

Enhancing Smart Grid Performance: A Multi-Objective V2G and Capacitor Allocation with Rigorous Load Modeling

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ABSTRACT

Abstract—This paper presents a comprehensive strategy to enhance the performance of smart distribution grids through a multi-objective optimization approach targeting both power loss minimization and voltage stability improvement. A novel voltage stability index (VSI) is derived from the bi-quadratic load flow formulation, integrated with a modified load flow algorithm based on the Bus-Injection to Branch-Current (BIBC) and Branch-Current to Bus-Voltage (BCBV) matrices, enabling efficient computation for large-scale radial distribution networks (RDNs). Unlike conventional approaches, this work incorporates detailed load modeling, including constant power, constant current, constant impedance (CP, CI, CZ), composite (ZIP), and exponential models, to capture realistic system behavior under varying load conditions. Simulation studies on IEEE 29- and 85-bus test feeders validate the proposed strategy. Results show that, for the 29-bus RDN, optimal allocation of Vehicle-to-Grid (V2G) units and Shunt Capacitors (SCs) reduces real power losses by 45% (from 46.8 kW to 25.7 kW) and improves the minimum bus voltage from 0.8348 p.u. to 0.9631 p.u.. For the 85-bus RDN, losses are reduced by 44% (from 316.1 kW to 176.1 kW), with the minimum bus voltage improving from 0.8454 p.u. to 0.9245 p.u.. Moreover, the minimum VSI increased from 0.7289 to 0.8868 in the 29-bus system and from 0.5764 to 0.8149 in the 85-bus system, confirming substantial gains in system resilience. Comparative analysis demonstrates that rigorous load modeling significantly influences the identification of critical nodes and the optimal placement of compensating devices. The proposed approach consistently improves voltage profiles, enhances stability margins, and reduces network losses more effectively than conventional methods.

Keywords: Optimal Allocation; Voltage Stability; Smart Grid; Vehicle-to-Grid (V2G); Capacitor Placement; Rigorous Load Modeling.

Nomenclature:

Abbreviation	Definition
BCBV	Branch-Current to Bus-Voltage Matrix
BIBC	Bus-Injection to Branch-Current Matrix
CI	Constant Current Load
CP	Constant Power Load
CZ	Constant Impedance Load
DG	Distributed Generation
EXP	Exponential Load Model
p.u.	Per Unit
RDN	Radial Distribution Network
SC	Shunt Capacitor
V2G	Vehicle-to-Grid
VSI	Voltage Stability Index
ZIP	Composite Load Model (Combination of CP, CI, CZ)

I. INTRODUCTION

Modern power distribution networks face unprecedented operational challenges due to increasing load complexity, renewable energy integration, and the proliferation of electric vehicles

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(EVs) [1]. These developments have made voltage stability in radial distribution networks (RDNs) a critical concern, as voltage deviations can lead to inefficient power delivery, increased losses, and potential cascading failures [2]. The situation is further complicated by the growing penetration of intermittent renewable generation and the bidirectional power flows introduced by vehicle-to-grid (V2G) technologies [3],[4].

To ensure reliable operation, voltage stability assessment and enhancement have become vital components in the planning and operation of smart distribution systems [5]. While many studies have proposed methods for improving voltage profiles and minimizing power losses, most traditional approaches are based on simplified load models, typically assuming constant power (CP) or constant impedance (CZ) loads [6],[7]. However, real-world loads are far more complex, often exhibiting voltage-dependent behavior that cannot be accurately captured without more rigorous modeling techniques [8]. Inaccurate load representation can lead to misleading conclusions regarding system stability and inefficient allocation of compensating resources such as Vehicle-to-Grid (V2G) systems which act as Distributed Generators (DGs) or Shunt Capacitors (SCs) [9],[10].

Recent research demonstrated that simplified load models can result in voltage profile errors compared to actual measurements. This discrepancy becomes particularly significant when determining optimal locations for voltage support devices [11]. The work in [12] further showed that composite load models (ZIP) provide substantially better accuracy in stability analysis, especially under heavy loading conditions. These findings are particularly relevant for modern distribution systems where load composition is becoming increasingly diverse with the integration of power electronic-interfaced loads and generation [13].

The integration of V2G systems as distributed energy resources has introduced new opportunities for voltage regulation and loss reduction [4]. Studies in [6] have shown that properly coordinated V2G systems can provide effective voltage support while reducing peak demand stresses distribution transformers. However, in [14], most existing V2G coordination strategies fail to account for the dynamic voltage characteristics of modern loads, potentially leading to suboptimal performance in real-world applications.

Conventional approaches to voltage stability enhancement typically focus on either capacitor placement [15] or DG allocation [10] as separate problems. Recent work in [16] highlighted the benefits of coordinated optimization, but their methodology still relied on simplified load representations. This limitation was addressed in [17], incorporating ZIP load models in their optimal capacitor placement algorithm, demonstrating improved voltage profiles compared to traditional approaches.

Matrix-based power flow methods have emerged as computationally efficient alternatives for analyzing large-scale distribution networks [18]. The Bus-Injection to Branch-Current (BIBC) and Branch-Current to Bus-Voltage (BCBV) approach, first introduced by Teng [19], has proven particularly effective for radial networks. Recent enhancements by Wang et al. [20] have further improved the method's accuracy while maintaining its computational advantages.

A. Motivation

Despite these advancements, several critical gaps remain in literature: Most existing approaches treat V2G allocation and capacitor placement as separate optimization problems. Voltage stability indices often fail to account for realistic load behavior. Comprehensive load modeling is frequently omitted from optimization frameworks. Computational efficiency remains a challenge for large-scale networks.

The motivation for this study stems from two major gaps in existing literature: (i) the lack of integrated approaches that simultaneously address the placement of V2G units and SCs targeting both voltage stability enhancement and power loss minimization; and (ii) the underutilization of realistic load models in stability studies, which can significantly affect the accuracy of both analysis and optimization.

As smart grids evolve to support more dynamic and decentralized power systems, there is an

increasing need for multi-objective optimization frameworks that can account for the dual goals of system performance and stability while incorporating load behavior with higher fidelity.

B. Contribution and Novelty

This paper proposes a comprehensive strategy for enhancing smart grid performance through a multi-objective optimization framework that simultaneously targets loss reduction and voltage stability enhancement. The key contributions and novelties of this work include:

- Development of a voltage stability index (VSI) enabling precise identification of weak nodes in RDNs.
- Integration of a modified load flow allowing efficient and scalable analysis of large distribution systems.
- Implementation of comprehensive load modeling, including CP, CI, CZ, ZIP, and exponential models, to reflect realistic power consumption patterns and assess their impacts.
- Introduction of two optimization-based enhancement strategies for the optimal placement and sizing of V2G units and SCs: one focused on loss minimization, and the other on VSI maximization.
- Validation of the proposed methods through simulations on standard IEEE 29 and 85 bus RDNs, demonstrating the superiority of the proposed approach over traditional methods.

The results clearly show that rigorous load modeling not only improves the reliability of voltage stability assessments but also leads to more effective planning decisions in smart grid environments.

II. PROPOSED METHODOLOGY

A. Problem Statement

Voltage instability in radial distribution networks (RDNs) arises primarily due to increased power demand, inadequate reactive power support, and poor voltage regulation across long feeder sections. Traditional voltage stability analyses often rely on idealized load assumptions and fail to accurately capture node-specific vulnerability. Furthermore, suboptimal placement of V2G units – act as distributed generation (DG) - or shunt capacitors (SCs) may exacerbate the instability or increase system losses. Thus, there is a pressing need for a strategy that:

- Accurately identify weak buses using a dedicated Voltage Stability Index (VSI),
- Enhance voltage profiles while minimizing losses,
- Reflects realistic load behavior through advanced modeling, and
- Efficiently handles large-scale distribution systems using computationally scalable techniques.

This study addresses these needs by developing a robust and integrated methodology that combines advanced load flow analysis, rigorous load modeling, and multi-objective optimization for system enhancement. The main flowchart displays the steps for the proposed methodology shown in Figure.1.

The optimization techniques for SC and DG placement were applied under two objectives:

- Minimizing Total Power Loss, and
- Maximizing the Global Minimum VSI

These case studies provide a comprehensive evaluation of the proposed methodology under both typical and stressed operating conditions.

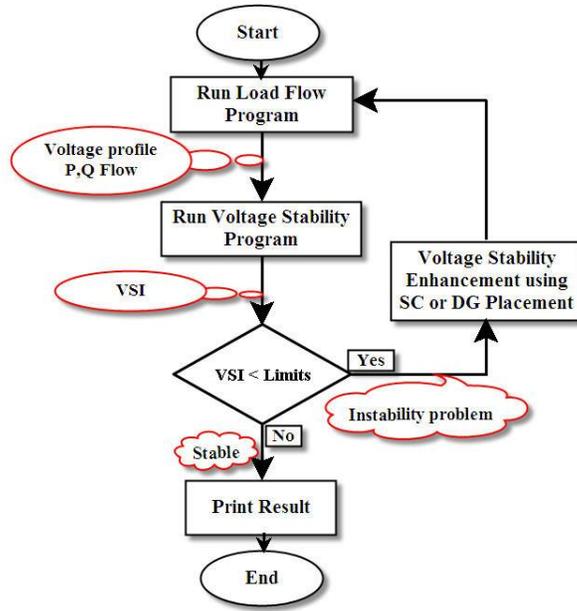


Figure 1. Main flowchart of the proposed methodology.

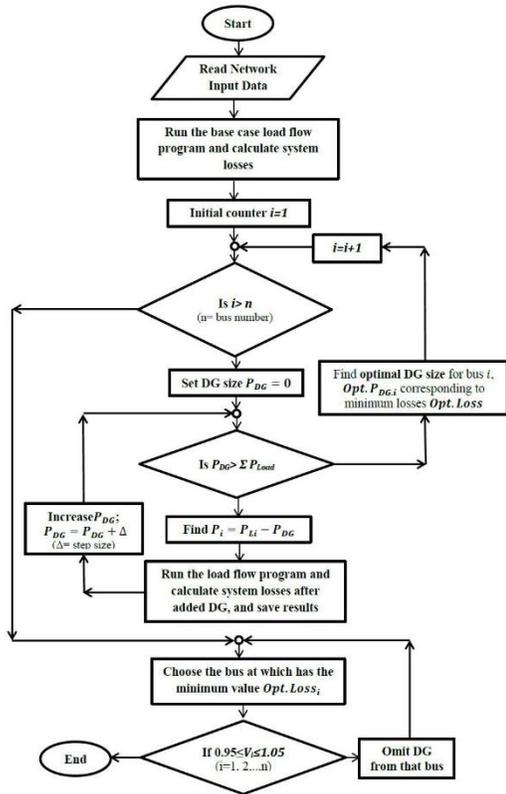


Figure 2. Flowchart of the proposed algorithm based on minimizing losses

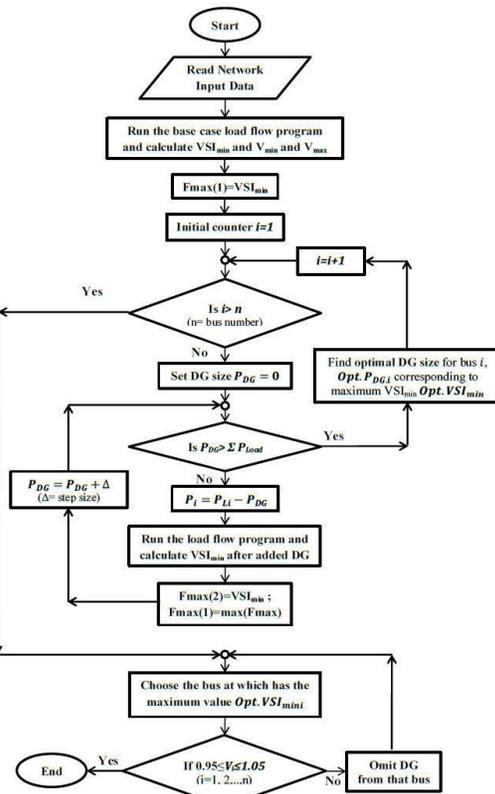


Figure 3. Flowchart of the proposed algorithm based on maximizing VSI

Objective functions and Constraints:

The objective of the placement technique is to minimize the total real power loss (P_{loss}) and

maximize the global minimum VSI by injecting active power as DG (P_{V2G}) for V2G placement, and by injecting reactive power (Q_{SC}) for shunt capacitors placement. Mathematically, the objective function can be written as:

$$\text{To minimize the total power losses: } f1(P_{V2G}, Q_{SC}) = P_{loss} \quad (1)$$

$$\text{To maximize the global minimum VSI: } f2(P_{V2G}, Q_{SC}) = VSI_{min} \quad (2)$$

Subject to:

$$\text{Voltage constraints: } 0.95 \leq |V_i| \leq 1.05 \text{ p.u. } i = 1, 2, \dots, n \quad (3)$$

$$\text{Maximum unit size: } \begin{cases} 0 \leq P_{V2G} \leq \sum P_{load} \\ 0 \leq Q_{SC} \leq Q_{g_{stack}} \end{cases} \quad (4)$$

The loss in the system can be calculated by:

$$P_{loss} = \sum_{i=1}^{nb} I_i^2 R_i \quad (5)$$

The line stability indicator VSI(r) of the line's receiving end bus can be calculated by:

$$VSI(r) = V_s^4 - 4(PX - QR)^2 - 4V_s^2(PR + QX) \quad (6)$$

where R_i , and I_i are the i^{th} branch resistance and current respectively. V_s is the sending end node voltage, and P and Q are the branch active and reactive power respectively. The voltages of all nodes and the branch currents are known after the load flow study, therefore P and Q at the receiving end of each line can easily be calculated.

The goal is to determine the optimum size of V2G (P_{V2G}) or SC (Q_{SC}) at any location so as to minimize total power losses and maximize the voltage stability index.

B. Load Flow

To perform accurate voltage and current assessments across RDNs, a modified load flow algorithm based on Bus-Injection to Branch-Current (BIBC) and Branch-Current to Bus-Voltage (BCBV) matrices are employed. This matrix-based formulation offers a computationally efficient solution tailored for radial topologies. The algorithm involves the following steps:

- Formulation of BIBC matrix: Captures the relationship between bus injection currents and branch currents based on the network topology.
- Formulation of BCBV matrix: Describes the relationship between branch currents and node voltages.
- Voltage update: Bus voltages are iteratively updated using the matrix product of BCBV and BIBC until convergence.

This method avoids the use of Jacobian matrices, making it particularly effective for weakly meshed or purely radial networks with high R/X ratios. The solution for distribution network load flow can be obtained by solving the power flow equations iteratively as in Figure. 4 which shows the flowchart of the used algorithm for load flow analysis.

C. Voltage Stability

Voltage stability is assessed by introducing a novel Voltage Stability Index (VSI), derived analytically from the bi-quadratic form of the distribution load flow equations. The index quantifies the proximity of each node to voltage collapse, where lower VSI values indicate greater sensitivity. After the load flow study, the voltages of all nodes and the branch currents are known, therefore P and Q at the receiving end of each line can easily be calculated and hence the voltage stability index of each bus can be calculated. The flowchart of the proposed algorithm for calculating the VSI of each node and finding the minimum value of VSI and its node is given in Figure. 5.

D. Load Modeling

To capture the actual behavior of electric loads in the network, five types of static load models are incorporated:

- Constant Power (CP): Load remains unaffected by voltage variations.
- Constant Current (CI): Load current remains constant; power varies linearly with voltage.

- Constant Impedance (CZ): Load power varies with the square of the voltage.
- ZIP Composite: A weighted mix of CP, CI, and CZ components.
- Exponential (EXP): Nonlinear dependence of active/reactive power on voltage with user-defined exponents.

Each load model influences the voltage stability assessment differently. For example, exponential loads are more sensitive to voltage changes and can shift the location of the weakest bus. These models are embedded directly into the load flow and VSI computation steps.

The following load models are considered in the paper. A balanced load that can be represented either as constant power, constant current, constant impedance, composite load, or as an exponential load is considered here. The general expression of load is shown below.

$$P = P_o [a_o + a_1 V + a_2 V^2 + a_3 V^{e1}] \quad (7)$$

$$Q = Q_o [b_o + b_1 V + b_2 V^2 + b_3 V^{e2}] \quad (8)$$

Where, P_o and Q_o are nominal real and reactive power respectively and V is the voltage. For all the loads, equations (7) and (8) are constrained as:

$$a_o + a_1 + a_2 + a_3 = 1.0 \quad (9)$$

$$b_o + b_1 + b_2 + b_3 = 1.0 \quad (10)$$

In this study the parameters are taken as following:

- CP load: $a_o = b_o = 1.0$ and $a_i = b_i = 0$ for $i = 1, 2, 3$.
- CI load: $a_1 = b_1 = 1.0$ and $a_i = b_i = 0$ for $i = 0, 2, 3$.
- CZ load: $a_2 = b_2 = 1.0$ and $a_i = b_i = 0$ for $i = 0, 1, 3$.
- ZIP load: is a combination of 40% CP, 30% CI and 30% CZ.
- Exp. load: $a_3 = b_3 = 1.0$ and $a_i = b_i = 0$ for $i = 0, 1, 2$, and $e1 = 1.38$ and $e2 = 3.22$.

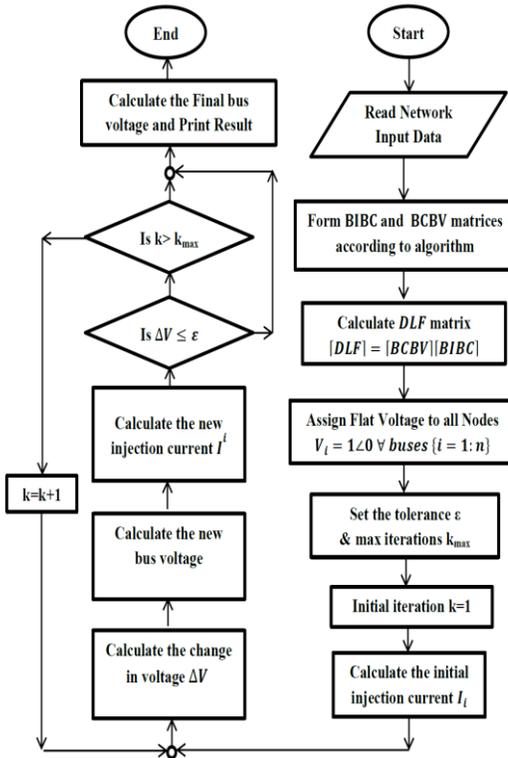


Figure 4. Flowchart of load flow method

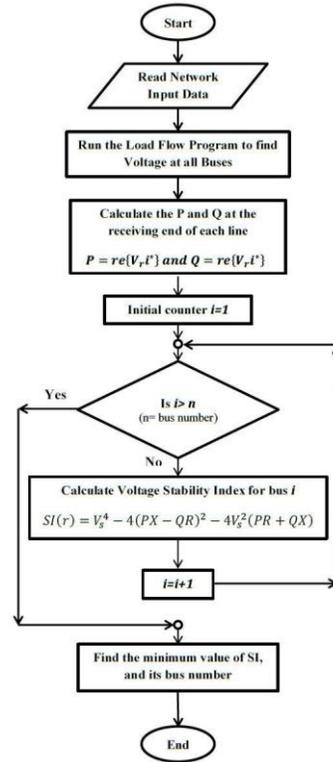


Figure 5. Flowchart of voltage stability method

E. Case Study Data

To validate the proposed methodology, simulation studies were conducted on two standard IEEE radial distribution test systems (IEEE-29 Bus and IEEE-85 Bus). For each system, line data and load data are taken from standard literature. Various load models were tested independently to evaluate their impact on voltage profiles and critical node identification.

III. RESULTS AND DISCUSSION

To assess the effectiveness of the proposed strategy for voltage stability enhancement and loss minimization, extensive simulations were conducted using MATLAB on two different RDNs (IEEE 29 and 85 bus test systems). The study evaluates the impact of both load modeling and optimal allocation of V2G and SC on voltage stability and network losses. Two optimization objectives were considered independently:

- (i) Loss minimization, and
- (ii) Voltage Stability Index (VSI) maximization.

A. Optimum allocation via losses minimization

In the 29-Node RDN, the optimum sizes of V2G unit as DG and SC placed on each bus are determined by the two methods, and the corresponding total power losses for each bus, shown in Figures 6 and 7. Also Figures 8 and 9 show the results in 85-Node RDN.

As clearly seen, in 29-Node RDN, the optimum size of V2G and SC at each bus is different; and the difference between the results that are obtained with two methods, are not significant. The optimum place of V2G and SC is bus 15 where the total power losses are minimal for this test system, with size of 0.381 MW, and 0.3398 MW for V2G and SC respectively. Also, in 85-Node RDN, the optimum place of V2G and SC is bus 8, with size of 2.209 MW, and 2.16 MW for V2G and SC respectively.

In Table I, for two different test systems, the size and location of V2G and SC, the minimum voltage magnitude, and the total power losses with and without for the two methods, are tabulated. It is seen that the total power losses are significantly reduced for all test systems. In addition, the optimum placement and size of V2G and SC determined by the two methods are in close agreement.

B. Optimum allocation via VSI Maximization

For each bus of 29-node RDN, the optimum V2G and SC sizes placed, and the corresponding VSI_{min} are shown in Table II. It is shown that the maximum value of VSI_{min} is 0.6313 and occurred when DG size of 0.6313 MW is placed at bus # 11 and it is shown that the maximum value of VSI_{min} is 0.8507 and occurred when SC size of 0.58 MVAR is placed at bus # 15.

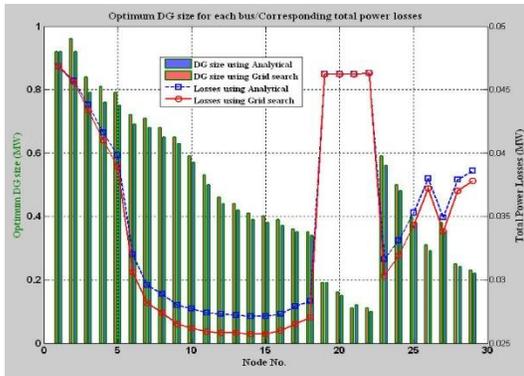


Figure 6. The optimal size for each bus and total power losses for corresponding DG in the 29-Node RDN

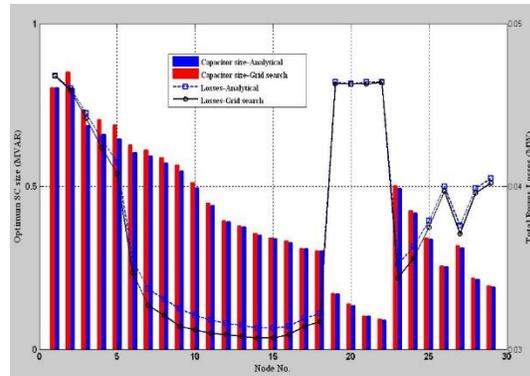


Figure 7. The optimal size for each bus and total power losses for corresponding SC in the 29-Node RDN

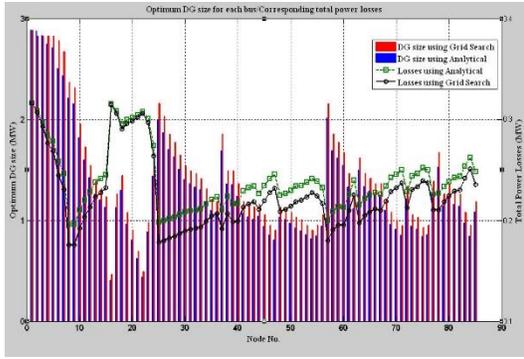


Figure 8. The optimal size for each bus and total power losses for corresponding DG in the 85-Node RDN

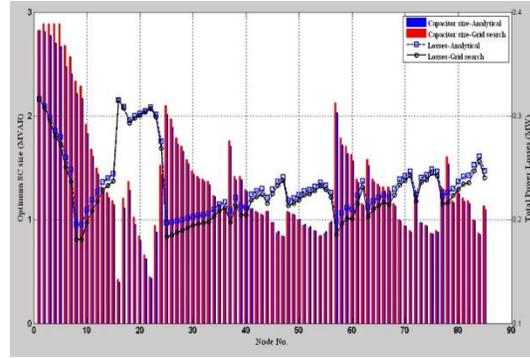


Figure 9. The optimal size for each bus and total power losses for corresponding SC in the 85-Node RDN

TABLE I. COMPARISON OF ALGORITHMS RESULTS FOR TEST SYSTEMS

Test system	Method	Optimal Allocation		Active Losses	Reactive Losses	Minimum Voltage
		Bus No.	Size (MW)	(KW)	(KVAR)	(p.u)
29-Node RDN	Before	NL	NL	46.8	28.48	V18= 0.8348
	V2G	15	0.381	25.74	15.29	V29= 0.9631
	SC	15	0.34	30.72	18.37	V18= 0.9240
85-Node RDN	Before	NL	NL	316.12	198.60	V54= 0.8454
	V2G	8	2.209	176.13	104.53	V54= 0.9245
	SC	8	2.16	180.8	107.42	V54= 0.9081

TABLE II. OPTIMAL V2G-SC SIZES FOR EACH BUS VIA MAXIMIZE VSI FOR 29-NODE RDN

Node Number	V2G size (MW)	VSI _{min} (p.u)	V _{min} (p.u)	Losses (kW)	SC size (MVAR)	VSI _{min} (p.u)	V _{min} (p.u)	Losses (kW)
Before	NL	0.7289	0.8348	46.81	NL	0.7289	0.8348	46.81
1	0.9236	0.7289	0.924	468	0.8018	0.7289	0.9240	46.8
2	0.9644	0.733	0.9253	456	0.8506	0.7325	0.9251	45.9
3	0.9644	0.7448	0.929	435	0.8506	0.7426	0.9283	44.3
4	0.9644	0.7582	0.9331	412	0.8506	0.7541	0.9319	42.6
5	0.9644	0.7703	0.9368	393	0.8506	0.7645	0.9351	41.2
6	0.9644	0.8295	0.9543	324	0.8506	0.7793	0.9396	36.3
7	0.9644	0.8485	0.9598	305	0.8506	0.7952	0.9443	34.8
8	0.9644	0.8626	0.9637	306	0.8506	0.8070	0.9478	34.8
9	0.9644	0.8811	0.9689	308	0.8506	0.8224	0.9523	35
10	0.8066	0.8867	0.9704	288	0.8506	0.8351	0.9560	37.7
11	0.6313	0.8868	0.9704	267	0.8506	0.8470	0.9593	42.7
12	0.5436	0.8865	0.9703	264	0.7733	0.8500	0.9602	44.3
13	0.5436	0.8864	0.9703	268	0.6882	0.8496	0.9601	40.6
14	0.5436	0.8862	0.9703	276	0.6418	0.8507	0.9604	40.8
15	0.5436	0.8861	0.9702	281	0.5800	0.8507	0.9604	37.8
16	0.5436	0.8859	0.9702	291	0.5490	0.8507	0.9604	37.5
17	0.5436	0.8855	0.9701	308	0.5336	0.8496	0.9602	38.7
18	0.5524	0.8866	0.9704	322	0.5413	0.8504	0.9604	40.3
19	0.9644	0.733	0.9253	555	0.8506	0.7324	0.9251	53.7
20	0.9644	0.7329	0.9253	633	0.8506	0.7324	0.9251	60.2
21	0.9644	0.7329	0.9252	759	0.8506	0.7323	0.9251	70.9
22	0.9644	0.7328	0.9252	818	0.8506	0.7323	0.9251	76
23	0.9644	0.8476	0.9595	366	0.8506	0.7945	0.9441	39.9
24	0.9644	0.8464	0.9592	437	0.8506	0.7935	0.9438	46.1
25	0.9644	0.8445	0.9586	555	0.8506	0.7919	0.9433	56.7
26	0.9644	0.8416	0.9578	750	0.8506	0.7892	0.9425	75.4
27	0.9644	0.8751	0.9672	614	0.8506	0.8173	0.9508	62.9
28	0.9644	0.8685	0.9654	953	0.8506	0.8108	0.9489	97.8
29	0.9644	0.8662	0.9647	107	0.8506	0.8084	0.9482	111.2

C. Comparative study

Table III shows the DG placement for each bus using VSI_{min} maximization as well as losses minimization for 29-node RDN. From table we can say that both methods increase VSI_{min} but in case of VSI_{min} maximization the value of VSI_{min} is higher (but losses is higher also); and vice versa for losses minimization technique; and the two techniques occurred in different node (11 for VSI_{min} maximization and 15 for losses minimization).

While, Table IV shows the SC placement for each bus using VSI_{min} maximization as well as losses minimization. From the table we can say that both methods increase VSI_{min} but in case of VSI_{min} maximization the value of VSI_{min} is higher (but losses is higher also); and vice versa for losses minimization technique; and the two techniques occurred in the same node (node # 15).

For the two test systems, comparison between the results of V2G-SC placement when obtained via VSI maximization and losses minimization is given in Table V for V2G allocation and Table VI for SC allocation. From the tables we can say that both methods increase VSI_{min} but in case of VSI_{min} maximization the value of VSI_{min} is higher (but losses is higher also); and vice versa for losses minimization technique.

Figure 10 show both voltage magnitude and VSI for all nodes of this system before adding SC, and after adding SC via both VSI maximization and losses minimization. From this figure we can say that in case of VSI maximization method, both voltage profile and VSI profile are better than the case of minimization losses method; but both methods improved voltage and VSI profiles.

D. Limitations of the study.

The following limitations have been added in the conclusion section:

- The optimization strategies were applied separately; simultaneous multi-objective optimization will be explored in future work.
- Economic aspects of V2G and SC deployment were not analyzed.
- Renewable energy variability was not included in this stage of the study.

TABLE III. V2G PLACEMENT VIA MINIMIZE LOSS AND MAXIMIZE VSI FOR 29-NODE RDN

Node Number	Loss Minimization			VSI Maximization		
	DG size (MW)	Losses (MW)	VSImin (p.u)	DG size (MW)	Losses (MW)	VSImin (p.u)
1	0.9236	0.0468	0.7289	0.9236	0.0468	0.7289
2	0.9644	0.0456	0.733	0.9644	0.0456	0.733
3	0.8417	0.0434	0.7448	0.9644	0.0435	0.7448
4	0.8066	0.041	0.7582	0.9644	0.0412	0.7582
5	0.7891	0.0389	0.7703	0.9644	0.0393	0.7703
6	0.7189	0.0306	0.8295	0.9644	0.0324	0.8295
7	0.7102	0.0282	0.8485	0.9644	0.0305	0.8485
8	0.6839	0.0274	0.8626	0.9644	0.0306	0.8626
9	0.6488	0.0265	0.8811	0.9644	0.0308	0.8811
10	0.5874	0.0262	0.9181	0.8066	0.0288	0.8867
11	0.5261	0.0259	0.9543	0.6313	0.0267	0.8868
12	0.4647	0.0258	0.9527	0.5436	0.0264	0.8865
13	0.4384	0.0258	0.9519	0.5436	0.0268	0.8864
14	0.4121	0.0257	0.9506	0.5436	0.0276	0.8862
15	0.4033	0.0257	0.9498	0.5436	0.0281	0.8861
16	0.3858	0.026	0.9488	0.5436	0.0291	0.8859
17	0.3595	0.0265	0.9476	0.5436	0.0308	0.8855
18	0.3507	0.027	0.9468	0.5524	0.0322	0.8866
19	0.1929	0.0462	0.733	0.9644	0.0555	0.733
20	0.1578	0.0462	0.7329	0.9644	0.0633	0.7329
21	0.114	0.0462	0.7329	0.9644	0.0759	0.7329
22	0.1052	0.0463	0.7328	0.9644	0.0818	0.7328
23	0.5874	0.0303	0.8476	0.9644	0.0366	0.8476
24	0.4997	0.0319	0.8464	0.9644	0.0437	0.8464
25	0.4033	0.0343	0.8445	0.9644	0.0555	0.8445
26	0.3069	0.0372	0.8416	0.9644	0.075	0.8416
27	0.377	0.0338	0.8751	0.9644	0.0614	0.8751
28	0.2543	0.037	0.8685	0.9644	0.0953	0.8685
29	0.228	0.0378	0.8662	0.9644	0.1072	0.8662

TABLE IV. SC PLACEMENT VIA MINIMIZE LOSSES AND MAXIMIZE VSI FOR 29-NODE RDN

Node Number	Loss Minimization			VSI Maximization		
	SC size (MVAR)	Losses (MW)	VSImin (p.u)	SC size (MVAR)	Losses (MW)	VSImin (p.u)
1	0.8018	0.0468	0.7289	0.8018	0.0468	0.7289
2	0.8506	0.0459	0.7325	0.8506	0.0459	0.7325
3	0.7346	0.0442	0.7426	0.8506	0.0443	0.7426
4	0.7037	0.0424	0.7541	0.8506	0.0426	0.7541
5	0.6882	0.0408	0.7645	0.8506	0.0412	0.7645
6	0.6263	0.0347	0.7793	0.8506	0.0363	0.7793
7	0.6109	0.0327	0.7952	0.8506	0.0348	0.7952
8	0.5877	0.0321	0.8070	0.8506	0.0348	0.8070
9	0.5645	0.0314	0.8224	0.8506	0.0350	0.8224
10	0.5104	0.0312	0.8351	0.8506	0.0377	0.8351
11	0.4485	0.0310	0.8470	0.8506	0.0427	0.8470
12	0.3944	0.0309	0.8613	0.7733	0.0443	0.8500
13	0.3789	0.0308	0.8764	0.6882	0.040	0.8496
14	0.3557	0.0307	0.8870	0.6418	0.040	0.8507
15	0.3402	0.0307	0.8893	0.5800	0.037	0.8507
16	0.3325	0.0309	0.8884	0.5490	0.0375	0.8507
17	0.3093	0.0314	0.8871	0.5336	0.0387	0.8496
18	0.3016	0.0317	0.8864	0.5413	0.0403	0.8504
19	0.1701	0.0463	0.7324	0.8506	0.0537	0.7324
20	0.1392	0.0463	0.7324	0.8506	0.0602	0.7324
21	0.1005	0.0463	0.7323	0.8506	0.0709	0.7323
22	0.0928	0.0464	0.7323	0.8506	0.0760	0.7323
23	0.5026	0.0344	0.7945	0.8506	0.0399	0.7945
24	0.4253	0.0356	0.7935	0.8506	0.0461	0.7935
25	0.3402	0.0375	0.7919	0.8506	0.0567	0.7919
26	0.2552	0.0397	0.7892	0.8506	0.0754	0.7892
27	0.3170	0.0371	0.8173	0.8506	0.0629	0.8173
28	0.2165	0.0396	0.8108	0.8506	0.0978	0.8108
29	0.1933	0.0402	0.8084	0.8506	0.1112	0.8084

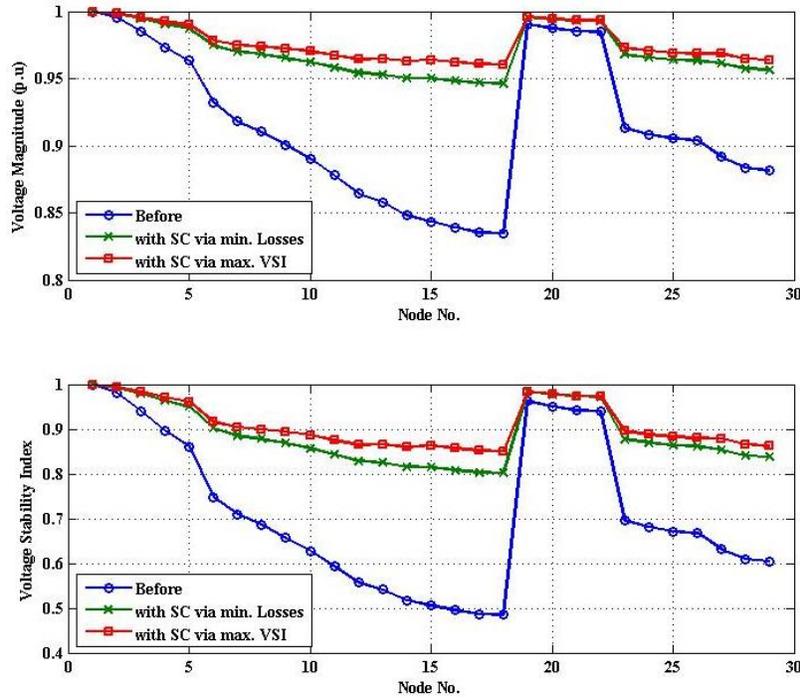


Figure 10. Voltage profile and VSI profile before and after adding SC.

TABLE V. COMPARISON BETWEEN V2G PLACEMENT VIA VSI MAXIMIZATION AND LOSSES MINIMIZATION RESULTS

Test system	Place Using	V2G Optimum		Active Losses	Reactive Losses	Min. VSI	Max. Voltage	Min. Voltage
		Bus No.	Size (MW)	(KW)	(KVAR)	(p.u)	(p.u)	(p.u)
29-Node RDN	Before	NL	NL	46.81	28.48	VSI18= 0.7289	V1= 1.0000	V18= 0.8348
	Max. VSI	11	0.631	26.75	14.736	VSI18= 0.8868	V1= 1.0000	V18= 0.9704
	Min. Loss	15	0.412	25.69	15.088	VSI29= 0.8654	V1= 1.0000	V29= 0.9645
85-Node RDN	Before	NL	NL	316.1	198.601	VSI54= 0.5764	V1= 1.0000	V54= 0.8713
	Max. VSI	26	2.698	192.7	112.322	VSI76= 0.8149	V1= 1.0000	V76= 0.9501
	Min. Loss	8	2.365	175.5	104.224	VSI54= 0.7417	V1= 1.0000	V54= 0.9280

TABLE VI. COMPARISON BETWEEN SC PLACEMENT VIA VSI MAXIMIZATION AND LOSSES MINIMIZATION RESULTS

Test system	Placed Using	SC Optimum		Active Losses	Reactive Losses	Min. VSI	Max. Voltage	Min. Voltage
		Bus No.	Size (MVAR)	(KW)	(KVAR)	(p.u)	(p.u)	(p.u)
29-Node RDN	Before	NL	NL	46.81	28.48	VSI18= 0.7289	V1= 1.0000	V18= 0.8348
	Max. VSI	15	0.58	37.83	20.88	VSI18= 0.8507	V1= 1.0000	V18= 0.9604
	Min. Loss	15	0.3402	30.72	18.37	VSI18= 0.8020	V1= 1.0000	V18= 0.9463
85-Node RDN	Before	NL	NL	316.1	198.6	VSI54= 0.5764	V1= 1.0000	V54= 0.8713
	Max. VSI	27	2.779	223.1	127.11	VSI76= 0.7490	V1= 1.0000	V54= 0.9303
	Min. Loss	8	2.33	180.7	107.18	VSI54= 0.6879	V1= 1.0000	V54= 0.9107

IV. CONCLUSION

This paper proposed a comprehensive strategy for enhancing smart grid performance through a multi-objective optimization framework targeting both power loss minimization and voltage stability enhancement in radial distribution networks (RDNs). A Voltage Stability Index (VSI) was formulated based on bi-quadratic load flow principles, and an efficient matrix-based power flow method (BIBC-BCBV) was developed to evaluate and enhance system stability. Importantly, the proposed framework integrates rigorous load modeling including CP, CI, CZ, ZIP, and exponential types to capture realistic load behavior.

In modern power systems, operating conditions are increasingly close to voltage instability due to rising load demands. To address this, Vehicle-to-Grid (V2G) units and Shunt Capacitors (SCs) were optimally placed and sized using two strategies: Loss Minimization, which indirectly improves voltage stability by enhancing the overall voltage profile, and VSI Maximization, which directly targets system resilience.

Simulation results on standard IEEE 29 and 85-bus systems confirm that both approaches enhance voltage stability, as reflected by an increase in VSI values. The VSI maximization strategy yields higher VSI improvements but with slightly higher power losses, while the loss minimization strategy achieves lower losses at the expense of smaller VSI gains.

Interestingly, although the optimal sizes of V2G and SC units differ per bus and method, the difference in outcomes between the two strategies is relatively small and often negligible. The optimal placement results are summarized as follows:

- For loss minimization, the best V2G/SC placement buses are at Bus 15 (29-bus RDN) and at Bus 8 (85-bus RDN).
- For VSI maximization, the best placements are: V2G units at Bus 11 (29-bus RDN) and Bus 26 (85-bus RDN) while SC units at Bus 15 (29-bus RDN) and Bus 28 (85-bus RDN).

These results demonstrate that both methods are viable, and their use can be tailored to the operational priorities of a given smart distribution network whether focused on reducing energy losses or maximizing voltage stability margins.

Future work includes extending the method to dynamic voltage stability analysis, integrating renewable energy sources, and developing real-time stochastic optimization. An economic study will also be conducted to evaluate the cost-effectiveness of V2G and capacitor deployment in smart grids under varying operational and market conditions.

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