Effect of Multi-SVC Installation for Loss Control in Power System using Multi-Computational Techniques

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***Abstract*—Flexible AC Transmission Systems (FACTs) play a vital role in minimizing the power losses and improving voltage profile in power transmission system. These increase the real power transfer capacity of the system. However, optimal location of sizing of the FACTs devices determines the extent of benefits provided by the FACTs devices to the transmission system. Non-optimal solution in terms of the location and sizing may possibly lead to under-compensation or over-compensation phenomena. Thus, a robust optimization is a priori for optimal solution achievement. This paper presents a study on the effect on multi static VAR compensators (SVC) installation for loss control in power system using evolutionary programming (EP), artificial immune system (AIS) and immune evolutionary programming (IEP). The objective is to minimize the real power loss transmission and improve the voltage profile of the transmission power system. The study reveals that installation of multi-units SVC significantly reduces the power loss and increases the voltage profile of the system, validated on the IEEE 30-Bus Reliability Test System (RTS).**

Keywords*—Flexible AC Transmission Systems (FACTs); Shunt VARs Compensators (SVCs); Evolutionary Programming (EP); Artificial Immune System (AIS); Immune Evolutionary Programming (IEP)

I. Introduction

The world electricity demand has been steadily increasing over the past few decades due to various factors such as population growth, urbanization, economic development, and technological advancements [1]. Conventional approach such as construction of new power plant and transmission lines to meet the increasing demand of electricity is not a feasible option due to many reasons such as high cost, environmental concerns, technical and time constraints. One of the vital ways to optimize the current system is by reducing the loss in the power system which can be achieved by injecting or retrieving the reactive power with the assistance of FACTs. Installation of FACTs devices can be one of the popular initiatives.

The concept of FACTs was first introduced by Hingorani in 1998 [2]. The working principle of FACTS is to enable the system electric parameters to change fast and flexibly while maintaining the security, stability and reliability of power system; thus, optimizing the existing resources in reducing power loss and cost, while improving the efficiency of the power grid operation [3]. It is important to understand that FACTs devices confined several compensation devices such as unified power flow controller (UPFC), static VAR compensator (SVC), thyristor-controlled series compensator (TCSC), and static synchronous compensator (STATCOM). SVC is considered as a popular compensating device in power system. SVC is a parallel connected device which can act as variable capacitor or variable inductor.

The important uses of SVC are voltage stabilization of weak networks, reducing transmission losses, increasing power transfer capacity, increasing the small disturbance damping, improving voltage stability and removing power fluctuations [4]. SVC is chosen in this work based on its functionality. Optimal placement and sizing remain as a challenge in application of SVCs in voltage stability enhancement [5],[6]. Several optimization techniques have been invented to achieve the optimal solution for SVC installation for the purpose of minimizing the loss in power system or controlling the voltage level in a system within the acceptable limit determined by IEEE or IET standards. Otherwise, a power system will operate under low voltage level which in turn affecting the life time of a transmission cable in the system.

Heuristic optimization techniques have become an important approach in solving complex which is difficult to be solved using traditional approach [6],[7]. Heuristic optimization technique has been adopted in determining the optimization of FACTs devices for power system performance improvement. EP was used to optimize the size of SVC for minimization of loss and voltage profile improvement [8]. EP and AIS were used for SVC location and sizing optimization in IEEE 30-Bus RTS [9]. This application indicates that both EP and AIS is robust in achieving the optimal solution for SVC installation in power system.

On the other hand, improved version of traditional optimization techniques has also been proposed. Among the important techniques that can be highlighted, is a novel improved differential evolutionary (IDE) algorithm which is applied to optimize SVC and TCSC location and sizing for reactive power management in IEEE Bus-30 RTS, IEEE-57 RTS and IEEE-118 RTS [10]. Improved particle swarm in [11] is successfully applied in solving multi-objectives problems. However, the application dealt with the available transfer capability (ATC) study. Other important work that can be highlighted is the work conducted [12] where SVC and

The authors appreciate the support given by the Ministry of Higher Education and Universiti Kebangsaan Malaysia for the operational and financial support to this project under Project Codes GUP-2022-010 and RHB-UKM-2021-002.

TCSC were used as the compensating devices. Gravitational search algorithm (GSA) is proposed for the loadability enhancement of the power system under different loading conditions by determining the optimal placement of different TCSC and SVC [13]. Another work conducted using whale optimization technique in [14] can be considered useful involving SVC and TCSC installation. Thus, a critical review may lead to an efficient decision in any compensation effort in power system.

This paper presents effects of multi-SVC installation for loss control in power system using multi-computational techniques. In this study, EP, AIS and Immune EP (IEP) were applied to identify the locations and sizing of SVC installation in controlling the transmission loss in power system. Controlling transmission loss in power systems is important as it enables optimal voltage control, reactive power compensation, and power flow regulation. By strategically placing SVCs, voltage stability is maintained, transmission losses are minimized, and system efficiency is improved, leading to reliable and secure operation. Results validated on the IEEE 30-Bus RTS revealed that all the techniques are comparable for loss control scheme in power system.

This paper is organized as follows. The objectives and problem formulations are established in Section II. Section III describes the optimization techniques used in detail. Section IV presents the test system used in the work. Section V presents the simulation results and discussions. Finally, Section VI concludes the paper with recommendations.

II. Objective and Problem Formulation

Loss minimization is a vital remedial action applied in power system planning and operation. Transmission loss is proportionally translated to monetary loss as not all electricity generated is delivered to the customers. Compensation scheme such as installation of SVC can greatly reduce losses in the system. This research holds significant importance as its main objective is to study the effect of installing multi SVCs for loss control in power system using multi-computational intelligence techniques. The optimization of SVC location and sizing plays a crucial role in achieving this objective. By formulating the problem in terms of power loss minimization, this study addresses a critical aspect of enhancing power system efficiency and sustainability, thereby contributing to the advancement of power grid operations and control strategies.

The objective function, (OF) of this work is to minimize total loss in a transmission power system, which is mathematically represented by:

$$OF = min \sum_{i=1}^{n} P_{Loss,i} \quad (1)$$

where n is number of buses in the system, and $P_{Loss,i}$ is power loss for line i which can be determined using (2), (3) and (4).

$$P_{Loss} = \sum_{i=1}^{n} \sum_{j=1}^{n} \left[\alpha_{ij}\left(P_i P_j + Q_i Q_j\right) + \beta_{ij}\left(Q_i P_j + P_i Q_j\right)\right] \quad (2)$$

$$\alpha_{ij} = \frac{r_{ij}}{V_i V_j} \cos(\delta_i - \delta_j) \quad (3)$$

$$\beta_{ij} = \frac{r_{ij}}{V_i V_j} \sin(\delta_i - \delta_j) \quad (4)$$

where

r_{ij} = line resistance between bus i and bus j

P_i and P_j = active power at bus i and bus j

Q_i and Q_j = reactive power at bus i and bus j

V_i and V_j = voltage magnitude

δ_i and δ_j = voltage angles

α_{ij} = active power loss factor

β_{ij} = reactive power loss factor

The objective function is subjected to voltage constraints and SVC location and sizing during the optimization process. The minimum voltage must be kept within the specified limits during the optimization process as indicated in (5).

$$0.95\ p.u. \leq V_i \leq 1.05\ p.u. \quad (5)$$

Electrical utilities maintain the voltage level to be in the range ±5 from the nominal voltage level. SVC can be located at load bus only.

The sizing of the SVC is subjected to constraint as shown in (6).

$$0\ MVar \leq Q_{SVC} \leq 100\ MVar \quad (6)$$

Loss reduction percentage (LRP) and V_{min} improvement percentage (VIP) are used for comparison. LRP and VIP are computed based on (7) and (8).

$$LRP = \frac{P_{Loss\,(pre\_SVC)} - P_{Loss\,(post\_SVC)}}{P_{Loss\,(pre\_SVC)}} \quad (7)$$

$$VIP = \frac{V_{min\,(post\_SVC)} - V_{min\,(pre\_SVC)}}{V_{min\,(pre\_SVC)}} \quad (8)$$

III. Optimization Techniques

Optimization technique is a collection of mathematical principles and methods used in solving a quantitative problem. Optimization technique is one of the most preferred and widely used techniques to solve SVC location and sizing optimization for minimization of transmission loss. In this study, three promising and evolving optimization techniques are applied, namely EP, AIS, IEP for location and sizing optimization of SVC for power loss reduction.

A. Evolutionary Programming

Evolutionary Programming (EP) is an artificial intelligence method inspired from natural selection process to find the global optimum of a complex problem. It was first invented by Lawrence J. Fogel in the US in 1960 [15]. The mechanics of EP algorithm is illustrated in Fig. 1.

Step 1: Initialization

The initialization process of EP begins with generating the control variables for optimal location and sizing of SVC using a uniformly distributed random number generator. 20

individuals (parents) are generated based on the control variables for the first iteration. In this case, the control variables will represent the locations and sizing of the SVC units. Apparently, the number of control variables or decision variables will be doubled of the number of SVC units to be installed into the system. During initialization, parameters such as: number of individuals, mutation step size and maximum number of iterations are specified. The total loss of the system before optimization, $P_{Loss\ (pre\_SVC)}$ is calculated as the reference value. The individuals that violate the requirements and constraints are subsequently exterminated from the population pool.

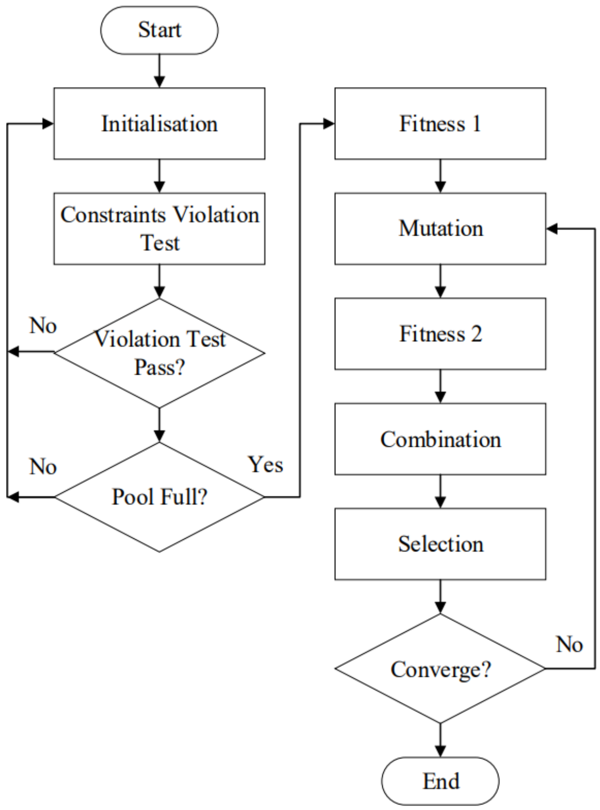

Fig. 1. Flow chart of EP algorithm.

Step 2: Fitness 1 Calculation

Load flow programs are performed to calculate the fitness value which is the real power loss, $P_{Loss\ (post\_SVC)}$. If $P_{Loss\ (post\_SVC)} < P_{Loss\ (pre\_SVC)}$, and fulfils the other constraints specified, they will be accepted into the initial population pool. The general matrix for the initial population, X is given by (9).

$$X = \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1q} & f_1 \\ x_{21} & x_{22} & \dots & x_{2q} & f_2 \\ \vdots & \vdots & \cdots & \vdots & \vdots \\ x_{p1} & x_{p2} & \dots & x_{pq} & f_p \end{bmatrix} \quad (9)$$

where:

p = population size

q = no. of variable

f = fitness of the individual (parent)

Step 3: Mutation

Mutation is a process to breed offspring. The individuals (parents) in the population pool are mutated to breed offspring using the Gaussian mutation operator [16]–[18]. The Gaussian mutation equation is given in (10).

$$x_{i+m,j} = x_{i,j} + N\left(0, \beta\left(x_{jmax} - x_{jmin}\right)\left(\frac{f_i}{f_{max}}\right)\right) \quad (10)$$

where

$x_{i+m,j}$ = offspring (mutated parent)

$x_{i,j}$ = parent

N = Gaussian random variable

β = mutation scale $0 < \beta < 1$

x_{jmax} = maximum value of parent

x_{jmin} = minimum value of parent

f_i = fitness of the i^{th} random number

f_{max} = maximum fitness

Step 4: Fitness 2 Calculation

Fitness 2 calculation is performed by running the load flow again, using the offsprings bred during the mutation process. The matrix for the offspring population, X_{off} is given by (11).

$$X_{off} = \begin{bmatrix} \alpha_{11} & \alpha_{12} & \dots & \alpha_{1q} & F_1 \\ \alpha_{21} & \alpha_{22} & \dots & \alpha_{2q} & F_2 \\ \vdots & \vdots & \cdots & \vdots & \vdots \\ \alpha_{p1} & \alpha_{p2} & \dots & \alpha_{pq} & F_n \end{bmatrix} \quad (11)$$

where

n = population size

m = no. of variable

F = fitness of the offspring

Step 5: Combination Process

The parent matrix and the offspring matrix are then combined in a cascaded form as in (12).

$$X_{combined} = \begin{bmatrix} X \\ X_{off} \end{bmatrix} \quad (12)$$

Step 6: Selection Process and Convergence Test

The individuals in matrix $X_{combined}$ is ranked in ascending order based on fitness value. 20 best individuals from matrix $X_{combined}$ are selected for the next iteration. New individuals are identified for the next iteration process. In this case, the new individuals will be equipped together with the corresponding fitness value for the next iteration or evolution. However, if the new individuals do not bring together the corresponding fitness values, Fitness 1 calculation needs to be conducted. A convergence test is used to check if the optimal solution has been achieved. Otherwise, Step 2 through Step 4 will be repeated until the convergence criterion is met or the iteration cycle reaches the maximum value set. EP algorithm converges when the difference between the maximum and minimum fitness values is 0.00001 presented mathematically in (13).

$$P_{Loss(max)} - P_{Loss(min)} \leq 0.00001 \quad (13)$$

That ends the EP process.

B. *Artificial Immune System*

Artificial Immune System (AIS) technique is inspired by biological immune system and has been used for computational models in solving complex real-world problems. The algorithms in artificial immune system adapt the immune system features of learning and memory to solve a problem. The evolution of AIS has its roots from the work of Farmer, Packard and Perelson [19]. The AIS flowchart is presented in Fig. 2.

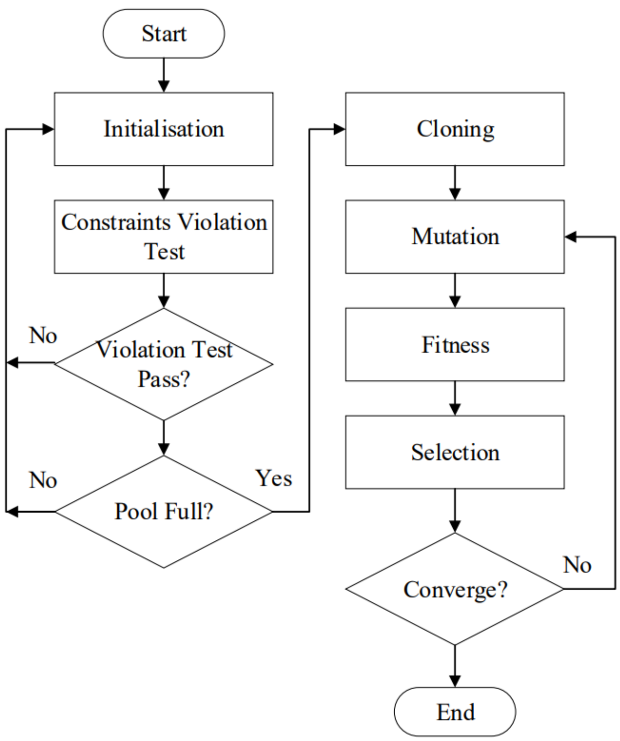

Fig. 2. Flowchart of AIS algorithm.

Step 1: Initialization

The initialization process of AIS begins with generating the control variables for optimal SVC using a uniformly distributed random number generator. 20 individuals (parents) are initially generated based on the control variables for the first iteration. During initialization, parameters such as: number of individuals, mutation step size and maximum number of iterations were to be specified. The total loss of the system before optimization, $P_{Loss\ (pre\_SVC)}$ is calculated as the reference value. The individuals that violate the requirements and constraints are subsequently exterminated from the population.

Step 2: Parent Fitness Calculation

Load flow programs is performed to calculate the fitness value which is real power loss, $P_{Loss\ (post\_SVC)}$. If $P_{Loss\ (post\_SVC)} < P_{Loss\ (pre\_SVC)}$, and fulfils the other constraints specified, they are accepted into the initial population pool. The general matrix for the initial population, X is given by (9).

Step 3: Cloning Process

The individuals in the initial pool, which are referred as parents, are cloned with a factor of 10 as suggested [20], [21]. The population size increases 10 folds after cloning. The general cloned matrix is given in (14) where k is the cloning factor.

$$X_{clone} = \begin{bmatrix} \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1q} & f_1 \\ x_{21} & x_{22} & \dots & x_{2q} & f_2 \\ \vdots & \vdots & \cdots & \vdots & \vdots \\ x_{p1} & x_{p2} & \dots & x_{pq} & f_p \end{bmatrix}_1 \\ \vdots \\ \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1m} & f_1 \\ x_{21} & x_{22} & \dots & x_{2q} & f_2 \\ \vdots & \vdots & \cdots & \vdots & \vdots \\ x_{p1} & x_{p2} & \dots & x_{pq} & f_p \end{bmatrix}_k \end{bmatrix} \quad (14)$$

Step 4: Mutation

Mutation is a process to produce offspring. The individuals of the cloned population, X_{clone} are mutated to breed offspring. Mutation equation in (10) is adapted.

Step 5: Offspring Fitness Calculation

Then, load flow analysis is performed to determine the fitness of the offspring. The matrix for the offspring population, X_{cloned_off} is given by (15).

$$X_{cloned\_off} = \begin{bmatrix} \begin{bmatrix} \alpha_{11} & \alpha_{12} & \dots & \alpha_{1q} & F_1 \\ \alpha_{21} & \alpha_{22} & \dots & \alpha_{2q} & F_2 \\ \vdots & \vdots & \cdots & \vdots & \vdots \\ \alpha_{p1} & \alpha_{p2} & \dots & \alpha_{pq} & F_p \end{bmatrix}_1 \\ \vdots \\ \begin{bmatrix} \alpha_{11} & \alpha_{12} & \dots & \alpha_{1q} & F_1 \\ \alpha_{21} & \alpha_{22} & \dots & \alpha_{2q} & F_2 \\ \vdots & \vdots & \cdots & \vdots & \vdots \\ \alpha_{p1} & \alpha_{p2} & \dots & \alpha_{pq} & F_p \end{bmatrix}_k \end{bmatrix} \quad (15)$$

where

p = population size

q = no. of variable

F = fitness of the offspring

k = cloning factor

Step 6: Selection Process and Convergence Test

Selection process is conducted to identify the survivors among the fittest. In this case, the individuals in matrix X_{cloned_off} are ranked in ascending order based on fitness value. For this study, the individuals are ranked based on the lowest fitness value since the objective function is minimization of total transmission loss. 20 best individuals from the matrix X_{cloned_off} are selected for the next iteration. A convergence test is used to check if the optimal solution has been achieved. Otherwise, Step 2 through Step 5 will be repeated until the convergence criterion is met or the iteration cycle reaches the maximum value set. AIS algorithm converges when the difference between the maximum and minimum fitness values is 0.00001as presented in (13). That ends the AIS process.

C. Immune Evolutionary Programming

Immune Evolutionary Programming (IEP) is derived by integrating the traditional EP and AIS. The IEP flowchart is presented in Fig. 3.

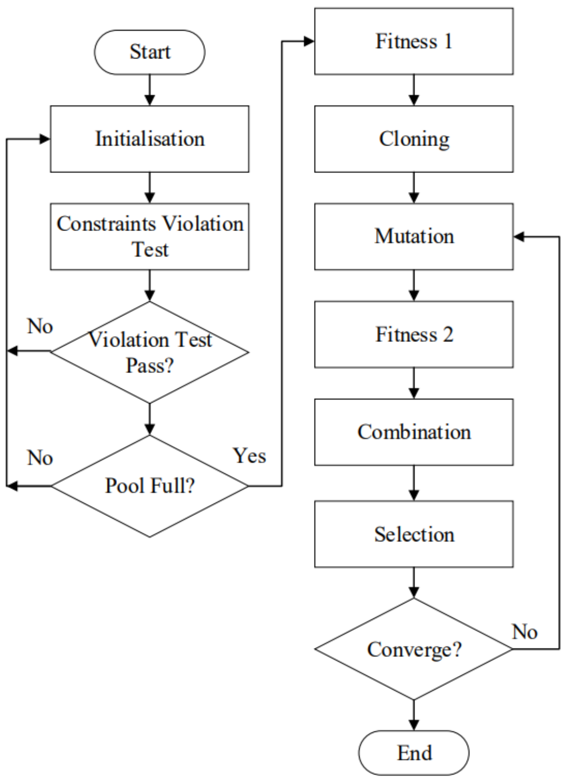

Fig. 3. Flowchart of IEP algorithm.

Step 1: Initialization

The initialization process of EP begins with generating the control variables for optimal SVC using a uniformly distributed random number generator. 20 individuals (parents) are generated based on the control variables first iteration. During initialization, parameters such as: number of individuals, mutation step size and maximum number of iterations were to be specified. The total loss of the system before optimization, $P_{Loss\,(pre\_SVC)}$ is calculated as the reference value. The individuals that violate the requirements and constraints are subsequently exterminated from the population.

Step 2: Fitness 1 Calculation

Load flow programs are run to calculate the fitness value which is real power loss, $P_{Loss\,(post\_SVC)}$. If $P_{Loss\,(post\_SVC)} < P_{Loss\,(pre\_SVC)}$, and fulfils the other constraints specified, they will be accepted into the initial population pool. The general matrix for the initial population, X is given by (9).

Step 3: Cloning

The individuals in the initial pool which are referred as parents are cloned with a factor of k as in (14).

Step 4: Mutation

Mutation is a process to produce offspring. The individuals in the cloned population pool are mutated to breed offspring. The Gaussian mutation equation in (10) is adapted.

Step 5: Fitness 2 Calculation

Then, load flow analysis is performed to determine the fitness of the offspring. The matrix for the offspring population, X_{cloned_off} is obtained as shown in (15).

Step 6: Combination Process

The parent matrix and the offspring matrix are then combined in a cascaded form. If the parent matrix and the offspring matrix are represented by (9) and (15), respectively, then the combined matrix, C, has the form as in (16).

$$X_{combined} = \begin{bmatrix} X \\ X_{cloned\_off} \end{bmatrix} \tag{16}$$

Step 7: Selection Process and Convergence Test

The individuals in matrix $X_{combined}$ are ranked in ascending order based on fitness value. 20 best individuals from matrix $X_{combined}$ are selected for the next iteration. A convergence test is used to check if the optimal solution has been achieved. Otherwise, Step 2 through Step 4 will be repeated until the convergence criterion is met or the iteration cycle reaches the maximum value set. IEP algorithm converges when the difference between the maximum and minimum fitness values is 0.00001as presented in (13).

That ends the IEP process.

IV. Test System

The single line diagram of IEEE 30-Bus RTS used in this study [22] is shown Fig. 4, depicts the configuration of the power system. This system consists of five generators located at Bus 2, Bus 5, Bus 8, Bus 11, and Bus 13. There is a slack bus located at Bus 1 which serves as the reference point for voltage and frequency. There are 24 load buses in the system. The system is interconnected through a total of 41 bus interconnecting lines, forming a complex network. This power system topology is used for identifying and analyzing optimum location and sizing of SVC installation in controlling the transmission loss in power system.

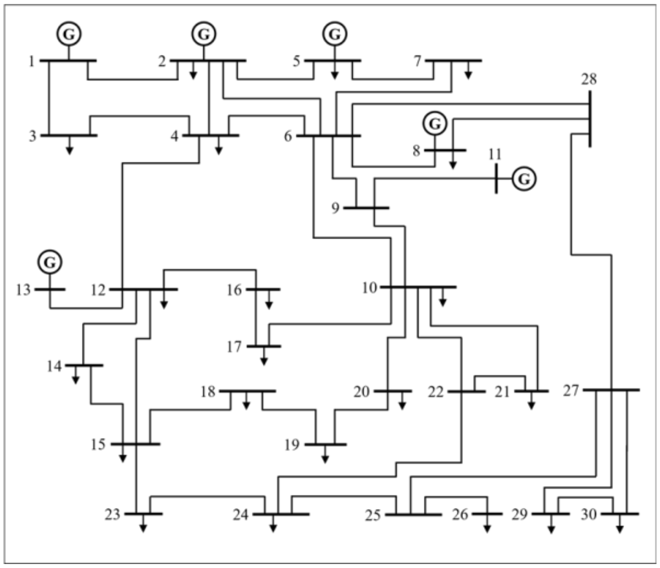

Fig. 4. IEEE 30-Bus reliability test system.

V. Results and Discussions

This section presents the results of multi-SVC installation for loss control in power system using multi-computational techniques.

A. Bus Category Identification

Test was performed on IEEE 30-Bus RTS to identify the weak and strong buses of this system. An increasing reactive power load, Q_d was subjected to each of the load bus in the system and the corresponding voltage at the bus is recorded until the system collapsed. The results are presented in Fig. 1. From the figure, buses 26,29 and 30 are identified as the weak buses indicated by their low maximum loadability value, $Q_{d,max}$ of each bus. For instance, the $Q_{d,max}$ for Bus 26 is 30 MVAR with its corresponding voltage 0.6997 p.u.. Other weak buses can be referred to the same figure. The identified strong buses for this system are buses 6, 4 and 3 due to maximum loadability of each bus. The $Q_{d,max}$ for all the three strong buses are 200 MVAR. The summary of all the details of weak and strong buses are tabulated in Table I.

B. Multi SVCs Installation

In this study, EP, AIS and IEP are validated on IEEE 30-Bus RTS to determine the effect of SVC installation on power loss and voltage profile of the system. In this study, three scenarios have been considered as follows:

- Scenario 1: Single SVC installation.
- Scenario 2: 2 units of SVC installation.
- Scenario 3: 3 units of SVC installation.

Error! Reference source not found.TABLE 2 tabulates the implementation scope of the multi-SVC installation on IEEE 30-Bus RTS. These are the scenarios studied to evaluate the proposed optimization algorithm in finding the optimal location and sizing of SVCs.

1) Scenario 1: Single SVC installation: This section discusses the optimization results of single SVC installation in the attempt to minimize the P_{Loss} of the system. All together 6 buses were subjected to reactive power load; 3 weak buses (Bus 26, 29, 30) and 3 strong buses (Bus 6, 4, 3).

III presents the results for single SVC installation involving weak buses at Buses 26, 29 and 30 and strong buses involving Buses 6, 4 and 3. In general, all techniques managed to reduce the power loss in the system. For instance, when Bus 26 was subjected to 10 MVAR, the installation of single SVC managed to reduce the loss from 18.230 MW to 17.820 MW, solved using EP. The LRP is 2.249%. When the load is increased to 30 MVar, loss was reduced from 26.109 MW to 17.542, where the LRP is 32.815%. AIS and IEP also managed to achieve these results, which imply that all the three techniques are comparable. Generally, the values of LRP increase as the reactive power loading is increased regardless of any optimization technique. The details can be referred to the same table.

Table IV presents V_{min} and VIP before and after the single SVC installation. When Bus 26 was subjected to 10 MVAR, the installation of single SVC managed to increase the V_{min} of IEEE 30-Bus RTS from 0.940 p.u. to 0.957 p.u., solved using EP. The VIP is 1.841%.

When the load is increased to 30 MVAR, the V_{min} increased from 0.691 p.u. to 0.973 p.u., where the VIP is 40.799%. AIS and IEP also managed to achieve these results. Generally, the values of VIP increase as the reactive power loading is increased regardless of any optimization technique. More details can be referred to the same table.

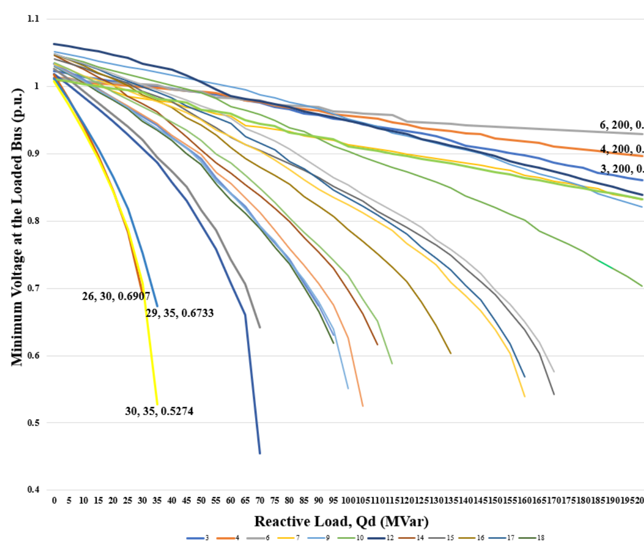

Fig. 5. Minimum voltage profile of IEEE 30-Bus RTS with load variation.

TABLE I. SUMMARY OF 3 WEAKEST AND 3 STRONGEST BUSES IN IEEE 30-BUS RTS

Bus category	Bus Number	Reactive Load (MVar)	Voltage at loaded bus(p.u.)
Weak	26	30	0.6907
	30	35	0.5274
	29	35	0.6733
Strong	6	200	0.9286
	4	200	0.8963
	3	200	0.8602

TABLE II. IMPLEMENTATION SCOPE

Scenario	SVC	Bus Category	Bus Subjected to Q_d Load
1	1	Weak	26, 29 ,30
	1	Strong	6,4,3
2	2	Weak Strong	26, 29 ,30
	2		6,4,3
3	3	Weak Strong	26, 29 ,30
	3		6,4,3

TABLE III. P_{Loss} AND LRP OF SINGLE SVC OPTIMIZATION

Bus	Q_d (MVar)	Pre SVC P_{Loss} (MW)	Single SVC Post Installation					
			EP		AIS		IEP	
			P_{Loss} (MW)	LRP (%)	P_{Loss} (MW)	LRP (%)	P_{Loss} (MW)	LRP (%)
26	10	18.230	17.820	2.249	17.820	2.249	17.820	2.249
	20	20.252	17.573	13.227	17.573	13.227	17.573	13.227
	30	26.109	17.542	32.815	17.542	32.815	17.542	32.815
29	10	18.116	17.559	3.080	17.559	3.080	17.559	3.080
	20	19.386	17.562	9.406	17.562	9.406	17.562	9.406
	30	22.441	17.571	21.704	17.571	21.704	17.571	21.704
30	10	18.109	17.753	1.969	17.753	1.969	17.753	1.969
	20	19.548	17.550	10.222	17.552	10.215	17.552	10.215
	30	23.442	17.732	24.360	17.552	25.124	17.732	24.360
6	50	18.017	17.603	2.297	17.603	2.297	17.603	2.297
	100	19.139	17.608	8.001	18.022	5.838	18.022	5.838
	150	20.568	19.041	7.424	19.041	7.424	19.041	7.424
4	50	18.265	17.479	4.301	17.479	4.301	17.479	4.301
	100	19.838	17.626	11.148	17.626	11.148	17.626	11.148
	150	22.431	18.359	18.153	18.359	18.153	18.359	18.153
3	50	18.529	17.508	5.511	17.508	5.511	17.508	5.511
	100	20.724	17.764	14.282	17.764	14.282	17.764	14.282
	150	24.463	18.533	24.243	18.533	24.243	18.533	24.243

TABLE IV. V_{MIN} AND VIP OF SINGLE SVC OPTIMIZATION

Bus	Q_d (MVar)	Pre SVC V_{min} (p.u.)	Single SVC Post Installation					
			EP		AIS		IEP	
			V_{min}(p.u.)	VIP(%)	V_{min}(p.u.)	VIP(%)	V_{min}(p.u.)	VIP(%)
26	10	0.940	0.957	1.841	0.957	1.841	0.957	1.841
	20	0.845	1.006	19.124	1.006	19.124	1.006	19.124
	30	0.691	0.973	40.799	0.973	40.799	0.973	40.799
29	10	0.944	0.951	0.774	0.951	0.774	0.951	0.774
	20	0.865	1.008	16.461	1.008	16.461	1.008	16.461
	30	0.752	1.007	33.838	1.007	33.838	1.007	33.838
30	10	0.933	0.953	2.230	0.953	2.230	0.953	2.230
	20	0.844	1.007	19.282	1.007	19.353	1.007	19.353
	30	0.707	1.006	42.241	0.997	40.996	1.006	42.241
6	50	0.978	0.994	1.615	0.987	0.910	0.994	1.615
	100	0.950	0.966	1.694	0.982	3.357	0.966	1.705
	150	0.931	0.954	2.437	0.954	2.437	0.954	2.437
4	50	0.986	0.996	0.994	0.989	0.243	0.996	0.994
	100	0.956	0.964	0.847	0.966	0.962	0.964	0.847
	150	0.923	0.952	3.208	0.952	3.208	0.952	3.208
3	50	0.987	0.991	0.355	0.992	0.506	0.991	0.355
	100	0.949	0.952	0.305	0.954	0.495	0.952	0.305
	150	0.905	0.956	5.634	0.956	5.634	0.956	5.634

TABLE V. P_{LOSS} AND LRP OF 2 SVCS OPTIMIZATION

Bus	Q_d (MVar)	Pre SVC P_{Loss} (MW)	2 SVCs Post Installation					
			EP		AIS		IEP	
			P_{Loss} (MW)	LRP (%)	P_{Loss} (MW)	LRP (%)	P_{Loss} (MW)	LRP (%)
26	10	18.230	17.799	2.362	17.806	2.324	17.799	2.362
	20	20.252	17.638	12.906	17.638	12.905	17.638	12.906
	30	26.109	17.663	32.352	17.663	32.352	17.663	32.352
29	10	18.116	17.595	2.880	17.595	2.880	17.595	2.880
	20	19.386	17.672	8.837	17.864	7.849	17.673	8.837
	30	22.441	17.885	20.304	17.571	21.704	17.885	20.303
30	10	18.109	17.775	1.843	17.769	1.879	17.775	1.843
	20	19.548	17.576	10.091	17.576	10.091	17.576	10.091
	30	23.442	17.664	24.649	17.664	24.649	17.664	24.649
6	50	18.017	17.520	2.754	17.520	2.754	17.520	2.754
	100	19.139	18.115	5.351	18.365	4.045	18.115	5.351
	150	20.568	18.999	7.627	19.141	6.937	18.999	7.627
4	50	18.265	17.480	4.296	17.622	3.519	17.480	4.296
	100	19.838	17.572	11.423	17.572	11.423	17.572	11.423
	150	22.431	17.929	20.071	17.929	20.071	17.929	20.071
3	50	18.529	17.615	4.932	17.615	4.931	17.615	4.931
	100	20.724	17.926	13.503	17.926	13.503	17.926	13.503
	150	24.463	18.467	24.510	18.628	23.853	18.467	24.510

TABLE VI. V_{MIN} AND VIP OF 2 SVCS OPTIMIZATION

Bus	Q_d (MVar)	Pre SVC V_{min} (p.u.)	2 SVCs Post Installation					
			EP		AIS		IEP	
			V_{min}(p.u.)	VIP(%)	V_{min}(p.u.)	V_{min}(p.u.)	VIP(%)	V_{min}(p.u.)
26	10	0.940	0.953	1.458	0.953	1.405	0.953	1.458
	20	0.845	1.008	19.313	1.010	19.586	1.008	19.313
	30	0.691	0.955	38.193	1.006	45.635	0.955	38.193
29	10	0.944	0.983	4.144	0.959	1.664	0.983	4.144
	20	0.865	0.991	14.507	1.005	16.114	0.991	14.507
	30	0.752	1.009	34.157	1.010	34.237	1.009	34.157
30	10	0.933	0.971	4.107	0.960	2.917	0.971	4.107
	20	0.844	1.008	19.495	0.996	17.978	1.008	19.495
	30	0.707	1.010	42.877	1.009	42.764	1.010	42.877
6	50	0.978	0.9969	1.922	0.9804	0.235	0.9969	1.922
	100	0.950	0.9843	3.589	0.965	1.558	0.9843	3.589
	150	0.931	0.9653	3.651	0.9832	5.573	0.9653	3.651
4	50	0.986	0.9988	1.267	1.0001	1.399	0.9988	1.267
	100	0.956	0.9813	2.614	0.9669	1.108	0.9813	2.614
	150	0.923	0.9528	3.262	0.9642	4.498	0.9528	3.262
3	50	0.987	1.0088	2.188	0.9896	0.243	1.0088	2.188
	100	0.949	0.9613	1.264	0.955	0.600	0.9613	1.264
	150	0.905	0.9918	9.567	0.9598	6.032	0.9918	9.567

2) Scenario 2: 2 SVCs installation: Table V presents the results for 2 SVCs installation involving weak buses and strong buses. In general, all techniques managed to reduce the power loss in the system with 2 SVCs installation. For instance, when Bus 26 was subjected to 30 MVAR, the installation of 2 SVCs managed to reduce the loss from 26.109 MW to 17.663 MW, solved using EP. The LRP is 32.352%. AIS and IEP also managed to achieve similar results. On the other hand, when strong buses (Bus 6, 4, 3) were subjected to 50 MVAR, the installation of 2SVCs managed to reduce the losses, solved using all the three techniques. However, the LRP in the range of 2.5% to 5% only. This implies that SVC installation reduces the loss in the power system greatly when weak buses are subjected to reactive power load compared to strong buses.

Tale VI presents V_{min} and VIP before and after the 2 SVCs installation. Overall, 2 SVCs installation increases the V_{min} in both weak buses and strong buses regardless the optimization techniques applied. For instance, when Bus 30 is subjected to 30 MVAR, V_{min} is increased from 0.707 p.u. to 1.010 p.u., solved using EP. The VIP is 42.877%. AIS and IEP also managed to achieve VIP in the similar range. Details on other buses can be referred to Table VI.

3) Scenario 3: 3 SVCs installation: Table VII presents the results for 3 SVCs installation involving weak buses and strong buses. 3 SVCs installation reduced loss in the system regardless the techniques applied. When Bus 30 is subjected to 30 MVAR, the loss was reduced from 26.109 MW to 19.140 MW which implies a LRP of 26.695% solving with EP. For the same scenario the LRP was 32.815% for single SVC installation and 32.352% for 2 SVCs installation. Similar results were observed with AIS and IEP. These results indicate, installation of multi-SVC not necessarily further reduces the loss of the power system. Based on the results, a maximum of 2 SVCs installation is recommended. However, other constraints of the power system need to considered. The details can be referred Table VII.

Table VIII presents V_{min} and VIP before and after the 3 SVCs installation. Overall, 3 SVCs installation increases the V_{min} in both weak buses and strong buses regardless of the optimization techniques applied. The best VIP was recorded when Bus 30 was subjected to 30 MVAR. The V_{min} was increased from 0.691 p.u. to 1.010 p.u. solving using EP. The VIP is 46.228%. AIS and IEP also managed to achieve same results. Results for other buses can be referred to Table VIII.

TABLE VII. P_{Loss} AND LRP OF 3 SVCS INSTALLATION

Bus	Q_d (MVar)	Pre SVC P_{Loss} (MW)	3 SVCs Post Installation					
			EP		AIS		IEP	
			P_{Loss} (MW)	LRP (%)	P_{Loss} (MW)	LRP (%)	P_{Loss} (MW)	LRP (%)
26	10	18.230	17.922	1.688	17.871	1.967	17.922	1.688
	20	20.252	18.005	11.095	17.638	12.905	18.005	11.093
	30	26.109	19.140	26.695	18.756	28.162	19.140	26.693
29	10	18.116	17.579	2.969	17.579	2.968	17.579	2.968
	20	19.386	17.517	9.638	17.550	9.470	17.517	9.638
	30	22.441	18.553	17.327	17.885	20.303	18.553	17.326
30	10	18.109	17.533	3.181	17.623	2.686	17.533	3.181
	20	19.548	17.585	10.043	17.583	10.056	17.585	10.043
	30	23.442	17.526	25.237	17.654	24.692	17.526	25.237
6	50	18.017	17.515	2.783	17.515	2.783	17.515	2.783
	100	19.139	17.716	7.435	17.878	6.590	17.716	7.435
	150	20.568	18.382	10.629	17.539	14.727	18.382	10.629
4	50	18.265	17.582	3.742	17.621	3.525	17.582	3.742
	100	19.838	17.663	10.964	17.663	10.964	17.663	10.964
	150	22.431	17.804	20.629	17.804	20.629	17.804	20.629
3	50	18.529	17.518	5.457	17.898	3.408	17.518	5.457
	100	20.724	18.118	12.573	18.118	12.573	18.118	12.573
	150	24.463	18.175	25.705	18.293	25.221	18.175	25.705

TABLE VIII. V_{MIN} AND VIP OF 3 SVCS INSTALLATION

Bus	Q_d (MVar)	*Pre SVC* V_{min} *(p.u.)*	3 SVCs Post Installation					
			EP		AIS		IEP	
			V_{min}(p.u.)	VIP(%)	V_{min}(p.u.)	V_{min}(p.u.)	VIP(%)	V_{min}(p.u.)
26	10	0.940	0.953	1.458	0.971	3.310	0.953	1.458
	20	0.845	1.010	19.597	1.008	19.408	1.010	19.597
	30	0.691	1.010	46.228	1.010	46.228	1.010	46.228
29	10	0.944	1.006	6.560	0.963	2.077	1.006	6.560
	20	0.865	0.959	10.843	0.993	14.819	0.959	10.843
	30	0.752	1.010	34.237	1.010	34.237	1.010	34.237
30	10	0.933	0.952	2.059	1.008	8.053	0.952	2.059
	20	0.844	0.955	13.119	1.008	19.448	0.955	13.119
	30	0.707	0.959	35.649	1.010	42.877	0.959	35.649
6	50	0.978	1.001	2.351	0.995	1.748	1.001	2.351
	100	0.950	0.972	2.315	1.003	5.578	0.972	2.315
	150	0.931	0.984	5.659	0.967	3.812	0.984	5.659
4	50	0.986	1.003	1.673	0.996	1.004	1.003	1.673
	100	0.956	0.979	2.342	0.986	3.074	0.979	2.342
	150	0.923	0.999	8.302	0.959	3.923	0.999	8.302
3	50	0.987	1.006	1.935	0.998	1.074	1.006	1.935
	100	0.949	0.965	1.664	0.974	2.549	0.965	1.664
	150	0.905	0.976	7.855	1.001	10.561	0.976	7.855

TABLE IX. LOCATION AND SIZING OF SINGLE SVC INSTALLATION

Bus	Q_d (MVar) Max	OT	Single SVC Installation		
			Location 1	Sizing 1 (MVar)	LRP (%)
26	30	EP	26	31.161	32.815
		AIS	26	31.159	32.815
		IEP	26	31.161	32.815
29	30	EP	26	31.161	32.815
		AIS	29	35.691	33.838
		IEP	29	35.691	33.838
30	30	EP	30	24.405	24.360
		AIS	30	33.207	25.124
		IEP	30	24.405	24.360
6	150	EP	4	94.770	7.4240
		AIS	4	94.774	7.4240
		IEP	4	94.774	7.4240
4	150	EP	4	94.776	18.153
		AIS	4	94.775	18.153
		IEP	4	94.776	18.153
3	150	EP	3	99.874	24.243
		AIS	3	90.464	18.242
		IEP	3	90.465	18.242

C. Location and Sizing of SVCs

The installation of SVCs into the system as the initiative to reduce the total power loss will require the optimal locations and sizing. The multi-SVC locations and sizing details for all the three scenarios are tabulated in Tables IX to XI.

Scenario 1: Location and sizing of single SVC: The results for Scenario 1 are tabulated in Table IX. Only location and sizing of single SVC for $Q_{d,max}$ for each bus are shown to simplify the results. For instance, when Bus 26 is subjected to 30 MVAR, the single SVC to be installed at Bus 26 of a 31.161 MVAR for a LRP of 32.815%, solved by EP. AIS and IEP also solved the same location for SVC installation and same range of SVC sizing, which implies that all the three techniques are comparable. Details of single SVC location and sizing when other buses are subjected to $Q_{d,max}$ can be referred to Table IX.

1) Scenario 2: Location and sizing of 2 SVCs: The results for Scenario 2 are tabulated in Table X. Only location and sizing of 2 SVCs for $Q_{d,max}$ for each bus are shown for simplification purpose. For instance, when Bus 26 is subjected to 30 MVAR, the 2 SVCs to be installed are at Bus 28 (27.535 MVAR) and Bus 26 (27.893 MVAR) for a LRP of 32.352%, solved by EP. The total SVC sizing was 55.428 MVAR. AIS and IEP also solved the same location for SVC installation and same range of SVC sizing, which implies that all the three techniques are comparable.

However, it was observed the sizing of single SVC is much lower for the same scenario compared to total SVC sizing when 2 SVCs installation was opted. In this case, single SVC and 2 SVCs installations has same range of LRP. This implies, multi-SVC is not always an option to reduce loss in the system. Other factors such as installation cost, maintenance cost and accessibility need to be considered before opting for multi-SVC installation. Details of 2 SVCs location and sizing when other buses are subjected to $Q_{d,max}$ can be referred to Table X.

2) Scenario 3: Location and sizing of 3 SVCs: The results for Scenario 3 are tabulated in Table XI. Only location and siz ing of 3 SVCs for $Q_{d,max}$ for each bus are shown for simplificat ion purpose. For instance, when Bus 26 is subjected to 30 MV AR, the 3 SVCs to be installed are at Bus 10 (35.094 MVAR), Bus 16 (59.106 MVAR) and Bus 26 (41.203 MVAR) for a L RP of 26.695%, solved by EP. The total SVC sizing was 135.4 03 MVAR. IEP also solved the same location and sizing while AIS solved different location and sizing as shown in the same table.

TABLE X. LOCATION AND SIZING OF 2 SVCS INSTALLATION

Bus	Q_d *(MVar) Max*	OT	2 SVCs Installation					
			Location 1	**Sizing 1 (MVar)**	**Location 2**	**Sizing 2 (MVar)**	**Total Sizing (MVar)**	**LRP (%)**
26	30	EP	28	27.535	26	27.893	55.428	32.352
		AIS	28	27.534	26	27.891	55.425	32.352
		IEP	28	27.535	26	27.893	55.428	32.352
29	30	EP	3	44.272	29	46.766	91.038	20.304
		AIS	5	55.284	29	35.691	90.975	21.704
		IEP	3	44.277	29	46.771	91.048	20.303
30	30	EP	30	24.405	25	13.645	38.050	24.649
		AIS	30	24.403	25	13.643	38.046	24.649
		IEP	30	24.405	25	13.645	38.050	24.649
6	150	EP	28	38.985	9	69.217	108.202	7.6270
		AIS	4	94.773	3	50.068	144.841	6.9370
		IEP	28	38.985	9	69.217	108.202	7.6270
4	150	EP	4	94.776	3	50.071	144.847	20.071
		AIS	4	94.774	3	50.068	144.842	20.071
		IEP	4	94.776	3	50.071	144.847	20.071
3	150	EP	3	99.873	23	12.221	112.095	24.510
		AIS	5	10.998	3	97.245	108.243	23.853
		IEP	28	27.535	26	27.893	55.428	32.352

TABLE XI. LOCATION AND SIZING OF 3 SVCS INSTALLATION

Bus	Q_d (MVar) Max	OT	3 SVCs Installation							
			Location 1	**Sizing 1**	**Location 2**	**Sizing 2**	**Location 3**	**Sizing 3**	**Total Sizing**	**LRP**
26	30	EP	10	35.094	16	59.106	26	41.203	135.403	26.695
		AIS	4	51.876	2	56.146	26	51.689	159.710	28.162
		IEP	10	35.099	16	59.109	26	41.206	135.414	26.693
29	30	EP	3	92.551	29	46.659	9	46.018	185.228	17.327
		AIS	3	44.277	29	46.771	11	44.591	135.639	20.303
		IEP	3	92.558	29	46.664	9	46.023	185.244	17.326
30	30	EP	22	5.1940	27	7.1640	30	26.992	39.349	25.237
		AIS	30	24.403	25	13.642	13	60.099	98.143	24.692
		IEP	22	5.1940	27	7.1640	30	26.992	39.349	25.237
6	150	EP	4	84.149	12	42.380	10	71.345	197.874	10.629
		AIS	6	82.832	6	98.791	8	23.357	204.980	14.727
		IEP	4	84.155	12	42.386	10	71.351	197.892	10.629
4	150	EP	4	94.776	3	50.071	12	27.708	172.555	20.629
		AIS	4	94.774	3	50.068	12	27.706	172.548	20.629
		IEP	4	94.776	3	50.071	12	27.708	172.555	20.629
3	150	EP	4	80.912	28	4.5520	3	82.972	168.437	25.705
		AIS	6	53.351	3	99.870	23	12.220	165.441	25.221
		IEP	4	80.912	28	4.5520	3	82.972	168.437	25.705

On the other hand, it was observed the sizing of single SVC and 2 SVCs are much lower for the same scenario compared to total SVC sizing when 3 SVCs installation was opted. In this case, single SVC and 2 SVCs installations have higher LRP compared to 3 SVCs. This implies, multi-SVC is not necessarily an option to obtain the highest LRP in the system. Based on the results, installation of 3 SVCs in not recommended as the LRP achieved is lower compared to single SVC and 2 SVCs. Other factors such as installation cost, maintenance cost and accessibility need to be considered before opting for multi-SVC installation. Details of 3 SVCs location and sizing when other buses are subjected to $Q_{d,max}$ can be referred to Table XI.

VI. CONCLUSION

Based on the key findings of this study, it can be concluded that the three optimization techniques, namely EP, AIS and IEP are effective solutions for addressing the complex task of optimal location and sizing of multi-SVC installation in the IEEE 30-Bus RTS power system. The work successfully explored the optimal positions, sizes, and number of SVCs while considering network operational constraints and SVC limitations, ultimately aiming to reduce total active power loss.

Findings of this study have broader implications for the field of power system optimization and control. It contributes to advancing the understanding of SVC installation for enhancing power system performance using multi-computational intelligence techniques It also showcases the effectiveness of EP, AIS and IEP in tackling large-scale technical challenges and highlights their potential for addressing similar optimization problems in other power system scenarios.

In summary, this work demonstrates the efficacy of EP, AIS, and IEP in solving the optimal location and sizing problem of multi-SVC allocation. These results provide valuable insights for power system optimization and have broader implications for improving power grid performance, reliability, and efficiency.

ACKNOWLEDGMENT

The authors appreciate the support given by the Ministry of Higher Education and the Universiti Kebangsaan Malaysia for the operational and financial support to this project under Project Codes GUP-2022-010 and RHB-UKM-2021-002.

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