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Research paper

Coordinated Allocation of Dispersed Reactive Power Resources for Voltage Regulation and Loss Minimization

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Abstract

The major problems faced by utility companies are to provide standard voltage levels and to minimize system power losses. This paper introduces a coordinated allocation of multiple distributed reactive energy resources to regulate system voltage and minimize power losses. For this purpose sensitivity study is used to determine the appropriate location for placing distributed reactive energy resources and thereby reduce the search. The Al-Ain power distribution network (AADN) is considered as a real-world case study. For the AADN under investigation, a suitable objective function is formulated to lessen the installation cost and electric power losses. The problem is resolved by using the tabu search optimization method and DIgSILENT PowerFactory simulation software. Results depict that the proposed method can minimize system electric power losses and improve voltage regulation.

Keywords: *distribution network; reactive power sources; optimal planning; tabu search algorithm.*

1. Introduction

Voltage drops and power losses occur during the transfer of electrical energy from the generation station to customers through transmission and distribution networks. These losses can be minimized by using reactive power resources, such as capacitor banks, static VAR compensators (SVCs), and distributed generators (DGs). Although these elements are widely used as reactive power resources, defining their optimal size and location remains a challenging task. Transmission lines absorb most of the reactive power supplied. Thus, the installation of local reactive power resources is suggested by many experts to reduce the power losses in transmission lines.
The aim of this study is to determine the optimal placement and sizing of capacitor banks, SVCs, and reactive dispersed energy resources, such as cogenerators, to minimize energy losses and capital investment. Many techniques, such as gradient-based optimization and iterative and heuristic search, in addition to artificial intelligence-based approaches, have been developed for optimal sizing and location of reactive power resources. A newly developed optimization technique that combines genetic algorithm (GA) and particle swarm optimization was proposed in [1] to find the optimal capacitor installation and sizing in the electric distribution system. In [2], a new optimization algorithm called ant-lion optimizer was proposed to find the optimal reactive capacity and locations of fixed capacitors. For the same purpose, a new accelerated particle swarm optimization method was implemented in [3] to solve the capacitor placement issue. Ref. [4] presented a model for concurrently allocating capacitor banks for reactive power mitigation in power systems with a substantial amount of dynamic rotary machine load. Optimal capacitor placement was also proposed using a newly developed teaching–learning-based optimization in [5]. A related work [6] presented a modest and effective analytical technique to decide the optimal sizing and placement of capacitors in radial distribution systems to decrease the overall electric power losses and elevate the system voltage profile. For the best capacity and location of switched and fixed capacitor banks under unbalanced condition, a nonlinear optimization algorithm was employed in [7]. Artificial intelligence-based methods and evolutionary programming are other popular methods to solve capacitor placement [8, 9, 10]. The objective functions in these approaches are focused on how to reduce the cost of electric power losses while minimizing the investment cost of capacitor banks without considering other reactive power resources.
Similarly, many techniques can be used for SVC placement and sizing. In [11], an artificial immune system (AIS) was presented for the optimal placement of SVC. This study showed that the AIS can significantly minimize system losses and improve system voltage profiles. How mixed integer nonlinear programming can be used for the optimal placement of SVC-based online flows was presented in [12]. In [14, 13], the authors focused on quantifying the benefits of DGs in improving system voltage profiles and thus minimizing power losses. A simple analysis was conducted for a radial feeder with a lumped load and DGs to reduce line losses by using a primal–dual interior method. In [15], an optimal control technique was proposed to improve the system voltage in synchronization with distributed energy resources. GA was utilized to regulate the voltage at each busbar. In line with the method in [15], a new method was developed in [16] by utilizing linear programming to decide the optimal placement of embedded generation. The results proved that placing and sizing embedded generation are critical to system stability and operation. In a related work, voltage and loss sensitivity analyses were performed [17] to identify sites for the replacement of dispersed energy sources. These techniques were applied iteratively and heuristically

to find the best location. Tabu and parallel tabu search (TS) were presented by the researchers of [18, 19, 20, 21] for capacitor placement and network and feeder reconfigurations; in [22, 23], these techniques were applied to solve the distributed generation location problem. However, the TS algorithm has not been used for coordinated placement and sizing of dispersed reactive power sources. In the present study, the determination of multiple distributed reactive power sources and their impact on enhancing voltage profiles and system energy losses are investigated. The application of the TS technique and sensitivity study to improve the dispersed reactive power sources in an Al-Ain distribution network (AADN) is the main contribution of this study.
The remainder of this paper is arranged as follows. Section 2 presents the AADN. Section 3 explains the optimal resource allocation problem. Section 4 indicates the results. Section 5 concludes the study.

2. System Description and Modelling

The AADN was formed in 1998 as an ancillary of the electricity and water authority of Abu Dhabi. The system started operating in year 1999 with the goal of distributing electricity and water in Al-Ain City, which lies in the western and eastern territory of Abu Dhabi. The AADN mainly obtains electricity from the Abu Dhabi power substation over 220 and 400 kV transmission lines. Its maximum demand reaches approximately 1516 Mega Watt (MW) throughout the summer period.
The AADN consists of 9 grid stations and over 66 primary substations (33/11 kV) and switching stations (Fig. 1). It is a radially operated system that comprises underground power cables and overhead power lines for delivering electricity for various customers. The distribution network is connected to 400/220 kV transmission systems via TransCo grid stations. Approximately 71% of the AADN load is an air-conditioning load. The company serves over 60000 households and some retail stores, malls, and hotels. The city is situated in a dry topographical region with temperatures that reach over 36 °C for extended periods within a year.

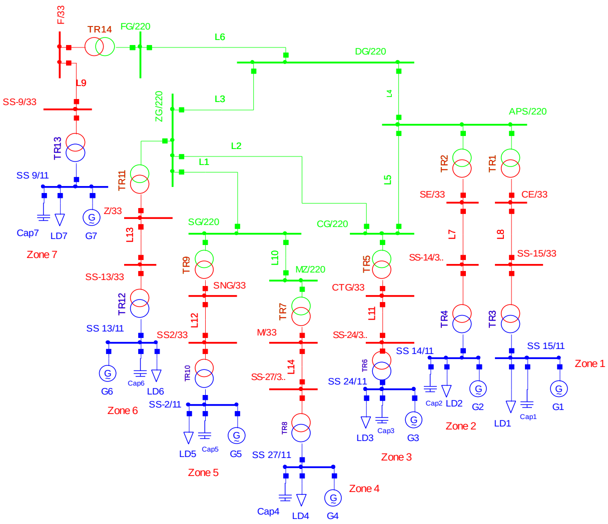

Fig. 1: Single-line diagram of the AADN

The AADN is comparable to any other utilities worldwide that are facing the problems of power losses and voltage regulation. In this hot-temperature country, the air-conditioning loads are high all year round, and these issues now require immediate attention. The difficulties are resolved on the basis of observations by using capacitor banks and voltage compensators. A justifiable long lasting operation strategy must be determined to use existing dispersed reactive power resources in the AADN in a synchronized manner to control voltage profiles with lowest losses. In this work, an precise network model of the AADN is assembled in DIgSILENT PowerFactory software by using network data obtained from different utility departments to achieve all the study objectives. The full model of the system is not presented in this paper due to security issues. The developed AADN model is used to determine the impacts of capacitor banks, cogenerators, SVCs, and various combinations to reduce network losses and enhance the voltage profile of the AADN. A residential load is developed for winter and summer periods as constant impedance and constant power centered on the exponential load-modeling technique. Fig. 2 shows the load distribution in the AADN.

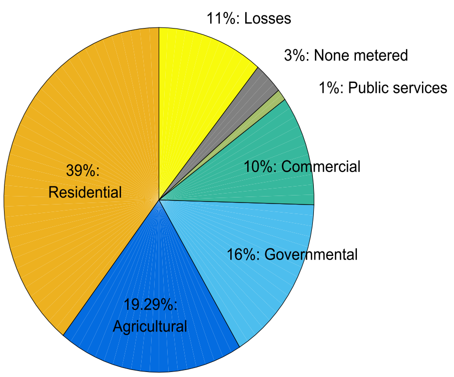

Fig. 2: Load distribution in the AADN

The result of load combination shows that 40% of the load includes constant impedance and that the other 60% is constant power load in case of domestic load for the winter and summer periods.

3. Description of the Allocation Problem for Optimal Energy Resources

Dispersed reactive power resources are installed in a power utility network system for supplying reactive power [2] and thus reducing power losses and improving voltage profile. The financial payback benefits of these resources rely on how the equipment is placed and sized, as well to the proper monitoring and control structures of these resources at various load conditions in the power utility network system. The general placement problem for dispersed reactive power resources is handled as a mixed integer optimization problem, which involves optimizing the type, number, place, and size of the dispersed reactive power sources that have to be connected in a system. The aim is to reduce the total power losses while incorporating the reactive power resource installation cost and sustaining the system voltage constraint.
In this work, the system power losses are determined by considering different load profile periods. In the AADN, yearly load duration intervals are divided into the high, average, and low load levels, and each load has a day-to-day load pattern from which the yearly load duration curve can be generated (Fig. 3).

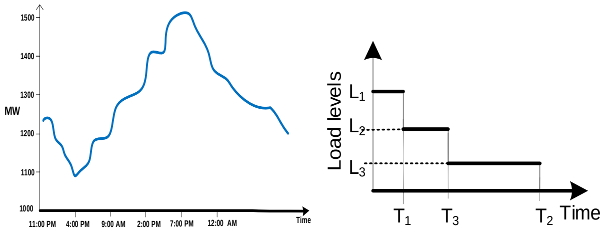

Fig. 3: Typical daily load curve and load duration levels

During individual period, the load level is supposed to be constant, and a cost related with the per unit energy losses is defined, as shown in Table 1.

Table 1: Energy cost and load level

Load level			Energy cost \$/kWh
High	Average	Low	
1	0.7	0.3	0.041

3.1. Problem Design

The cost function, which reduces the investment, cost system energy loss and cost of dispersed reactive power resources, is formulated as follows [24].

$$Min \sum_{k=l}^{n_c} C_k(u_k^0) + k_c \sum_{l=1}^{N} T_l P_{loss,l}(x^l, u^l) \tag{1}$$

subjected to
$P_{flow}(x^l, u^l) = 0, i \in N_T$ (power flow constraints),
$V_{min} \leq |V_{lk}| \leq V_{max}$ (voltage constraints),
where
C_k is the dispersed energy resource cost function,
u is the control and sizing variable,
$x = [P, Q, |V_k|^2]$ is the state variable vector,
k_c is the constant for capacitor cost,
$P_{loss,l}$ is the power loss at any load level l,
T_l is the duration, and
$l \epsilon \{1, 2..N\}$ if N load levels exist.

3.2. Sensitivity Study

The objective of the sensitivity study in this work is to identify locations that have the greatest effect on reactive power injection. The active and reactive power equations for the bus k can be computed as

$$P_k = V_k \sum_{i=1}^{n} (G_{ki} V_i \cos\theta_i + B_{ki} V_i \sin\theta_i) \tag{2}$$

$$Q_k = V_k \sum_{i=1}^{n} (G_{ki} V_i \cos\theta_i - B_{ki} V_i \sin\theta_i) \tag{3}$$

By differentiating P_k and Q_k with respect to voltage magnitudes (Vi) and voltage angle (θ_i), the incremental changes of real power (ΔP_k) and reactive power (ΔQ_k) can be expressed as

$$\begin{bmatrix} \Delta \boldsymbol{P} \\ \Delta \mathbf{Q} \end{bmatrix} = \text{J} \begin{bmatrix} \Delta \boldsymbol{\theta} \\ \Delta \boldsymbol{V} \end{bmatrix} \tag{4}$$

where $\boldsymbol{J}=\begin{bmatrix} \frac{\partial P}{\partial \theta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \theta} & \frac{\partial Q}{\partial V} \end{bmatrix} = \begin{bmatrix} \boldsymbol{H} & \boldsymbol{N} \\ \boldsymbol{K} & \boldsymbol{L} \end{bmatrix}$ is the Jacobian matrix

$\Delta\mathbf{P}=0$ is assumed in (4) to determine the sensitivity of a bus; therefore,

$$[\Delta \boldsymbol{Q}] = [\boldsymbol{L} - \boldsymbol{K}\boldsymbol{H}^{-1}\boldsymbol{N}]\,[\Delta \mathbf{V}]. \quad (5)$$

Hence, the reactive power voltage sensitivity for all system buses is given by

$$\left[\frac{\partial V}{\partial Q}\right] = [\boldsymbol{L} - \boldsymbol{K}\boldsymbol{H}^{-1}\boldsymbol{N}]^{-1}. \quad (6)$$

The buses with the highest sensitivities are selected for placing dispersed reactive power resources in the AADN. Sensitivity study mainly helps in reducing the search area for the optimizer [24, 25, 26].

4. TS Algorithm

After the sensitivity analysis and identification of a set of locations, the next step is to optimize the size of the distributed reactive resources. For this purpose, the TS is applied to find the distributed reactive resources' size and control settings using (1). The following steps illustrate the implementation of the sensitivity analysis and the procedure of the TS algorithm to find the location, sizing, and control scheme of the distributed reactive sources.

1- The system and network data, capacitor/SVC/cogenerator costs (cc), minimum and maximum allowable operating voltages (Vmin, Vmax), and tabu list size data are loaded as inputs.
2- Sensitivity analysis is performed, and the suitable locations where sensitivity is high for the placement of distributed reactive sources are selected as candidate locations for distributed energy resource placement.
3- The TS algorithm is started by randomly selecting an initial solution S_0, and load flow analysis is performed for each load level. If any constraints are violated, then another S_0 is found.
4- Neighborhood solutions S_n are generated from the locality of the present solution N(s) using a sample set of candidates.
5- The current move is estimated. If the move produces a greater assessment than any other, then it is acceptable, and step 6 is continued. Otherwise, step 9 is performed.
6- The tabu condition is checked. Step 7 is continued if the candidate move is tabu. Or else, step 8 is performed.
7- The aspiration criterion is checked. Step 8 is performed if the move passes the aspiration criterion. Otherwise, step 9 is performed.
8- If the move is acceptable, then it is stored as the current best move.
9- Example criteria are checked. If extra move in the list needs to be checked, step 5 is repeated.
10- The selected best move is determined.
11- Ending criteria are checked. If they are not satisfied, then step 4 is repeated.
12- The best solutions are printed out.

4.1. Use of Cogeneration for Power Loss Reduction

Cogeneration is the use of a heat engine or an on-site power plant to generate electricity and useful heat at the same time. Cogeneration devices can be installed at certain locations and used as a power source by providing power to the loads. In the AADN, the locations where the load is greater than 3000 kW and those with thermal or high AC loads, such as hospitals, commercial buildings and hotels, are selected for cogeneration. Table 2 shows the selected locations to use cogeneration in the AADN.

Table 2: Customers with their chiller load and cogenerator size

Customer types	MW	MVA	Chillers MW	Cogen MW	New MW	New MVAr
Complex 1	27	14.22	8	5.333	19	7.42
University 1	28	14.75	10	6.667	18	6.25
Mall 1	27	14.22	8	5.333	19	7.42
Hospital 1	15	7.902	5	3.333	10	3.65
Mall 2	10	5.268	3.5	2.333	6.5	2.29
Hospital 2	12	6.321	4	2.667	8	2.92
Municipality	25	13.68	9	6	16	6.03
Mall 3	7.5	3.951	3	2	4.5	1.40
Hotel 1	13	6.848	4	2.667	9	3.44
Hotel 2	7.5	3.951	3	2	4.5	1.40
University 2	10	5.268	3	2	7	2.71
Complex 2	8	4.214	3	2	5	1.66
Complex 3	6.5	3.424	2.5	1.667	4	1.29
Total	196.5	104	66	44	130	47.9

As shown in the table, the power requirement at each location declines after the installation of the cogeneration plant. This reduction limits the amount of power to be transferred from the grid to the loads, thus reducing power losses in the transmission lines. The capacity (Cg) of the cogeneration plant for a specific location can be obtained as

$$(Cg) = 2Cp/3 \quad (7)$$

where Cp is the chiller load in MW

4.2. Test System and Results

The proposed methods are implemented by using the DIgSILENT PowerFactory software to calculate the optimal placement, type, and size of distribution resources. The recorded data indicate that the total peak demand for the Al-Ain City zone only reaches up to 980 MW during summer.

Before installing a capacitor/SVC or cogenerator, a power flow program based on the Newton–Raphson procedure is implemented to get the current system conditions. The base case power flow result that indicates the bus voltage magnitudes and power losses for the system is shown in Table 3.

Table 3: Base case voltage magnitudes and losses

No	Substation	V, pu	No	Substation	V, pu
1	Ss 1	0.937	16	Ss 16	0.923
2	Ss 2	0.901	17	Ss 17	0.946
3	Ss 3	0.911	18	Ss18	0.930
4	Ss 4	0.941	19	Ss19	0.935
5	Ss 5	0.928	20	Ss 20	0.947
6	Ss 6	0.913	21	Ss 21	0.926
7	Ss 7	0.942	22	Ss 22	0.925
8	Ss 8	0.916	23	Ss 23	0.946
9	Ss 9	0.935	24	Ss 24	0.911
10	Ss 10	0.912	25	Ss 25	0.943
11	Ss 11	0.944	26	Ss 26	0.921
12	Ss 12	0.935	27	Ss 27	0.939
13	Ss 13	0.912	28	Ss 28	0.940
14	Ss14	0.901	29	Ss 29	0.934
15	Ss15	0.906	-	-	-
	Power losses, MW	8.350			

For the base case, sensitivity analysis is also conducted, and the results are shown in Fig. 4.

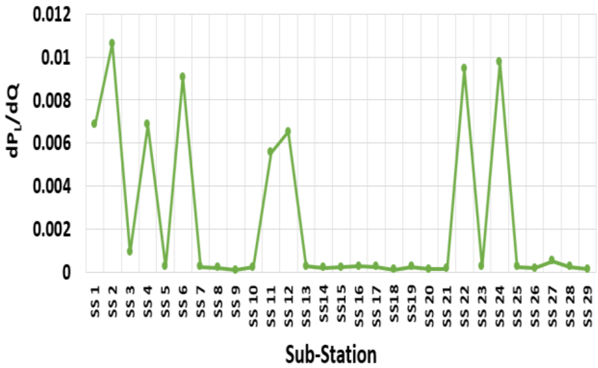

Fig. 4: Results of the base case sensitivity study

From the load flow results and sensitivity analysis, 29 buses out of 150 buses are selected for the installation of dispersed reactive energy resources. Five cases are studied, with cases 1, 2, and 3 focused on the installation of a capacitor bank, cogenerator, and SVC, respectively. The remaining two cases study the impacts of coordinated installation and sizing of capacitors, SVCs, and cogeneration plants.

Case 1: Optimal Location of Capacitor Bank

In this case, the test result of the switched capacitor placement in the AADN is investigated. The proposed TS is implemented, and the results are shown in Table 4.

As shown in the table, the system requires 204 MVAr to be installed in nine different substations. The MVAr injection from these capacitor banks varies depending on the loading conditions.

Fig. 5 shows the result of the voltage magnitudes before and after the installation of capacitor banks at various locations obtained by the proposed algorithm. The voltage magnitudes improve following the installation of the capacitor banks. With the enhancement in voltage magnitudes, power losses also improve at the substations where the capacitor banks are installed (Fig. 6).

Table 4: Optimal sizes of capacitor banks

Substation Name	Capacitor Size MVAr		
	Load level		
	Peak load	Medium load	Light load
Ss 2	28	25	25
Ss 14	27	24	24
Ss 15	20	20	17
Ss 3	25	25	25
Ss 24	20	18	20
Ss 10	20	20	18
Ss 13	42	40	35
Ss 14	10	8	8
Ss 27	12	12	12

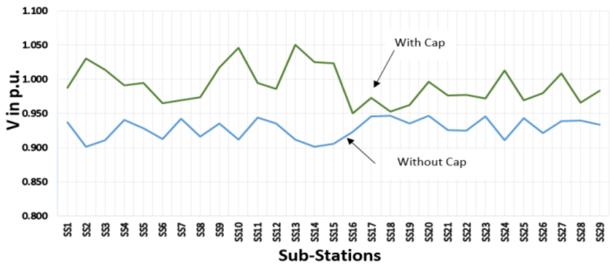

Fig 5: System voltage profile before and after capacitor bank installation

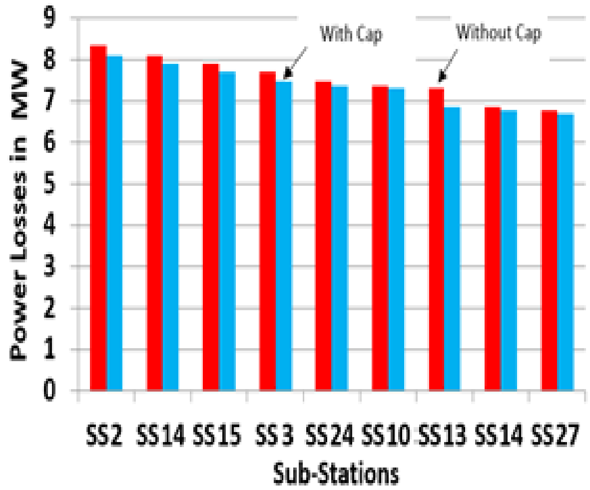

Fig 6: Power losses at the substations before and after capacitor bank installation

The payback period due to the installation of a 204 MVAr capacitor bank is calculated as the cost of installation divided by the cost of saving energy due to the cost of investment for capacitor banks. The installation cost of various reactive power resources is given in Table 5. Table 6 shows that the payback period for installing capacitor banks is 18.8 years.

Table 5: Investment and installation costs of capacitor banks and distributed energy sources

Description	Unit rate, $
5 MVAr capacitor bank	237,288.4
Detuning/filter reactor	28,280.74
Erection cost	7,871.97
Total price	273,441.1
11kV, 5 MW Cogen	285.000.00
11 kV, 5 MVAr SVC	307.871.97

Case 2: Optimal Placement of Cogeneration Plants

In this test case, the influence of installing cogeneration plants is analyzed. The optimization technique selects 29 buses out of 150 buses from the base case to install cogeneration plants for reducing the load demand from the network. Furthermore, to line power flow limits and voltage constraints, the maximum real and reactive power limits given in Table 2 are considered in this optimization problem. The results of the simulation based on the TS algorithm indicate that the required voltage profile can be obtained by installing 85 MW cogeneration plants in 13 different buses. With this 85 MW power injection, the real power losses are decreased from 8.35 MW to 5.64 MW. Fig. 7 shows the improvement in voltage magnitude attained in this case study. Table 7 presents a summary of the payback duration for installing an 85 MW cogenerator.

Table 6: System cost and payback period of capacitor banks

Substation Name	Energy loss /year in $	Investment cost in $	Total system cost in $	Energy save/year in $
Ss 2	2998174	1531269.6	4529444.3	86344.08
Ss 14	2911833	1476581.4	4388914.6	74919.17
Ss15	2836913	1093764	3930677.9	69412.67
Ss 3	2767506	1367205	4134711.5	78670.91
Ss 5	2688835	1093764	3782599.6	46140.87
Ss 10	2642694	1093764	3736458.7	15696.47
Ss 13	2626998	2296904.4	4923902.6	156731.3
Ss 9	2437661	437505.6	2875166.7	28969.11
Ss 27	2781952	1257829.1	4039781.2	33786.34
Total	24692566	11648587	36341657	590670.9
Total energy cost per year $			2249239.5	
Total cost of 204 MVAr of capacitor bank			11.156.397.24	
Total energy saving per year, $			593096.51	
Payback period			18.8	

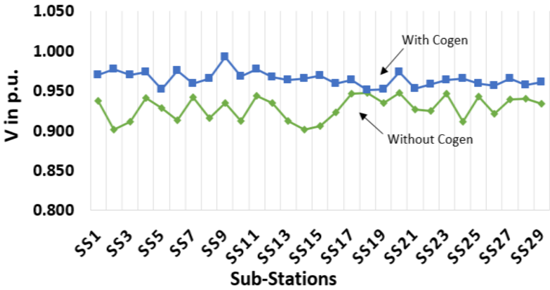

Fig 7: System voltage profile before and after cogenerator installation

Table 7: Summary of payback period of cogenerator installation

Total energy cost per year $	2249239.5
Total cost of 85 MW of Cogen	48450000
Total energy saving per year, $	24434552.7
Payback period	1.98

Case 3: Optimal Placement of SVC

From an operational point of view, SVCs can supply reactive power to regulate voltage magnitude at the point of connection in the power system. They are widely used to provide firm reactive power and voltage improvement. In this case, SVCs should be installed at 10 substations with a total capacity of 208 MVAr. This amount of reactive power injection from SVCs reduces power losses from 8.35 MW to 6.65 MW. Power loss reduction and the amount of reactive power requirements are similar to those in Case 1 with capacitor banks. Therefore, the voltage profiles obtained by installing SVCs are almost the same as those shown in Fig. 5. However, due to the huge investment cost of SVCs, the payback period for SVC installation is infeasible (Table 8).

Table 8: Summary of payback period of SVC installation

Total cost of energy per/year $	2249239.5
Total cost of 204 MVAr of SVC	1256117638
Total save of energy per/year, $	457929
Payback period	27.4

Case 4: Coordinated Placement of Capacitor Banks and Cogenerator Plants

The optimal placement of capacitor banks and cogeneration plants is studied in this case. The proposed TS algorithm determines the need to install 98 MVAr of capacitor banks in six buses and 35 MW of cogenerator plants in another five buses. With these installations, the voltage magnitudes at all substation buses improve, as shown in Fig. 8. In this case, significant loss reduction is observed (from 8.35 MW to 6.2 MW) relative to previous cases. Table 9 shows the summary of the payback period for the coordinated placement of capacitor banks and cogeneration plants. This solution may provide substantial benefits to utility companies and consumers.

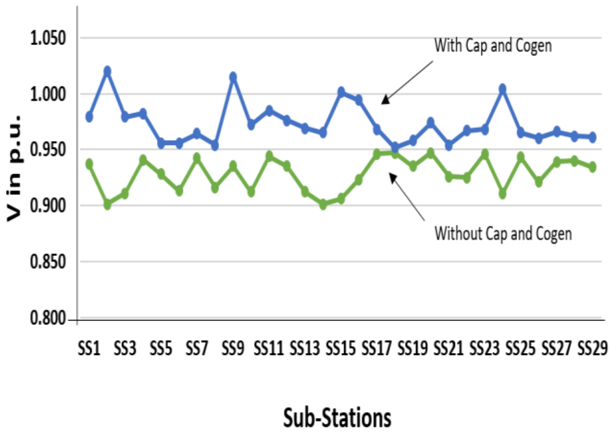

Fig 8: System voltage profile before and after capacitor and cogenerator installation

Table 9: Summary of payback period of coordinated placement of capacitor bank and SVC

Total energy cost per year $	2249239.5
Total cost of compensation equipment	25309445.6
Total energy saving per year, $	11713105.5
Payback period per year	2.16

Case 5: Coordinated Placement of Capacitor Banks, SVCs, and Cogenerator Plants

A combination of capacitor banks, cogenerators, and SVCs are optimized and tested in this study to identify their effects on voltage profiles and losses. The simulation results show that the distribution requires the installation of 95 MVAr of capacitor banks at three substations, 20 MW of cogenerators at three large consumer locations, and 52 MVAr of SVCs at three substations. With this sizing, voltage magnitudes are improved, and losses are decreased from 8.35 MW to 6.51 MW. Fig. 9 shows the voltage profile of this case study, and Table 10 shows the summary of the payback duration of the capacitor bank, cogenerator, and SVC for selected sizing and locations.

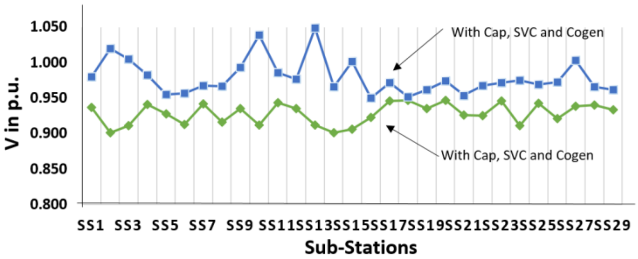

Fig. 9: Network voltage profile before and after the installation of capacitors, SCVs, and cogenerators

Table 10: Summary of payback period of coordinated placement of capacitor bank, SVC, and cogenerator

Total energy cost per year $	2249239.5
Total cost of Cogen and SVC	42595380.9
Total energy saving per year, $	8397160.8
Payback period per year	5.07

5. Conclusion

This paper presents a coordinated allocation of capacitors, SVCs, and cogeneration plants in the AADS by using the TS algorithm and sensitivity analysis. These techniques significantly reduce system losses and improve voltage profiles. Sensitivity analysis is performed to select suitable locations, and TS is utilized to determine the optimal sizing of equipment. The study shows that the best choice in the AADN is to use cogeneration plants to decrease power losses and enhance system voltages. The installation of capacitors and cogenerators is also found acceptable in case cogeneration plants are unavailable. The results reveal that the installation of SVCs is unsuitable due to the high cost and long payback periods.

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