Optimal investment framework of static VAr compensators in distribution system based on life cycle cost

Nguyen Hien Trung, Vu Van Thang
Department of Power System, Faculty of Electrical Engineering, Thainguyen University of Technology, Thainguyen City, Vietnam

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ABSTRACT

The distribution system planning and operating present significant challenges due to low voltage, high impedance, and large load density, which lead to substantial power losses and low voltage quality. To address this challenge, the paper proposes an optimal framework for the simultaneous determination of the placement and sizing of static VAr compensators (SVCs) in DSs. The proposed model is formulated as an optimization problem that minimizes the life cycle cost, while accounting for the varying lifespans and investment times of SVCs. The framework incorporates hourly load variation and employs full alternating current (AC) power flow analysis to improve the accuracy of results. Additionally, it considers the dependency of the reactive power injected by SVCs on the DSs and incorporates the discrete rated capacities of SVCs to ensure practical feasibility and enhance the accuracy of compensation power, effect of DSs. The proposed approach is validated using a modified 33-bus IEEE test system implemented in the general algebraic modeling system (GAMS). Numerical results from multiple case studies confirm the feasibility and high performance of the proposed model.

Corresponding Author:

Vu Van Thang
Department of Power System, Faculty of Electrical Engineering, Thainguyen University of Technology
No. 666, 3/2 Street, Thainguyen City, Vietnam
Email: thangvvhtd@tnut.edu.vn

1. INTRODUCTION

Distribution systems (DSs) are the points of contact between the electricity industry and the consumers, typically operating at medium or low voltage levels. They include numerous feeders and distribution transformers characterized by high impedance and dense loads, which result in elevated power losses and degraded voltage quality [1], [2]. These factors significantly reduce the technical and economic efficiency of DSs, requiring costly upgrades to feeders, transformers, and increased electricity purchases from the grid. Consequently, these issues are critical in DS planning, design, and operation [3].

Additionally, modern DSs face great challenges due to the increasing penetration of renewable energy sources and the integration of advanced power electronic devices. Effective planning and operational strategies are therefore necessary to enhance system performance, reduce operational costs, and improve voltage profiles [3], [4]. As a result, the traditional passive model of DSs is evolving toward active DSs, which integrate distributed generation (DG), energy storage systems, and reactive power compensation devices, allowing operators to manage power flows dynamically through flexible network topologies [5], [6]. In this context, reactive power compensation becomes a crucial aspect of DS planning and operation. Selecting the optimal type, size, and location of compensation devices is essential to minimize losses and maintain acceptable voltage profiles. Common techniques for improving DS performance include feeder upgrades, voltage level enhancement, distributed generation, and network reconfiguration [7], [8]. Among these, reactive power compensation is particularly attractive due to its cost-effectiveness, minimal disruption to the existing network, and relatively short implementation timeline [9].

Traditional compensation devices such as synchronous condensers, capacitors, and reactors have limitations. Synchronous condensers are less common today due to their high losses, high costs, and slower response times. Capacitors and reactors are more commonly used due to lower cost and simplicity, they lack the dynamic response required by modern DSs with variable load profiles and DG [6], [10]. Overcoming the above limitations, SVCs offer several advantages. By using thyristor-based switching, static VAr compensators (SVCs) provide fast, continuous control of reactive power without increasing fault current levels. They improve voltage stability, reduce system losses, and enhance power quality by mitigating voltage fluctuations and load imbalance [9], [11], [12]. Therefore, SVCs have become increasingly relevant in modern DS planning and operation.

Various optimization techniques have been proposed to determine the optimal location and size of reactive compensation devices, including genetic algorithms, dragonfly, flower pollination, whale optimization, and others [13]–[19]. Although these studies help reduce losses and improve voltage profiles, they often assume constant loads, ignore the voltage dependency of compensation power, and simplify objectives using weighting or sensitivity factors, which may cause errors in power flow and loss calculations. To overcome the limitations of capacitors, SVCs have been researched due to their superior dynamic response and control flexibility. Recent studies have employed multi-objective models to optimize SVC placement and sizing, taking into account voltage deviation, system losses, and investment cost [20]–[29]. However, most of these approaches assume a fixed load and overlook the time-varying operation parameters of DSs and the discrete nature of SVC rated capacities. They also often ignore differences in investment time and lifespans of SVCs, which can influence planning and operation results of DSs.

Life cycle cost (LCC) analysis is a comprehensive method for evaluating the total cost of a project over its entire lifespan, including investment, operation, maintenance, and end-of-life costs [30], [31]. This approach has been widely applied in power systems for optimizing distribution feeders or reinforce the DSs [32]. It has also been used to assess the economic performance of microgrids [33], energy hubs, renewable resources [34], [35], and transformers [36]. The abovementioned studies have shown the feasibility and effectiveness of the LCC analysis method.

To address the aforementioned challenges, this study proposes an optimal investment framework for the simultaneous determination of SVC placement and sizing in DSs. The framework aims to minimize the total LCC while incorporating realistic operational constraints, including load variation, voltage profile limits, transformer and feeder capacities, and the discrete rated capacities of SVCs. The novelty of this study lies in its comprehensive modeling of investment time, device lifespan, and dynamic system behavior, which enables more accurate, practical, and economically efficient planning for reactive power compensation using SVCs in DSs. The main contributions of this research are as follows:

a. A novel investment optimization model is formulated as a mixed-integer nonlinear programming (MINLP) problem with the objective of minimizing the total LCC. The model integrates various cost components as investment, operation, energy losses, replacement, and residual value over a multi-year planning horizon. This holistic approach provides a more realistic economic evaluation than single-objective formulations.
b. The proposed framework accounts for hourly load variation, different investment schedules, and varying lifespans of SVCs. It also considers the dependency of output reactive power of SVC on operation voltage and reflects actual device specifications by integrating discrete rated capacities of SVCs. These features significantly enhance the fidelity and practical relevance of the optimization outcomes.
c. This study employs the basic open-source nonlinear mixed integer programming solver (BONMIN) solver in the general algebraic modeling system (GAMS) environment to solve the MINLP model efficiently. The ability of solver to handle both continuous and discrete variables allows for improved convergence and reduced computational burden while ensuring solution quality and reliability. Therefore, the proposed solution can be appropriately applied to real-world, large-scale distribution systems.

Next sections of the paper are organized as follows: The mathematic model of SVC is introduced in section 2. An optimal investment framework with objective function and constraints are presented in section 3. Section 4 shows calculated results and discussions from the 33-bus IEEE test system. Finally, the conclusion is demonstrated in section 5.

2. MATHEMATIC MODEL OF SVC

SVC is defined as a thyristor-controlled generator of reactive power whose output varies to exchange capacitive or inductive current or both to maintain or control specific parameters of the electrical power system, typically bus voltages. SVC is a high-voltage device that regulates effectively the voltage, reactive power, and damping of power and voltage oscillations [11], [37], [38]. SVC is connected in a shunt with several different circuit structures. The general circuit structure of an SVC includes a fixed shunt capacitor and thyristor-controlled reactor as shown in Figure 1 [24], [29].

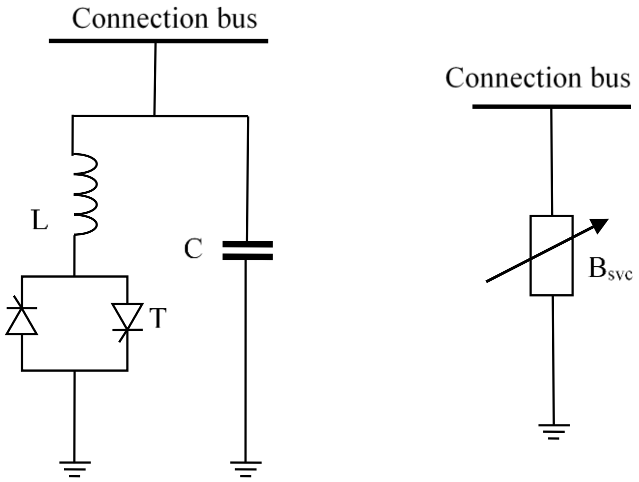


Figure 1. Circuit structure and equivalent model of SVC

As seen, an SVC is composed of a fixed capacitor and thyristor-controlled reactor. The reactive power injected by the SVC is controlled by the firing delay angle α of the thyristor. The firing delay angle α of the thyristor changes lead to a change value of equivalent susceptance of SVC according to (1) [12], [24]. Hence, the reactive power provided by SVC depending on the rated voltage profile can be expressed as (2). Where $Q^{svc}$is reactive power injected by the SVC, B^{svc} is equivalent susceptance of SVC, U_r is the rated voltage profile of SVC, and L and C are the inductance of the reactor and the capacitance of the capacitor, respectively.

$$\begin{aligned} B^{svc} &= B_L(\alpha) + B_C \\ B_L(\alpha) &= -\frac{1}{\omega L}\left(1 - \frac{2\alpha}{\pi}\right) \\ B_C &= \omega C \end{aligned} \tag{1}$$

$$Q^{svc} = -U_r^2 . B^{svc} \tag{2}$$

If the load of the electrical system is capacitive, the SVC controls thyristors so that coils generate maximum power, and the SVC consumes reactive power from the system. When the load is inductive, the SVC controls thyristors so that coils generate minimum power, and reactive power is injected into the system. SVC can achieve fast and continuous control and thus operating parameters of the system can be improved [10], [38].

3. OPTIMAL INVESTMENT FRAMEWORK

In DS, reactive power compensation by capacitors or SVCs can reduce power losses and energy losses. However, when SVC is invested in DS, the cost of the system will be increased along with the operating parameters of DS also being changed. Therefore, an optimal investment framework is proposed to optimally invest SVC in the DS described by the MINLP problem with objective function and constraints as below.

3.1. Objective function

In this study, an objective function minimizing the life cycle cost of the SVCs investment project in DS during planning horizon is proposed as shown in (3) [32], [34]. Where the life cycle cost is calculated to the present value at the base year by discount rate r, $C_{loss.t}$ is the energy loss cost of DS, $C_{inv.t}^{svc}$ is the investment cost of SVCs, $C_{ope.t}^{svc}$ is the operation and energy loss cost in the SVCs itself, and C_{rr} is the replaced and residual value of SVCs at the end of the computed period.

$$J = min[LCC]$$
$$LCC = \sum_{t=1}^{T} \frac{1}{(1+r)^t} \left(C_{loss.t} + C_{inv.t}^{svc} + C_{ope.t}^{svc} - C_{rr} \right) \quad (3)$$

The energy loss cost of DS is computed by (4) as follows [24], [25]. The capital cost per kVAr of SVC depends on the invested capacity calculated as (5) and is denoted as $C_{0.i,t}^{svc}$. So, the total investment cost for SVCs in the distribution system of the project is present in (6).

$$C_{loss.t} = \sum_{h=1}^{H} \beta_h . \sum_{i=1}^{N} \sum_{j=1,i\neq j}^{N} G_{ij} \left(U_{i,t,h}^2 + U_{j,t,h}^2 + 2U_{i,t,h} U_{j,t,h} cos(\delta_{i,t,h} - \delta_{j,t,h}) \right) \forall t \in T \quad (4)$$

$$C_{0.i,t}^{svc} = 0{,}0003. \left(Q_{r.i,t}^{svc} \right)^2 + 0{,}3051. Q_{r.i,t}^{svc} + 127{,}38 i \in N_{svc} \quad (5)$$

$$C_{inv.t}^{svc} = \sum_{i=1}^{N_{svc}} \alpha_{i,t}^{svc} . C_{0.i,t}^{svc} . Q_{r.i,t}^{svc} \; t \in T \quad (6)$$

SVC devices include the capacitor, the reactor, and the thyristors. So, there is energy loss in the SVC itself. The capacitor losses are small but constant, whereas the reactor and thyristor losses depend on the operating current. Hence, the operation cost of SVC can be computed as (7). The lifetime of SVCs is normally different with planning horizons, and they are not concurrently invested. At the end of the calculation period, the SVCs can continue to operate if the calculation time is shorter than the lifetime of the SVC. Whereas the SVCs need to be replaced if the calculation time is greater than the lifetime of the SVCs. Therefore, the replacement cost and residual value are presented in (8) and calculated at the base year in the objective function. Where, t_{inv}^{svc} and T_{lt}^{svc} are installation time and lifetime of SVCs [30], [32].

$$C_{ope.t}^{svc} = \sum_{i=1}^{N_{svc}} \sum_{h=1}^{H} k_0^{svc} . \beta_h . Q_{i,t,h}^{svc} \forall t \in T \quad (7)$$

$$C_{rr} = \frac{(t_{inv}^{svc} - T_{lt}^{svc})}{T_{lt}^{svc}} C_{inv,t}^{svc} \forall t \in T \quad (8)$$

3.2. Constraints

The technical constraints are utilized to guarantee the operability of the DSs and SVCs, which include alternating current power flow constraints, investing and sizing SVC constraints, and limitations of bus voltage profile and transmission power of feeders.

3.2.1. Constraints for power flow

To reduce the error of computed results, an AC nonlinear power flow model considering to change of load in each hour and computing year is utilized and expressed in (9) [23], [24]. The effects of both active and reactive power on the calculation of power and voltage losses are considered in the model leading to improved economic effect of the project and accuracy of operation parameters of DSs. Where the load at buses in each hour h and computing year t is analyzed as (10) follows.

$$P_{i,t,h}^s - P_{i,t,h}^l - k_0^{svc} . Q_{i,t,h}^{svc} = \sum_{j=1}^{N} |Y_{ij}| . |U_{i,t,h}| . |U_{j,t,h}| . cos(\theta_{ij} - \delta_{j,t,h} - \delta_{i,t,h})$$
$$Q_{i,t,h}^s - Q_{i,t,h}^l + Q_{i,t,h}^{svc} = -\sum_{j=1}^{N} |Y_{ij}| . |U_{i,t,h}| . |U_{j,t,h}| . sin(\theta_{ij} - \delta_{j,t,h} - \delta_{i,t,h})$$
$$\forall i \in N, t \in T, h \in H \quad (9)$$

$$P_{i,t,h}^l = k_h^l . P_{i,t}^l P_{i,t}^l = P_{i,t-1}^l (1 + k_l)$$
$$Q_{i,t,h}^l = k_h^l . Q_{i,t}^l \qquad Q_{i,t}^l = Q_{i,t-1}^l (1 + k_l) \quad (10)$$

3.2.2. Limits of SVC capacity

As is known, the participation of SVC in DS changes the power flow and affects the technical and economic parameters of systems. Therefore, to ensure the effect of the SVC investment, the annual installed capacity of SVC must be selected to optimize cost and guarantee the operation technic parameters of DS. The binary variable $\alpha_{i,t}^{svc}$ proposed in (11) limits the maximum and minimum invested capacity of SVC for each bus each year. Besides, the planning horizon of the DS is short-term, and thus only an SVC is chosen at each load bus in the overall planning horizon to reduce the capital cost as constrained in (12) with binary variable $\alpha_{i,t}^{svc}$.

$$Q_{r.i,t}^{svc} - Q_{rmin}^{svc}$$
$$\forall i \in N_{svc}, t \in T \tag{11}$$

$$\sum_{i=1}^{N_{svc}} \sum_{t=1}^{T} \alpha_{i,t}^{svc} \leq 1 \tag{12}$$

SVCs are often made into modules and their rated capacities are discrete values. Hence, the binary variables $\gamma_{k,i,t}^{svc}$ are integrated into the model to select optimal rated capacity according to the standard value of SVC as presented in (13) which $Q_{st.k}^{svc}$ is the rated capacity of module k.

$$Q_{r.i,t}^{svc} = Q_{r.i,t-1}^{svc} + \gamma_{k,i,t}^{svc}. Q_{st.k}^{svc} \sum_{k=1}^{K} \sum_{i=1}^{N_{svc}} \sum_{t=1}^{T} \gamma_{k,i,t}^{svc} \leq 1$$
$$\forall i \in N_{svc}, t \in T, k \in K \tag{13}$$

Moreover, the maximum capacity of SVC at each operation time depends on the rated capacity and operating voltage profile at bus-connected SVC. The operating capacity of SVC can be controlled to change to meet system requirements. So, constraints for SVC capacity depend on the bus voltage profile shown in (14) with the rated voltage of SVC denoted U_r [24], [25].

$$Q_{i,t,h}^{svc} = B_{i,t}^{svc} . U_{i,t,h}^2 B_{i,t}^{svc} = (B_{min.\,i,t}^{svc} \div B_{max.\,i,t}^{svc})$$
$$B_{min.\,i,t}^{svc} = -\frac{Q_{r.i,t}^{svc}}{U_r^2} B_{max.\,i,t}^{svc} = \frac{Q_{r.i,t}^{svc}}{U_r^2}$$
$$\forall i \in N_{svc}, t \in T, h \in H \tag{14}$$

3.2.3. Constraints of feeder

The power-carrying capability of feeders is primarily limited by their thermal ratings, which prevents overheating and potential equipment damage. Therefore, it is essential to impose constraints on the selection of SVC capacity to ensure safe system operation. These constraints are shown in (15). During the planning and operational period, the power flow through each feeder must remain within its allowable transmission limits. This helps maintain system reliability, avoid overloading, and extend the lifespan of distribution system.

$$S_{ij,t,h} \leq S_{F.ij}^{\max} \forall ij \in N, t \in T, h \in H \tag{15}$$

3.2.4. Constraints of transformer substation

During the planning time, the DSs receive the power through the utility grid-connected transformer substation. The transformer has a maximum transmission capacity that must not be exceeded to ensure safe and stable operation. Therefore, the transmission power through transformers must be guaranteed within the transmission limits of the transformers shown in (16).

$$S_{i,t,h} \leq S_{T.i}^{max_T} \tag{16}$$

3.2.5. Constraints on bus voltages

For the DSs connected to the large grid, the voltages at the connected bus are usually stabilized and assumed to be constant. However, a voltage loss is generated on the feeder leading to a drop in voltage at the load bus. The voltage profiles at load buses are changed according to the feeder parameters and the power flow. Thus, the limits on load bus voltages are shown in (17). U_i^{min}, U_i^{max} are maximum and minimum limit of load bus voltages.

$$U_i^{min} \leq \left|U_{i,t,h}\right|_i \leq U_i^{max} \tag{17}$$

3.3. Solution method

The above investment framework to optimize SVCs in DSs is formulated with nonlinear constraints integrated into binary variables. Hence, the proposed model is a mixed integer nonlinear programming. To solve the MINLP problems, several solvers have been introduced in the existing literature [39]. In particular, the BONMIN solver is the most suitable solution in the GAMS environment to solve the MINLP non-convex problems. It is a high-level modeling system for mathematical programming and optimization of the DSs.

BONMIN implements three different algorithms to solve MINLP problems consisting of simple branch-and-bound algorithms, outer-approximation-based decomposition algorithms, and outer-approximation based branch-and-cut algorithms [39]. This is not an exact solver only for convex problems but takes into consideration the values of the heuristic solutions to solve the problem efficiently for convergence compared to the other solvers mentioned or meta-heuristic algorithms. Moreover, the MINLP problems are successfully solved with the least computational burden. For the above reasons, this study is directed toward the use of the BONMIN solver to find an optimal solution to the proposed problem.

4. CALCULATIONS AND DISCUSSIONS

4.1. Analysis parameters and assumptions

The feasibility and efficiency of the proposed model have been investigated on a modified 33-bus radial distribution system operating at 22 kV, connected to the utility grid through transformers, as shown in Figure 2 [14], [40]. Parameters of loads and feeders changed to match this study are presented on Tables 1 and 2. The limit capacity of the transformer is assumed to be about 25 MVA. The hourly load curve of the system is computed by the proportionality factor of peak demand presented in Figure 3.

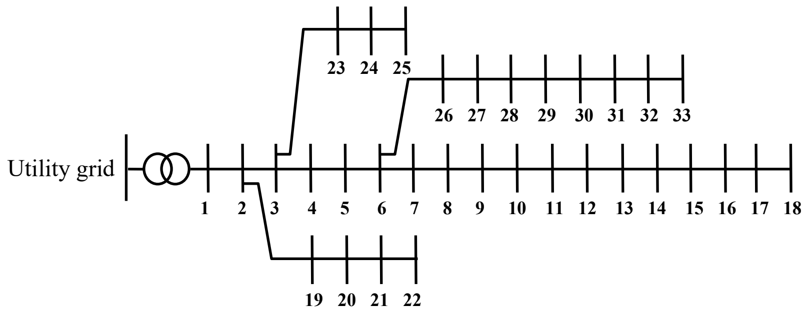


Figure 2. Diagram of the 33-bus IEEE test system

Table 1. Data of loads

Bus	$P_{i,0}^l$ (kW)	$Q_{i,0}^l$ (kVAr)	Bus	$P_{i,0}^l$ (kW)	$Q_{i,0}^l$ (kVAr)	Bus	$P_{i,0}^l$ (kW)	$Q_{i,0}^l$ (kVAr)	Bus	$P_{i,0}^l$ (kW)	$Q_{i,0}^l$ (kVAr)
1	-	-	10	220	160	18	490	440	26	660	525
2	200	160	11	145	110	19	190	140	27	560	525
3	290	240	12	160	135	20	290	220	28	360	310
4	320	250	13	460	435	21	190	140	29	420	370
5	160	130	14	220	180	22	390	340	30	300	200
6	360	310	15	560	460	23	390	350	31	550	470
7	300	200	16	260	200	24	420	350	32	310	260
8	300	210	17	360	320	25	220	200	33	460	390
9	160	120									

Where, $P_{i,0}^l, Q_{i,0}^l$ are active and reactive power demand at bus in base year of planning horizon

Table 2. Data of feeders

No	Bus i-j	$S_{max.ij}$ (MVA)	Rf_{ij} (Ω)	Xf_{ij} (Ω)	No	Bus i-j	$S_{max.ij}$ (MVA)	Rf_{ij} (Ω)	Xf_{ij} (Ω)	No	Bus i-j	$S_{max.ij}$ (MVA)	Rf_{ij} (Ω)	Xf_{ij} (Ω)
1	1-2	20	0.092	0.097	12	12-13	15	1.468	1.155	23	23-24	10	0.898	0.709
2	2-3	20	0.093	0.091	13	13-14	15	1.541	1.712	24	24-25	10	0.896	0.701
3	3-4	20	0.166	0.086	14	14-15	15	1.591	1.526	25	6-26	10	1.203	1.103
4	4-5	20	0.181	0.094	15	15-16	15	1.746	1.545	26	26-27	10	1.484	1.444
5	5-6	20	1.819	1.707	16	16-17	15	1.289	1.721	27	27-27	10	1.259	1.933
6	6-7	20	1.187	1.618	17	17-18	15	0.732	0.574	28	28-29	10	1.804	1.700
7	7-8	20	0.711	0.235	18	2-19	10	0.164	0.156	29	29-30	10	1.507	1.258
8	8-9	20	1.030	0.740	19	19-20	10	1.504	1.355	30	30-31	10	1.974	1.963
9	9-10	20	1.044	0.740	20	20-21	10	0.409	0.478	31	31-32	10	2.410	2.461
10	10-11	15	0.196	0.650	21	21-22	10	0.708	0.937	32	32-33	10	1.441	1.630
11	11-12	15	0.374	0.123	22	3-23	10	1.451	1.308					

Where, S_{max} is thermal limited power for feeders

The following assumptions are utilized in this study including:

a. The hourly load curve of Ds is set to be the same as in Figure 3. Similarly, the electrical price according to time of use is assumed in Figure 4. The selected planning horizon is 5 years with an annual growth factor of load of about 10% per year.
b. The investment cost of SVCs is computed as (5). The active power loss factor of the SVC itself is determined at about 1% [41], [42] with the SVC lifetime of about 20 years [11], [43]. The SVC can be selected to install at all load buses because of quick installation and small spaces of occupation. The parameters of candidate SVC with the rated powers being discrete values are presented in Table 3.
c. The voltage at load buses is allowed to change from 0.95 to 1.05 pu in order to guarantee the operation of devices. At the utility grid-connected transformer substation bus, the voltage usually is stabilized and assumed to be 1.05 pu.

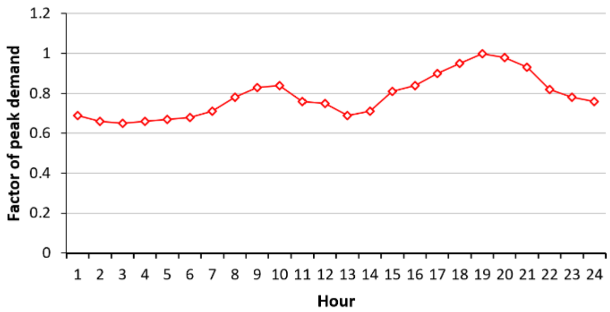


Figure 3. The hourly load curve of DS

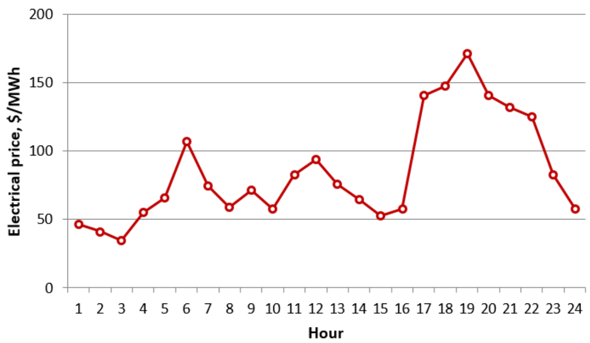


Figure 4. Electrical energy prices

Table 3. Parameters of candidate SVC

Type	1	2	3	4	5	6	7
Rated power (MVAr)	150	300	450	600	750	900	1050
Type	8	9	10	11	12	13	14
Rated power (kVAr)	1200	1350	1500	1650	1800	2100	2700

4.2. Results and discussions

To evaluate the feasibility and efficiency of the proposed investment framework, the test DS are investigated and compared in the following cases. Case 1 computes the DS with one load mode and unutilized SVC while SVC is selected to compensate for DS with constant load mode in case 2 during calculating time and the average price. Case 3 does not utilize SVC to compensate for DS with an hourly load curve. Finally, optimal compensation by SVC for DS is tasked in case 4 considering economic effectiveness by LCC objective function, load variation with hourly load curve, SVC compensating power according to bus voltage, and rated capacity with discrete values as optimal framework presented in section 2.

The numerical results with the above DS determine placement, sizing, and time of SVC invested in cases as shown in Table 4. Both case 2 and case 4 select the installed placement of SVC at buses at the feeder end because of the higher compensation effectiveness of SVC comparison with buses at the feeder beginning.

SVC is selected in the first year to maximize its efficiency by reducing power loss and improving operating voltage during planning horizon. The total invested capacity of case 2 is about 30 kVAr and bigger than case 4 by 150 kVAr, equivalent to 5%. Because case 2 is computed with the constant load being peak load during planning horizon, the SVC capacity selected is large. However, there is a significant error in this case due to the load variation in practice. Although there are the above disadvantages, the compensation by SVC in case 2 also improves the effectiveness of DS compared with case 1, without SVC, including 14.2% reduced LCC and 1.1% reduced loss of total electrical loss of DS as shown on Table 5.

Table 4. Invested capacity of SVC (MVAr)

Bus	Invested time (year)																			
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
	Case 1					Case 2					Case 1					Case 4				
13						750										750				
18						750										750				
27						750										750				
33						750										600				

Table 5. Comparison of the economic indicators

No	Cost	Case 1	Case 2	Case 3	Case 4
1	LCC (M$)	5.21	4.47	4.72	3.77
2	SVC investment cost (M$)	0	0.38	0	0.36
3	Electrical energy loss (%)	6.88	5.78	5.97	4.66

In case 4, the DS effectiveness is significantly improved when SVC is utilized and invested placement, sizing, and time of SVC are computed according to the proposed investment framework. The total selected capacity of SVC is 2850 kVAr compensated at bus 13, 18 and 27 about 750 VAr, and bus 33 about 600kVAr. Although the total compensation capacity is reduced by 150 VAr, equivalent to 5%, compared with case 2, electrical energy loss is reduced by 1.31%. The electrical energy loss is reduced in this case because it considers load variation with the hourly load curve and compensated power depending on the operation voltage of SVC. Hence, the accuracy of numerical results is enhanced and more suitable for the operating practices of SVC. The total rated capacity of the SVC selected is about 32% of the peak reactive power of DS and SVC can be controlled to change compensation power and response to the variation of load during computed time. Therefore, there is no overcompensation, and the number of SVCs in the system is reduced. Besides, the effectiveness of optimal compensation by SVC in DS in case 4 is also shown when compared to case 3, without SVC. LCC of the project decreases by about 0.95 M$, from 4.72 M$ to 3.77 M$, equivalent to 20.1%, although the invested cost of SVC increases about 0.36 M$ in the first computing year. Similarly, the energy loss of this case is reduced by 1.31% of the total electrical loss of DS, from 5.97% to 4.66%.

In analyzed cases, the feeders and transformer substations are always guaranteed for operation during planning horizon by constraints on the limited transmission powers. The maximum power on feeders and transformers during planning horizons of case 4 presented in Figures 5 and 6 shows the power of all of the devices in the system is always lower than limited power. The maximum power is on feeder 1.2 in the 5th year only 15.77MVA, equivalent to 78.9% of limited power, and decreases 15.6% compared with case 3. Similarly, the maximum operation power of the transformer is 15.7MVA in the 5th year, equivalent to 63% of the limited capacity of the transformer. This power is 13.39MVA and is 3.1% larger than the limit capacity in case 3 and thus must upgrade the transformer substation in the 4th year. The power flow in the feeders and transformers decreases due to being supported by installed SVCs at load buses. As a result, upgrades of feeders and transformers are deferred, leading to a decrease in the capital costs of DS.

One of the most important aspects of reactive power compensation is to reduce voltage loss and improve bus voltage profiles. This is also guaranteed by the constraints of limited voltages on the optimal model. However, the power flow in the feeders decreases due to being supported by SVCs at load buses. Hence, the voltage loss lessens, and voltage profiles at buses in the case with SVC are improved during planning horizon shown in Figures 7 and 8. The minimum voltage is 0.90 and 0.96 pu at buses 16, 17 and 18 in the 5th year of case 3 and case 4, respectively. The voltage profiles improve by about 6%, equivalent to 0.06 pu. The minimum voltage profile at buses 14, 15 and 33 is improved by about 5%, equivalent to 0.05 pu, while the voltage profile at buses 9 to 13 and 27 to 30 is enhanced by about 4%, equivalent to 0.05pu. The voltage of buses near the utility grid also improves by 0 to 3%. Similarly, the maximum voltage profile at most buses is improved from 1% to 4%, and it is always lower than the voltage profile limited to about 1.05 pu. Moreover, the bus voltage profile during computing time in case 2 compared with case 1 also improved from 1% to 5%. The above results show the effectiveness of reactive power compensation by SVC at DS in improving bus voltage profiles.

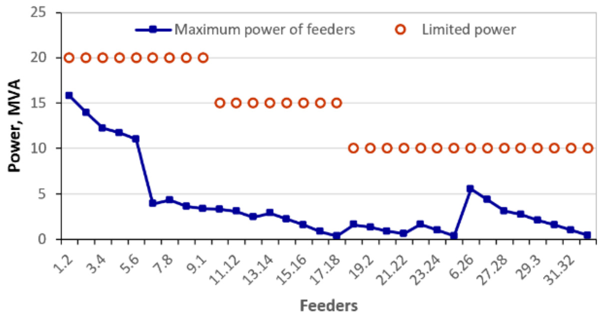


Figure 5. Limited and maximum power of feeders in case 4

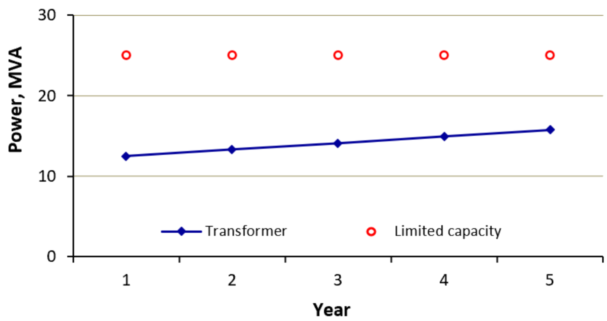


Figure 6. Limited and maximum power of transformer in case 4

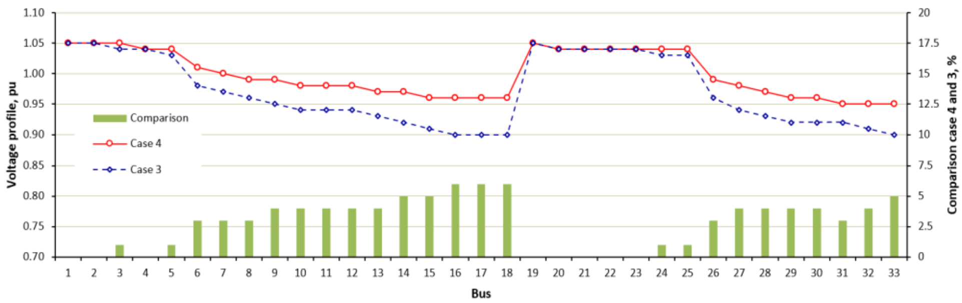


Figure 7. Minimum voltage profile during planning horizon

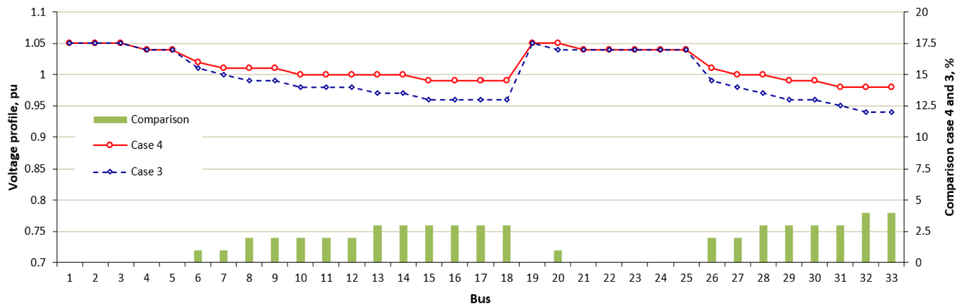
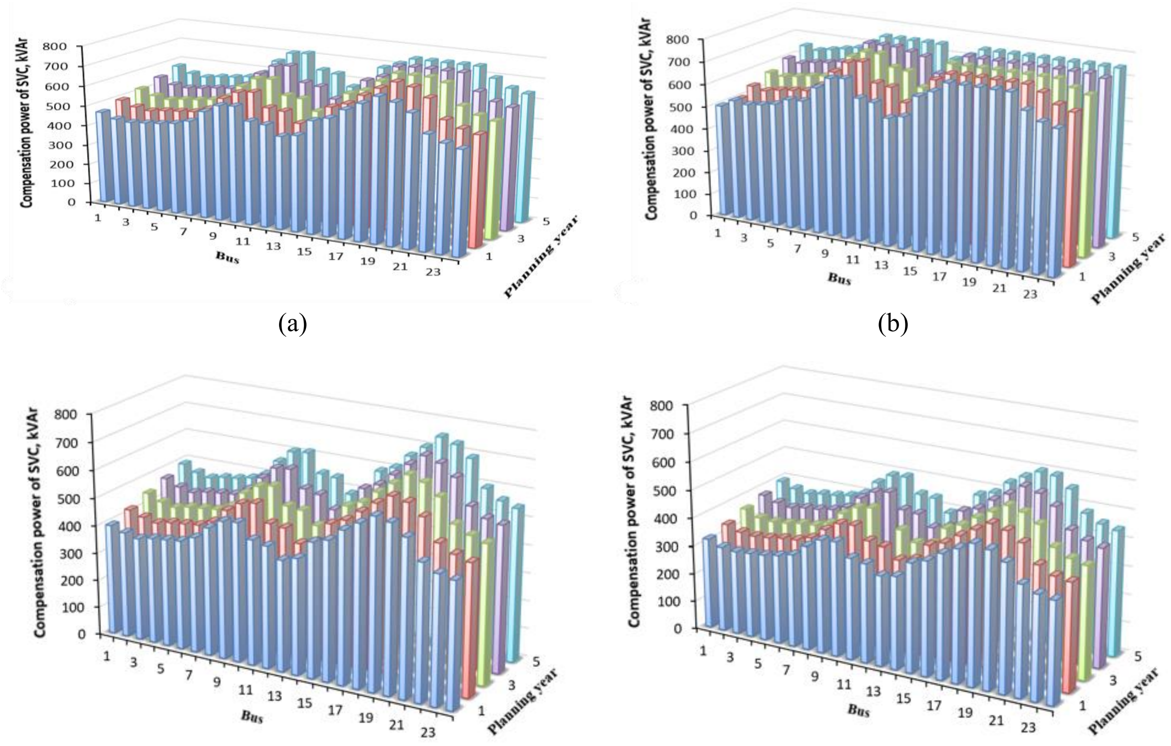


Figure 8. Maximum voltage profile during planning horizon

The compensation power of SVC in each operation state is controlled to change and respond to the variation of load or parameters of DS. Figures 9(a) to 9(c) show the compensation power of SVC during planning horizon in case 4 at buses 13, 18, 27 and 33 that are the feeder end-buses. The compensation power is equal to the rated power of SVC at peak hours at the end years of planning horizon due to the growing load, and it reduces at different times because of the load variation. At bus 18, compensation power equals the rated power of about 750 kVAr at the (8^{th}÷12^{th}) and (15^{th}÷24^{th}) hours of the 5^{th} year. It reduces at different hours when the load is reduced, and the minimum power is 500.5kVAr, equivalent to 73.4% of the rated power of SVC, at 1^{st} hour in the 1^{st} year. Similarly, the compensation power of SVC at bus 33 also changes from the rated power at the 19^{th} to the 20^{th} hour in the 5^{th} year to minimum power, which equals 302.2 kVAr, equivalent to 50.4% of the rated power of SVC, at the 2^{nd} hour in the 1^{st} year. On buses 13 and 27, the rated power of SVC only is generated at the 19^{th} and 20^{th} hours in the 5^{th} year then it changes and decreases at different operation states. The compensation power is minimum and equals 369.4 kVAr, equivalent to 49.7% of the rated power of SVC, at the 3^{rd} hour in the 1^{st} year. This is an advantage of SVC because the compensation powers can be controlled according to the variation of parameters of DS and thus increase the compensation power at peak load without overcompensation at off-peak load.



(a) (b) (c) (d)

Figure 9. Compensation power of SVC during planning horizon in case 4 (a) bus13, (b) bus 18, (c) bus 27, and (d) bus 33

5. CONCLUSION

This paper presents an optimal investment framework for simultaneously determining the location and sizing of SVCs in DSs, with the objective of minimizing the LCC of the investment project. The proposed model integrates critical practical factors such as hourly load variation, discrete SVC rated capacities, investment timing, and device lifespan. The optimal framework is formulated as a MINLP problem and solved using the BONMIN solver in GAMS, providing a rigorous and efficient solution method.

To evaluate the proposed framework, simulations are conducted on a modified 33-bus radial DS with time-of-use electricity pricing. Results unequivocally demonstrate the effectiveness and applicability of model. The optimal SVC placement, sizing, and investment timing are determined at feeder end-buses, achieving the lowest LCC. Specifically, the model yielded total energy loss reductions of approximately 0.99% and 1.48% compared to cases 3 and 2, respectively, reducing overall system losses from 6.03% to 5.04%. SVCs dynamically adjusted reactive power output, improving voltage profiles from 1% to 2% across all buses when compared to case without SVC integration. Additionally, operational limits of feeders and transformer substations were strictly maintained, with maximum loadings reaching only 77% and 86% of capacities.

Despite these promising outcomes, this study relies on deterministic load profiles, which may not fully capture real-world operating conditions. As renewable energy sources integration increases in DSs, uncertainties such as power output variability can impact optimization outcomes. To address this, future research should consider incorporating stochastic modeling techniques to improve the robustness and reliability of planning strategies.

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AUTHOR CONTRIBUTIONS STATEMENT

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Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Nguyen Hien Trung	✓	✓			✓	✓		✓	✓	✓			✓	
Vu Van Thang		✓	✓	✓		✓	✓	✓	✓	✓	✓	✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are available in the referenced article or are available from the corresponding author, vu van thang, upon reasonable request.

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BIOGRAPHIES OF AUTHORS

Nguyen Hien Trung received the Ph.D. degrees from Thainguyen University of Technology in 2013. Currently, he is working at the Faculty of Electrical Engineering, Thainguyen University of Technology. His research interests include renewable energy, power quality, power electronics, power generation, power grids, and power system stability. He can be contacted at email: nguyenhientrung@tnut.edu.vn.

Vu Van Thang received the Ph.D. degrees from Hanoi University of Science and Technology in 2015. Currently, he is an Associate Professor at the Department of Electrical Engineering, Thainguyen University of Technology. His major research interests include optimizing energy systems, distributed generations and distribution systems in deregulated electricity markets. He can be contacted at email: thangvvhtd@tnut.edu.vn.