 25.62 MW to 19.34 MW at loading factor of 3.5 p.u. with the reduction of 24.5% after the installation of SVCs devices. Hence, as shown in Table I, it can also be seen that at λ = 3.5 p.u. the optimal size to be installed are i.e. SVC_1, SVC_2, SVC_3, SVC_4 and SVC_5. The optimal values are -59.65, 5.25, 36.33, 138.06 and -35.31 in MVAr. The locations for installation indicated by sending to receiving buses are at line 27-29, 27-30, 28-27, 2-5 and 1-3, respectively. In addition, the range of total losses reduction for all loading conditions is between 8.3% to 24.5% as indicated in the table. Figure 7 further illustrates the voltage profile before and after the installation of SVCs. The SVC placement of voltage at bus 29 with the loading factor 2, 2.5, 3, and 3.5 have increased the p.u. voltage from 0.8651 p.u. to 0.9894 p.u., 0.8179 p.u. to 1.0607 p.u., 0.7524 p.u. to 1.0419p.u and 0.671 p.u. to 1.0115 p.u., respectively. It is obvious that implementation of SVC installation has significantly improved the voltage profile at all λ factors. It is found that the installations of the SVCs in the system can help to minimize the losses and improve the voltage profile for the system.

Table 1: Effect of SVC Installation for Loss Minimisation and Cost Installation at Bus 29

λ factor	Analysis	SVSI	Total Loss (MW)	%Δ_{Loss}	SVC_1	SVC_2	SVC_3	SVC_4	SVC_5	V_m (p.u)	Cost ($US)
					---MVAr---						
2	Line (S-R)			8.3	2-5	1-3	4-12	2-6	27-29		$4,637.66
	Pre-SVC	0.3193	19.39		0	0	0	0	0	0.8651	
	Post-SVC	0.3102	17.78		-60.02	-53.85	24.76	-46.72	-15.36	0.9894	
2.5	Line (S-R)			8.8	2-5	1-3	27-29	4-12	2-6		$9,868.78
	Pre-SVC	0.32	20.53		0	0	0	0	0	0.8179	
	Post-SVC	0.3185	18.73		35.25	7.23	-27.66	-96.46	-51.91	1.0607	
3	Line (S-R)			17.6	27-29	2-5	1-3	4-12	27-30		$9,090.06
	Pre-SVC	0.3722	22.44		0	0	0	0	0	0.7524	
	Post-SVC	0.3694	18.5		-39.39	172.18	-13.14	-48.65	7.03	1.0419	
3.5	Line (S-R)			24.5	27-29	27-30	28-27	2-5	1-3		$14,880.99
	Pre-SVC	0.5182	25.62		0	0	0	0	0	0.671	
	Post-SVC	0.3372	19.34		-59.65	5.25	36.33	138.06	-35.31	1.0115	

* Line (S-R) = Sending to Receiving buses

Table 2: Result for the Effect of Population Size Performed at Bus 29

Pop. Size	Total loss and voltage profile at Bus 29 for several loading factor					
	λ=2 p.u		λ=3 p.u		λ=3.5 p.u	
	Tot. Loss	Vm (p.u)	Tot. Loss	Vm (p.u)	Tot. Loss	Vm (p.u)
10	17.78	0.9894	19.72	1.0184	19.34	1.0115
20	17.56	1.0537	18.5	1.0419	19.34	1.0117
30	17.56	1.0536	18.5	1.0421	19.34	1.0119
50	17.56	1.0537	18.5	1.0422	18.56	1.0368

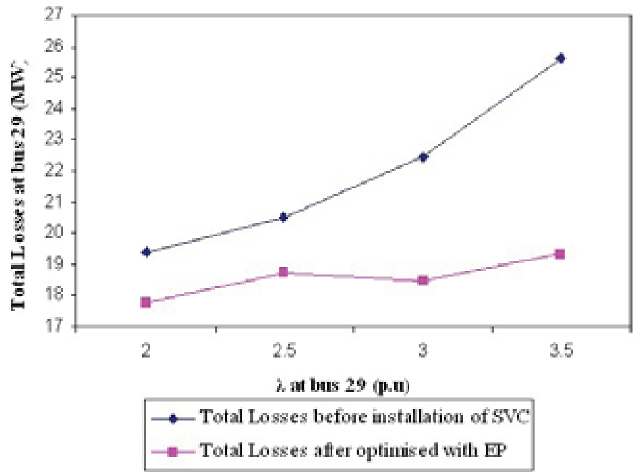

Fig. 6: Total loss profile with Bus 29 loaded

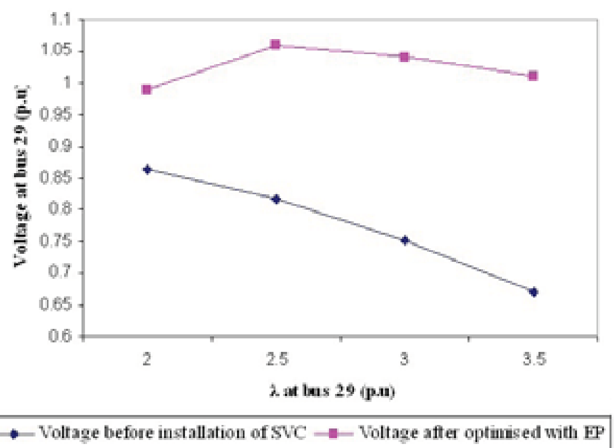

Fig. 7: Voltage profiles for Bus 29 loaded

The effect of population size pertaining to voltage profile improvement and total losses subjected to bus 29 is tabulated in Table 2. It is observed that larger population size gives the highest voltage profile in the system, and vice versa. This can imply that with 50 population size, it allows the process to search within broader search space from valley to the hill. For instance, at population size of 10, the voltage profile at λ = 3.5 p.u is 1.0115 p.u. and total loss is 19.34 MW, while the voltage and total loss is 1.0368 p.u. and 18.56 MW, respectively when population size is increased to 50. This indicates that higher population size gives better performance. Same scenarios can also be observed in different loading factors. As a matter of fact, large population size has a significant impact in performing optimization process using the proposed EP technique.

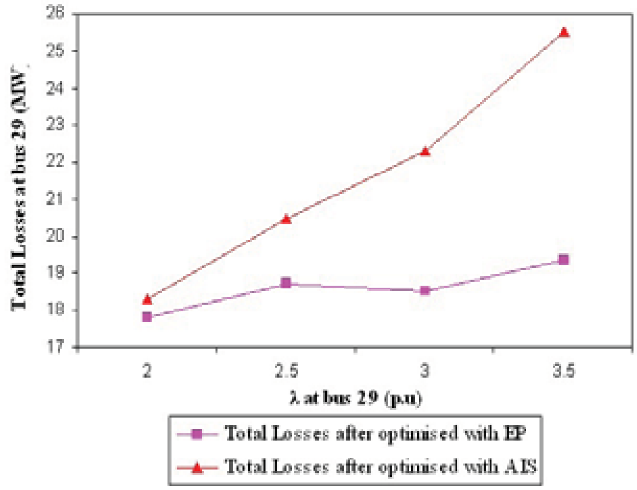

Fig. 8: Total loss using EP and AIS with Bus 29 loaded

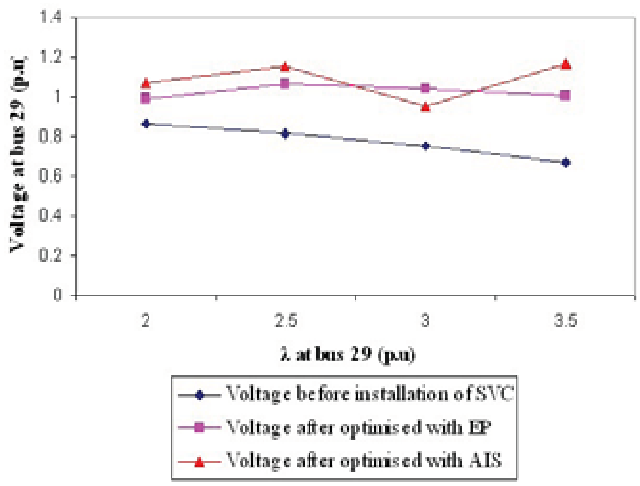

Figure 9: Voltage profiles using EP and AIS with bus 29 loaded

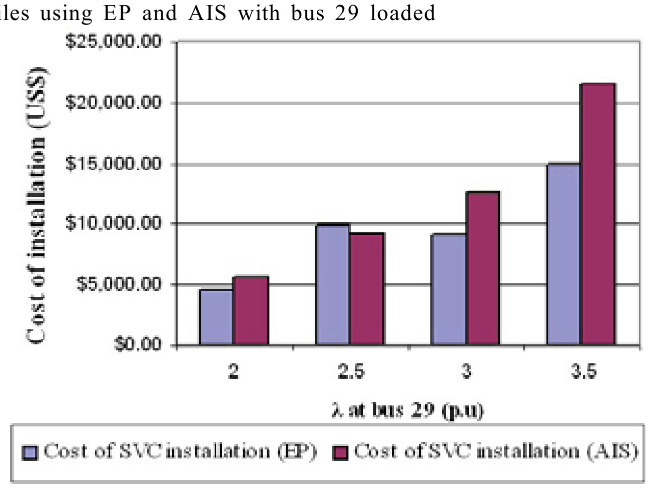

Figure 10: Cost of SVC's installation using EP and AIS with Bus 29

Comparative Studies with AIS:

Comparative study was performed by implementing similar scheme using AIS. The comparisons are made in terms of total loss minimisation, voltage profile and installation cost.

Table 3: Comparison Results for SVC Optimization Sizing between EP and AIS at Bus 29

λ factor	Pre SVC			Post SVC									
				EP					AIS				
	SVSI	Voltage	Loss	SVSI	Voltage	Loss	$\%_{Loss}$	Cost	SVSI	Voltage	Loss	$\%_{Loss}$	Cost
2	0.319	0.8651	19.4	0.31	0.9894	17.8	8.3	$4,637.66	0.311	1.0737	18.3	5.6	$5,638.90
2.5	0.32	0.8179	20.5	0.319	1.0607	18.7	8.8	$9,868.78	0.426	1.1535	20.5	0.2	$9,261.10
3	0.372	0.7524	22.4	0.369	1.0419	18.5	17.6	$9,090.06	0.367	0.9519	22.3	0.7	$12,560.44
3.5	0.518	0.671	25.6	0.337	1.0115	19.3	24.5	$14,880.99	0.931	1.1692	25.5	0.3	$21,450.27

In this section, the results of the SVC installation with loss minimisation as the objective function are verified from two aspects in terms of voltage profile improvement and loss minimisation using EP and AIS. Table 3 tabulates the results of comparative studies using EP and AIS. On the other hand, Figure 8 illustrates the total losses using EP and AIS as compared to the pre-optimisation process. From Figure 8 and Table 3, it is observed that when EP was used to optimise the size of SVC, it gives better results as compared to AIS in terms of total losses. For example, at loading factor, λ=3.5 p.u., EP methods has decreased the total losses in the system from 25.6 MW to 19.3 MW (24.5% reduction) for EP, while AIS; it is 25.5 MW (0.3% reduction) which is higher than EP. As for the voltage profile, the improvement of voltage profile for the bus is shown in Figure 9. From Figure 9 and Table 3, it is observed that when AIS was used to optimise the size of SVC, it gives better results as compared to EP at certain loading condition. At loading factor, λ=3.5 p.u., AIS methods has improved the voltage profile from 0.671p.u. to 1.1692 p.u. as compared to EP which can only manage to increase the voltage up to 1.0115 p.u.. The installation cost of multiple SVCs obtained by applying both techniques in this system is shown in Figure 10. For instance, at loading factor equal to 3.5 p.u., an installation cost of five SVCs devices equal to $14,880.99 is obtained by EP technique, while for the same number of SVCs devices the installation cost obtained by AIS technique is $21,450.27 which is higher while the reduction of total losses is lower than EP.

Conclusion:

This paper has presented the application of evolutionary programming technique for loss minimisation and SVC installation cost has been calculated accordingly. In this study, EP and AIS methods are applied at bus 29 for the minimisation of real power loss as the objective function. Simulation is carried out on the IEEE 30-bus RTS system. Both EP and AIS performed well in most cases. Simulation results demonstrated that the proposed EP technique is feasible for loss minimisation scheme in other power system network. For future work, other FACTS devices such as UPFC and TCSC can be incorporated together to achieve similar task.

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