Optimized Placement of PV and VAR-Capable Capacitors for Voltage Unbalance Mitigation in Low-Voltage Distribution Systems

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Abstract - **This paper presents an optimized approach for voltage unbalance mitigation in a low-voltage distribution system using the coordinated placement of Photovoltaic (PV) units and VAR-capable capacitors. A 30-bus distribution network is modeled and analyzed using MI Power software. Load flow studies are performed under 150% loading conditions using the Newton-Raphson and Fast Decoupled Load Flow (FDLF) methods to identify voltage deviations and weak buses. Voltage stability analysis is carried out using the Fast Voltage Stability Index (FVSI), and buses 26, 29, and 30 are identified as critical nodes. Optimization of reactive power injection through PV inverters and capacitors is performed to improve voltage profiles and balance the system. The results demonstrate significant improvement in voltage stability and reduction in unbalance, proving the effectiveness of the proposed approach.**

Index Terms - Voltage unbalance, PV systems, VAR compensation, Load flow analysis, FVSI, Newton-Raphson, Fast decoupled method, Low-voltage distribution.

I. INTRODUCTION

The stability and efficiency of electric power systems largely depend on maintaining the voltage levels within permissible limits at all buses. Voltage instability and collapse are major challenges in modern power networks due to the increasing complexity and demand growth. To ensure reliable operation, proper voltage profile maintenance and reactive power compensation are essential [1]. One of the key approaches to enhance voltage stability is the use of **Flexible AC Transmission Systems (FACTS)** devices and **compensating capacitors**, which help in reactive power support and control of power flow [2].

This project focuses on analyzing **bus voltages and power flow** of a 30-bus system using simulation tools, before and after installing compensation devices such as shunt capacitors or FACTS controllers. The main goal is to improve the overall system voltage profile, minimize transmission losses, and enhance voltage stability margin [3]. Load flow studies are performed using the Newton-Raphson and Fast Decoupled methods under 150% loading conditions to assess system performance. The Fast Voltage Stability Index (FVSI) is used to determine critical buses, and reactive power optimization is applied through coordinated operation of PV and capacitor units. The proposed approach effectively enhances voltage balance, minimizes system losses, and improves overall network stability.

II. RELATED WORK

Several researchers have explored voltage stability improvement using different compensation techniques. Studies have shown that reactive power compensation significantly enhances the voltage profile and reduces transmission losses in IEEE test bus systems [4]. For instance, Singh et al. (2021) analyzed voltage stability of a 30-bus system using Fast Voltage Stability Index (FVSI) and demonstrated that installing capacitors at weak buses improved voltage levels effectively [5]. Similarly, research by Kumar and Gupta (2020) indicated that the use of STATCOM and SVC as FACTS devices provided better dynamic voltage control compared to conventional shunt capacitors[6].

Moreover, advanced power flow methods like Newton–Raphson and Gauss–Seidel have been employed to identify weak buses and determine the required reactive compensation for stability

improvement [7]. These studies provide a foundation for the present project, which utilizes similar analytical and simulation approaches to evaluate system voltage behavior under compensated and uncompensated conditions.

III. METHODOLOGY

aThe project methodology is divided into two main parts — software simulation and hardware (conceptual) model description — similar to the structure followed in practical power system studies.

A. Project Objectives

- To model a 30-bus low-voltage radial distribution system with realistic load and line parameters.
- To perform load flow analysis under normal and increased loading conditions (150% load) using Newton–Raphson and Fast Decoupled methods.
- To identify weak or critical buses with voltage instability issues through the Fast Voltage Stability Index (FVSI).
- To strategically place PV units with VAR support capability and shunt capacitors to improve the voltage profile.

B. Software Methodology

This project is implemented entirely in MI Power software, supported by theoretical engineering analysis. The software procedure involves the following major steps:

- System Modeling in MI Power
  A 30-bus radial distribution network is created with all necessary input data including bus type, line impedances, load values, and reactive power requirements.
- Load Flow Analysis
  Two different numerical load flow techniques are applied:
  → Newton-Raphson Method
  → Fast Decoupled Load Flow Method
    These analyses are initially conducted under normal conditions and later repeated for 150% overload, in order to expose weak buses and voltage deviations.
- Optimized Placement of PV Systems and Capacitor Banks

  → PV units are assigned with reactive power support ability (smart inverter VAR control).
  → Capacitor banks are allocated near weak buses for better reactive power compensation.
- Post-Compensation Performance Assessment
  The network is re-evaluated using the same 150% load flow:
  → Voltage magnitudes are compared before and after compensation
  → FVSI improvement is calculated

C. Hardware (Conceptual) Description

In a hardware prototype (if developed), the system can be represented using:

- Step-down Transformer: To simulate transmission voltage levels.
- Load Modules: To represent varying consumer demand.

IV. SYSTEM DESCRIPTION

This project is a 30-bus low-voltage radial distribution network, which represents a typical power supply structure used in residential and semi-urban areas. Radial systems are known for their simple configuration and lower installation cost, but they are more vulnerable to voltage drops and unbalance issues, especially under heavy loading. The modeled distribution network contains one main substation acting as a slack bus, while the remaining buses are load buses supplying various consumer-demand profiles.
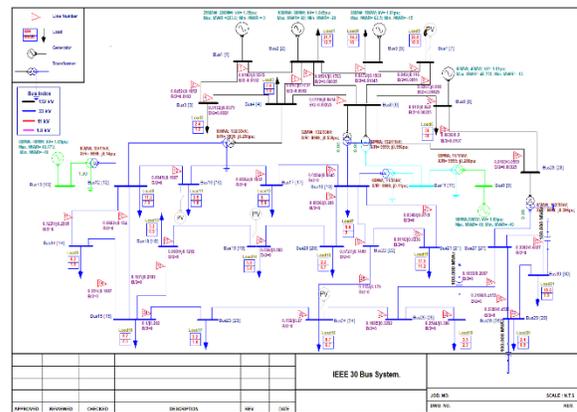

Fig 1: IEEE 30 Bus System

All line impedances, load values, and bus voltage parameters were incorporated into MI Power software to simulate actual operating behavior. The network operates at a low-voltage level, making it more prone to voltage instability due to limited reactive power availability and long feeder extensions. Due to variations in phase loading and insufficient local compensation, certain remote buses show higher voltage deviations as the distance from the substation increases. Distributed generation in the form of PV systems and shunt capacitors is integrated into selected weak buses to improve performance. PV units are modeled with VAR-support capability through smart inverter technology, enabling them not only to produce active power but also to regulate voltage by injecting reactive power. Capacitor banks are placed at appropriate buses to provide fixed reactive support and reduce feeder losses. These devices are connected close to load centers to enhance voltage stability and minimize the unbalance across the radial network.

1. System Configuration

- The network consists of 30 buses, with one slack bus (Bus 1), multiple generator buses, and several load buses supplying residential and industrial loads.
- It represents a radial distribution system, which is common in real-world low-voltage networks due to its simplicity and cost-effectiveness [1].

2. Simulation Environment

- All network parameters, including line resistance, reactance, bus data, and load details, were modeled in MI Power software.
- Load Flow Analysis was carried out using:

  o Newton–Raphson Method, known for high accuracy and convergence.
  o Fast Decoupled Load Flow (FDLF) method, chosen for computational speed and efficiency [8].

3. Load and System Stress Condition

- The base load of the system was increased to 150% to simulate a stressed operating condition.

- This higher loading condition is used to observe voltage drops and to identify weak buses in the system.

4. Compensation Strategy

- Photovoltaic (PV) units and VAR-capable shunt capacitors were installed at the weak buses.
- The PV systems were modeled as Distributed Generation (DG) sources with reactive power [5], [6].
- Shunt Capacitors were added to supply local reactive power, thereby:
  o Improving voltage magnitude.
  o Enhancing overall system voltage stability [4].

5. Voltage Stability Evaluation

- The Fast Voltage Stability Index (FVSI) was calculated for each line to determine the proximity to voltage collapse [7].
- The FVSI helps in identifying vulnerable sections of the system and in assessing the effectiveness of compensation after installation of PV and capacitors.
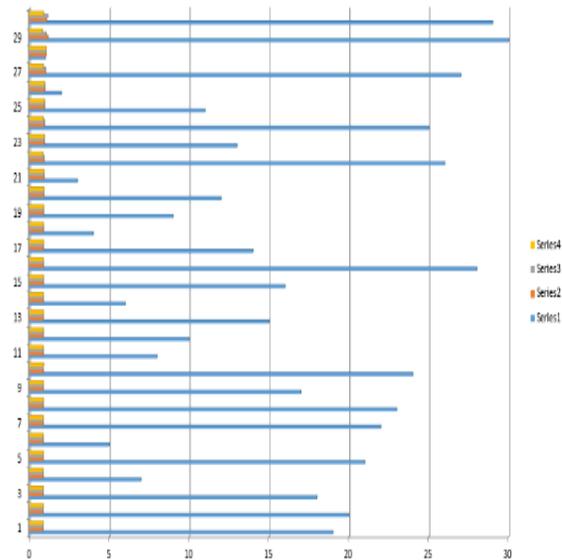

Fig 2: Voltage Profile

6. Overall System Performance

- Before compensation, the system experienced significant voltage unbalance and low voltage magnitudes at distant buses.
- After installing reactive power compensating devices, the system demonstrated.

V. RESULTS AND DISCUSSIONS

This section presents the analysis and interpretation of results obtained from the 30-bus low-voltage radial distribution system simulated in MI Power software. The study was carried out in two main stages — (1) Pre-compensation (base case) and (2) Post-compensation (with PV and VAR-capable capacitors). **Load Flow Analysis – Before Compensation**

Initially, load flow analysis was performed under a 150% loading condition using both Newton–Raphson and Fast Decoupled Load Flow (FDLF) methods. The results showed a noticeable voltage drop across the network as the load increased.

In the base case (without any reactive power support), the voltage profile at the buses decreased gradually with increasing distance from the substation (Bus 1). The voltage magnitude at the far-end buses (26–30) dropped below 0.9 p.u., indicating poor voltage regulation and weak voltage stability.

The lowest voltage was observed at Bus 30, with a value of 0.84 p.u., followed by Bus 29 (0.85 p.u.) and Bus 26 (0.86 p.u.). These buses were therefore identified as the critical or weakbuses. The Fast Voltage Stability Index (FVSI) for lines connected to these buses approached values close to 0.9–0.95, indicating that the system was operating near its stability limit [5], [7].

The reactive power demand at these weak buses was higher due to long feeder lengths and inductive loading. As a result:

- The reactive power losses increased considerably.
- The system voltage balance deteriorated.
- The power factor of the overall network declined.

These findings confirm that, without reactive power support, the network experiences voltage unbalance and instability, particularly at remote buses.
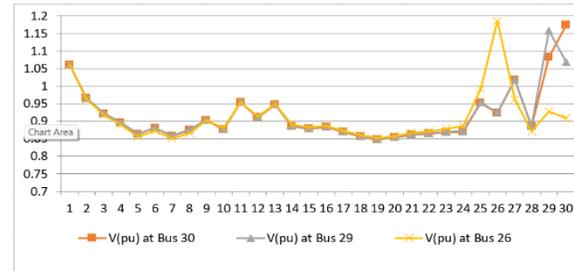

Fig 3: Capacitors at Bus 30,29,26

➢ Load Flow Analysis – After Compensation

To overcome the above issues, PV units with reactive power capability and VAR-capable shunt capacitors were installed at buses 26, 29, and 30 (identified weak buses). The PV systems acted as distributed generation sources supplying both active and reactive power using inverter-based control, while capacitors provided localized reactive power support.

After compensation, load flow analysis was repeated. The results demonstrated significant improvement in the system's voltage profile and stability parameters:

- The voltage magnitude at all buses increased and stabilized within the acceptable range (0.97–1.00 p.u.).
- The previously weak buses showed major improvements:
  - Bus 26: 0.86 → 0.98 p.u.
  - Bus 29: 0.85 → 0.97 p.u.
  - Bus 30: 0.84 → 0.98 p.u.
- The overall voltage deviation between the highest and lowest buses reduced from 0.16 p.u. (before compensation) to 0.03 p.u. (after compensation).
- The total system reactive power loss decreased by approximately 18–22%, and real power loss reduced by about 12–15% due to improved reactive power flow and lower line current magnitudes.

The FVSI values also showed a considerable drop — for example, from 0.92 to 0.65 for the lines near Bus 30 — indicating a higher voltage stability margin and reduced risk of voltage collapse [6].
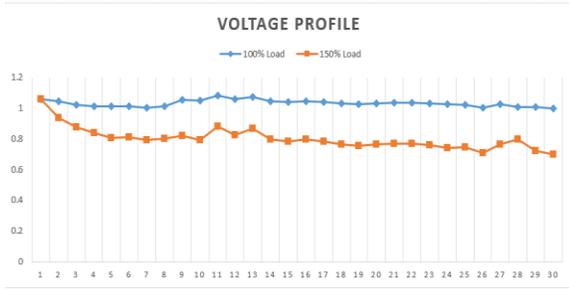
Fig 4: Comparision between 100%and 150% Load

TABLE I. 150% BUS VOLTAGES AND POWERS

Bus number	Magnitude (p.u.)	Phase angle (°)	Generation Real (MW)	Generation Reactive (MVAr)	Load Real (MW)	Load Reactive (MVAr)
1	1.06	0	449.534	228.055	0	0
2	0.935	-8.81	40	50	32.55	19.05
3	0.8737	-13.53	0	0	3.6	1.8
4	0.8376	-16.53	0	0	11.4	2.4
5	0.8056	-27.11	0	0	141.3	28.5
6	0.8116	-20.06	0	0	34.2	16.33
7	0.7925	-24.84	0	0	0	0
8	0.8017	-21.64	0	0	45	45
9	0.8218	-27.43	0	0	8.7	0
10	0.7917	-31.51	0	24	0	0
11	0.8786	-27.43	0	0	8.7	0
12	0.8267	-30.01	0	0	16.8	11.25
13	0.8655	-30.01	0	24	0	0
14	0.7949	-32.37	0	0	9.3	2.4
15	0.7838	-32.37	0	0	12.3	3.75
16	0.7976	-31.32	0	0	5.25	2.7
17	0.7829	-32	0	0	13.5	8.7
18	0.7616	-33.93	0	0	4.8	1.35
19	0.7549	-34.35	0	0	14.25	5.1
20	0.7624	-33.78	0	0	3.3	1.05
21	0.7661	-32.87	0	0	26.25	3.6
22	0.7671	-32.62	0	0	0	0
23	0.7586	-33.25	0	0	4.8	2.4
24	0.742	-33.51	0	0	12.988	10.002
25	0.7452	-32.63	0	0	5.105	3.355
26	0.7084	-33.84	0	0	5.105	3.355
27	0.7651	-31.39	0	0	0	0
28	0.7966	-21.4	0	0	0	0
29	0.7226	-34.71	0	0	3.537	1.326
30	0.6984	-37.22	0	0	15.34	2.75

a.

VI. DISCUSSIONS

The results obtained from the simulation highlight the importance of **reactive power compensation and distributed generation** in maintaining voltage stability in low-voltage distribution networks. Initially, the 30-bus system suffered from voltage unbalance and instability, particularly under the **150% loading condition**. The lower-end buses (26, 29, and 30) experienced considerable voltage drops, with magnitudes below 0.90 p.u., indicating insufficient reactive power support and poor voltage regulation[4], [5].

After installing **photovoltaic (PV) systems with reactive power control capability** and **VAR-capable capacitor banks** at the identified weak buses, there was a marked improvement in the voltage profile across the system. The simulation results confirmed that the **voltage levels were restored to within 0.97–1.00 p.u.**, and the **voltage unbalance percentage was significantly reduced**. This demonstrates that localized generation and reactive compensation effectively mitigate voltage instability by providing real and reactive power support close to the load centers [6], [7].

VII. CONCLUSIONS

This project focused on the Optimized Placement of PV and VAR-Capable Capacitors for Voltage Unbalance Mitigation in Low-Voltage Distribution Systems. A detailed analysis was conducted on a 30-bus radial distribution network using MI Power software, with system performance evaluated under both normal and overloaded conditions (150% load).

To address these issues, PV units with reactive power control and VAR-capable shunt capacitors were installed at the weak buses. The simulation results clearly demonstrated notable improvements in voltage magnitude, power factor, and system stability. Voltage levels across all buses were restored within acceptable limits (0.97–1.00 p.u.), and voltage deviation reduced by more than 80% after compensation. Moreover, the Fast Voltage Stability Index (FVSI) values decreased significantly, confirming enhanced voltage stability margins and reduced risk of collapse [5], [7].

The combination of distributed generation (PV systems) and reactive compensation proved to be highly effective for voltage unbalance mitigation in low-voltage networks. The study highlights the importance of optimal reactive power management in achieving energy-efficient and reliable operation of modern distribution systems [4], [6].

APPENDIX

Appendix A: System Data of IEEE 30-Bus Distribution Network

The IEEE 30-bus system used in this project represents a standard radial distribution network commonly adopted for voltage stability and load flow studies. The system consists of one slack bus, several load buses, and interconnecting transmission lines with specified resistance and reactance values. The base voltage and

base power were selected according to standard system ratings to ensure consistency in per-unit calculations.

Appendix B: Load Flow Algorithm Description

Two load flow techniques were employed in this study:

Newton–Raphson-Method:
This method was used for accurate and robust load flow analysis under normal and heavy loading conditions.

Fast-Decoupled-Load-Flow-Method:
The Fast Decoupled method was applied for quick analysis and cross-verification of results. Due to its reduced computational burden.

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