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Role of Capacitor Banks in Voltage Regulation of Power Systems

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Abstract - One of the most important problems in the contemporary electrical power distribution systems is voltage regulation. The variations in nominal levels of voltage lead to degraded power quality, higher system losses, faster equipment wear, and possible instability cascades. The present paper is a detailed study of the use of capacitor banks as one of the primary tools of reactive power compensation and improvement of voltage profile in radial distribution networks. The paper systematically looks into the theoretical foundations, mathematical modelling, operational properties, and application implementation solutions of fixed, switched, and automatic capacitor banks. The IEEE 33-bus radial distribution system is used as a reference benchmark and three operating scenarios are analyzed using the load-flow simulation: a base configuration with no compensation, a uniformly compensated configuration with capacitor banks installed at uniform spacing, and an optimally placed configuration derived using sensitivity analysis. As shown in the results of the simulation, the optimal positioning of the capacitor banks will lead to a reduction in the total real power loss by approximately 29.8 per cent, increase in the minimum bus voltage per unit (p.u.) to 0.9680 p.u., and the power factor of the system increasing to 0.96. The results affirm that capacitor banks located in strategic locations are still one of the most affordable and technically feasible ways of regulating the voltage in modern distribution networks.

Keywords: Capacitor Banks, Voltage regulation, Reactive power compensation, Power factor correction, IEEE 33-Bus System, Distribution networks, Optimal placement, Smart grid

I. INTRODUCTION

Electric power systems need to provide electrical energy to consumers at voltages within accepted regulatory tolerances, typically within the range of ±5 percent of the nominal rated voltage as required by such standards as ANSI C84.1 and the IEC 60038. The capability of a power system to maintain sufficient voltage levels in all buses under different load conditions is collectively known as voltage regulation. The modern era of connected grids, intensifying demand densities, an increasing relative penetration of intermittent renewable energy sources, and the proliferation of sensitive loads all electronic in nature have dramatically added to the complexity of maintaining acceptable voltage profiles across distribution and transmission systems.

The radically problematic nature of the voltage regulation problem in radial distribution network is a result of the inherently resistive nature of distribution feeders, which leads to the occurrence of a significant voltage drop as current passes through the distribution feeder impedance. In contrast to transmission systems, which have relatively high X/R ratios, where the reactive power control is the most dominant factor in control of the magnitude of voltage, distribution systems have low X/R ratios, which makes both active and reactive power flows to be consequential to the control of the magnitude of voltage. Any localized deficit of reactive power at any load bus causes a localized voltage depression which propagates upstream, causing increasing losses to any point and potentially a voltage collapse further upstream unless mitigated.[1]

It is against this background that the capacitor banks have been widely deployed and cost-effective technology in reactive power compensation and voltage support in the distribution systems. When connected in parallel with inductive loads, a shunt capacitor bank provides a fraction of the reactive power locally, thus reducing the reactive component of the feeder current, alleviating voltage drop and minimizing resistive losses. Moreover, capacitor banks can be configured in modular, switchable configurations that allow adjustment of reactive power output stepwise in response to changes in system conditions.[3]

This paper will be structured in the following way. Section II presents a systematic literature analysis of available literature on voltage control techniques and research gaps. Section III details the operating principles of capacitor banks that are backed by a set of governing equations. Section IV outlines the key forms of capacitor bank setups. Section V builds mathematical models behind the power flow analysis with reactive power injection. Section VI outlines the simulation procedure and case study design as using the IEEE 33-bus system. Section VII introduces and discusses the outcomes of the simulation. Section VIII will assess the strengths and weaknesses of capacitor bank technology. Section IX entails challenges and directions of research in future. Section X is the final section of the paper in which a conclusion is drawn on the results.

II. LITERATURE REVIEW

A. Classical Voltage Control Methods

Historically, a combination of on-load tap changers (OLTCs) on distribution transformers, switched capacitor banks, voltage regulators, and generator excitation control, has been used to achieve voltage regulation in power systems. Kundur [1] gives a comprehensive discussion of the theory of voltage stability and the importance of OLTCs in ensuring bus voltages are not exceeded by statutory limits. Although effective at the substation level, the mechanical nature of OLTCs, their finite tap resolution, and their inability to act in response to localized reactive deficits on the feeder, limits their effectiveness as the sole regulation mechanism in densely loaded or geographically extended distribution networks.

B. Advanced Compensation Devices

With the introduction of power electronics, flexible AC transmission system (FACTS) devices were developed, which provide dynamic and continuously variable reactive power support. The Static Var Compensator (SVC) which consists of thyristor-controlled reactors and thyristor-switched capacitors arranged in parallel provides modulation of reactive power with response times of the order of tens of milliseconds. Although SVCs provide a better dynamic response than mechanically switched capacitors, they add harmonic currents and have much higher capital costs.

A second-generation FACTS device, the STATcom, is a device that can independently control the magnitude and phase of the terminal voltage it delivers, using a voltage-source converter (interfaced to the grid through a coupling transformer). But converter-based systems are complex, have switching losses, and require filters that significantly add to the installation and operating costs and limits the deployment of STATCOM to high-value nodes.[6]

Since the mid-twentieth century, shunt capacitor banks have been deployed on distribution feeders, and their advantages in terms of power factor correction, voltage support and loss reduction are well known. Grainger and Stevenson [2] give fundamental analyses that show how the best location of shunt capacitors on a radial feeder can result in the minimum I 2 R losses due to counteracting the reactive portion of current in a feeder. This work was extended by Baran and Wu [3], who developed the integer programming optimization problem based on the radial distribution load-flow computation. The optimal capacitor placement problem has received long research interest due to its combinatorial character and its potential value of great economic benefits. Early optimization models by Duran [6] used classical optimization methods in determining the location and size of capacitors that minimized the total system cost including energy losses and capacitor investment. Subsequent studies applied genetic algorithms, particle swarm optimization, simulated annealing, ant colony optimization, grey wolf optimizer, whale optimization algorithm and hybrid methods to the problem. The need to connect distributed generation with distribution networks has created a requirement to concurrently optimize capacitor placement and DG siting and sizing. High photovoltaic penetration may result in voltage-rise issues when both reactive and active injections of power are coincident at weak buses.

D. Research Gaps

Despite the richness of the body of literature, there are still a number of research gaps. Most models have assumed that load demand is deterministic, but in practice distribution systems have encountered probabilistic loading due to customer behavior and weather-induced renewable generation. The interplay between capacitor bank switching and power quality phenomena, and especially of transient overvoltages, harmonic resonance and voltage flicker, has not been fully characterized in a modern distribution system with large DG penetration. The possibilities of machine learning and artificial intelligence to control real-time adaptive capacitor bank control are also yet to be realized.[9]

III. WORKING PRINCIPLE OF CAPACITOR BANKS

A. Reactive Power Generation

A capacitor is a passive device that is used to store electric energy in an electrostatic field that is generated between the conducting plates that form the capacitor, and a dielectric material that separates these plates. A capacitor of capacitance C is connected to an alternating voltage source of angular frequency $\omega = 2\pi f$, and draws a leading current that leads the applied voltage by 90 electrical degrees. Capacitors can generate reactive power, which it provides to the network instead of using reactive power at the source. Where V is the line-to-line voltage and Xc is the capacitive reactance of a shunt capacitor bank connected at a bus:

$$Q_C = V^2 / X_C \quad (1)$$

where $X_c = 1/(\omega C) = 1/(2\pi f C)$ is the capacitive reactance in ohms, f is the system frequency, and V is the magnitude of bus voltage. The reactive power of a capacitor is proportional to the square of the terminal voltage.[10]

$$Q_{C(3\varphi)} = 3 \times V_{phase}^2 / X_C = V_{LL}^2 / X_C \quad (2)$$

B. Reactive Power and Voltage Profile Improvement

Consider a simple radial feeder segment with a source bus and a load bus connected through a line with resistance R and inductive reactance X. The voltage on the receiving-end can be given in terms of the standard voltage-drop approximation

$$V_i - V_j \approx (P \times R + Q \times X) / V_i \quad (3)$$

A lowering in Q which is locally achieved by supplying reactive power locally at a shunt capacitor bank directly reduces the voltage drop and in turn increases the load bus voltage. Also the magnitude of line current is provided by:

$$I = \sqrt{(P^2 + Q^2)} / V \quad (4)$$

$$I_{comp} = \sqrt{(P^2 + (Q - Q_C)^2)} / V \quad (5)$$

$$\Delta P_{loss} = R \times [I^2 - I_{comp}^2] = R \times [Q^2 - (Q - Q_C)^2] / V^2 \quad (6)$$

C. Power Factor Correction

$$pf = P / S = P / \sqrt{(P^2 + Q^2)} = \cos(\varphi) \quad (7)$$

The net reactive power drawn out of the source is decreased by injecting capacitive reactive power, QC, which alters the power factor to:[12]

$$pf_{new} = P / \sqrt{(P^2 + (Q - Q_C)^2)} \quad (8)$$

$$Q_C = P \times (\tan \varphi_{old} - \tan \varphi_{new}) \quad (9)$$

IV. TYPES OF CAPACITOR BANKS

A. Fixed Capacitor Banks

Fixed capacitor banks are units of capacitors connected permanently to the distribution bus or feeder in the absence of any switching mechanism. They provide a constant reactive power injection irrespective of system loading conditions. These are its benefits, which are simplicity, low cost and high reliability, and its major weakness is that there is a possibility of overcompensation during the light-load periods.[13]

B. Switched Capacitor Banks

Switched capacitor banks use mechanical or electronic switching devices which permit discrete on/off control of individual capacitor units or groups. The overall reactive power output may be so varied in steps to suit the current demand.

C. Automatic Capacitor Banks

Automatic capacitor banks combine sensing, measurement and control intelligence with the underlying capacitor assembly, allowing autonomous reactive power control. The automatic power factor correction relay constantly monitors the bus voltage, reactive power demand and power factor, and then sends switching commands to individual capacitor steps to hold a desired operating band.[14]

V. MATHEMATICAL MODELING

A. Power Flow Equations for Radial Distribution Systems

A radial distribution network load-flow problem can be solved with the backward-forward sweep method. The equations of the branch power flows of a branch connecting bus i to bus j with impedance Zij = Rij + jXij are:

$$P_{ij} = P_j + R_{ij} \times (P_{ij}^2 + Q_{ij}^2) / V_j^2 \quad (10)$$

$$Q_{ij} = Q_j + X_{ij} \times (P_{ij}^2 + Q_{ij}^2) / V_j^2 \quad (11)$$

$$V_j^2 = V_i^2 - 2(R_{ij} \times P_{ij} + X_{ij} \times Q_{ij}) + (R_{ij}^2 + X_{ij}^2)(P_{ij}^2 + Q_{ij}^2)/V_j^2 \quad (12)$$

B. Incorporation of Capacitor Banks in Load Flow

A bank of rated reactive power QC at bus j is modeled as a negative reactive power load in the load-flow formulation. The adjusted net reactive power on bus j is:

$$Q_{j\_net} = Q_{j\_load} - Q_C \quad (13)$$

$$P_{loss} = \Sigma R_{ij} \times (P_{ij}^2 + Q_{ij}^2) / V_j^2 \quad (14)$$

$$LRI = (P_{loss\_old} - P_{loss\_new}) / P_{loss\_old} \times 100\% \quad (15)$$

C. Voltage Stability and Reactive Power Sensitivity

A reactive powervoltage characteristic, a graph that plots the reactive power absorption needed to stabilize the voltage on a given bus, can be used to assess the voltage stability of a bus. Buses whose value of voltage stability index is nearer to zero are more voltage-sensitive and should be priority candidates to place capacitors.[15]

$$VSI_j = V_j^4 - 4(X_{ij} \times P_j - R_{ij} \times Q_j) \times V_i^{-2} \times V_j^2 - 4(R_{ij} \times P_j + X_{ij} \times Q_j)^2 \quad (16)$$

VI. CASE STUDY – IEEE 33-BUS DISTRIBUTION SYSTEM

A. System Description and Parameters

The IEEE 33-bus radial distribution system, proposed by Baran and Wu [3], is a popular benchmark against which the distribution-level compensation and optimization algorithms are evaluated. The system is set to operate at a nominal voltage of 12.66 kV and substation source bus is a slack bus at 1.0 p.u. The network consists of 32 line segments that are a radial feeder. The overall connected load is 3715kW of active power and 2300kVAR of reactive power.[2]

TABLE I. IEEE 33-BUS SYSTEM AGGREGATE PARAMETERS

Parameter	Value	Unit
Nominal Voltage	12.66	kV
Number of Buses	33	—
Number of Branches	32	—

Parameter	Value	Unit
Total Active Power Load	3715	kW
Total Reactive Power Load	2300	kVAR
Base Apparent Power	10	MVA
Source Bus (Slack Bus)	Bus 1 (V = 1.0 p.u.)	—
Convergence Tolerance	1×10^{-5}	p.u.

B. Simulation Scenarios

Scenario A — Base Case (No Compensation): The system is run with no reactive power compensation devices. The load-flow solution defines the base voltage profile, magnitudes of currents in individual branches, and systemwide losses.

Scenario B — Uniform Capacitor Placement: Uniform Capacitor Placement: The buses with 6, 12, 18, 25 and 30 kV capacitors installed. This is a pragmatic yet sub-optimal deployment plan on engineering judgment.

Scenario C — Optimal Capacitor Placement: Optimal Capacitor Placement: Capacitor banks are located at buses determined to be the most reactive-power-deficient nodes through voltage sensitivity analysis. The best buses that were foundare 18, 25, 30, and 33, with capacitor sizes of 450, 600, 300, and 200 kVAR respectively.[4]

C. Assumptions and Simulation Setup

The simulation is in the form of a fixed radial topology, constant power loads, a 1.0 p.u. source bus, neglected line charging capacitances, unity transformer tap ratios, and ideal reactive power injections at capacitor buses. A backward-forward sweep load-flow algorithm is used with a convergence tolerance of 10-5 p.u.

VII. RESULTS AND ANALYSIS

A. Voltage Profile Comparison

Table II shows the magnitude of voltages at the various buses in per unit in the three simulation scenarios. The base case exhibits a severe voltage depression, which is minimum of 0.9038 p.u. at bus 18. The minimum bus voltage with uniform capacitor placement is 0.9412 p.u., whereas optimal placement can be achieved with bus voltage of 0.9680 p.u. and all buses satisfying the lower bound of 0.95 p.u.

TABLE II. BUS VOLTAGE MAGNITUDES (P.U.) – SELECTED BUSES

Bus No.	Scen. A (p.u.)	Scen. B (p.u.)	Scen. C (p.u.)
1 (Source)	1.0000	1.0000	1.0000
2	0.9970	0.9975	0.9982
5	0.9817	0.9843	0.9879
6	0.9800	0.9868	0.9871
10	0.9583	0.9621	0.9698
14	0.9476	0.9520	0.9638
18 (Min A)	0.9038	0.9412	0.9680
22	0.9170	0.9423	0.9691
25	0.9338	0.9521	0.9714
30	0.9220	0.9408	0.9687
33	0.9131	0.9359	0.9680

B. Power Loss Comparison

The base case total real power loss of 202.7 kW is 5.46% of the total active power supplied. The uniform placement will give a reduction of 15.2 percent to 171.9 kW, whereas optimal placement will give a reduction of 29.8 percent to 142.3 kW. The overall decrease in reactive power loss is following the same pattern.[5]

TABLE III. POWER LOSS COMPARISON ACROSS SCENARIOS

Performance Metric	Scen. A	Scen. B	Scen. C
Total P_loss (kW)	202.67	171.85	142.31
Total Q_loss (kVAR)	135.1	112.4	98.7
P_loss Reduction (%)	—	15.20%	29.78%

Performance Metric	Scen. A	Scen. B	Scen. C
Min. Bus Voltage (p.u.)	0.9038	0.9412	0.9680
Buses Below 0.95 p.u.	16	7	0
System Power Factor	0.78	0.87	0.96
Total Q_C Installed (kVAR)	0	1500	1550
Investment Cost (approx. USD)	—	~15,000	~15,500

C. Power Factor Improvement

The system-wide power factor increases as the base case is uniformly located, increasing the power factor to 0.87 and as the base case is optimally located the power factor increases to 0.96. This minimizes the apparent power demanded at the source and has far-reaching consequences on the utilization of transformers and the thermal loading of feeders, as well as the utility demand charges.[7]

D. Discussion of Results

The comparative study gives quantitative information on the effectiveness of the reactive power compensation by using capacitor banks. Reactive power injection Local reactive power injection can reduce the reactive portion of feeder current, minimizing voltage drop and I 2 R losses. The economic benefits of systematic optimization are brought into the limelight by the superiority of optimal placement to uniform distribution. Scenario B and C utilize almost the same total reactive power, 1500 kVAR and 1550 kVAR, but with very different results. This proves that it is not the amount of reactive compensation but its spatial distribution that is decisive. Assuming that the weighted average cost of energy is USD 0.08/kWh and the annual load duration is 8000 hours, the annual energy saving due to optimal location will be approximately USD 38,600/per year.

VIII. ADVANTAGES AND LIMITATIONS

A. Advantages

Capacitor banks have a myriad of benefits, which have justified their continued extensive use in distribution networks all over the world over the last 70 years. Their cost-effectiveness, reduction of real and reactive power losses, improvements in voltage profiles, corrections in power factor, operationally simplicity, dependability, and a modular scalability as the load increases, make them cost-effective.

B.Limitations

Although capacitor banks have advantages, they have drawbacks that need to be taken into account when planning and operating. Switching transients and inrush currents can be created by energization. Fixed banks may lead to overcompensation and leading power factor in times of light loads. Capacitor banks have the ability to communicate with the system inductances to generate harmonic resonance. Mechanically switched banks only offer discrete step control and the output of reactive behaviour goes down with the square of voltage when in depressedvoltage conditions. Aging, dielectric failure, thermal cycling, and overvoltage stress are also likely to cause issues in capacitors.[8]

IX. CHALLENGES AND FUTURE SCOPE

A. Integration with Smart Grid Infrastructure

Smart grid architectures provide possibilities to have more coherent capacitor bank operation. Advanced metering infrastructure, distribution management systems, and a communication network provide the capability to monitor bus voltages, feeder currents, and reactive flows of power in real-time. This information can serve to support centralized volt/VAR optimization algorithms which coordinate capacitor banks, OLTC operations, and distributed generation reactive power setpoints.

B. Renewable Energy Integration

The increasing infiltration of photovoltaic power generation and wind turbines changes the reactive power environment that capacitor banks are operating in. The grid codes are progressively demanding inverter connected distributed generation to provide reactive power support, such that the interaction between inverter control and capacitor bank behaviour should be co-ordinated to avoid oscillatory hunting or voltage instability.

C. Artificial Intelligence-Based Control

Capacitor bank control and optimization is becoming more and more the application of the artificial intelligence and machine learning techniques. Reinforcement learning agents are capable of learning switching policies, deep learning may be used to improve short-term load forecasting, and graph neural networks can be used to represent distribution system topology to quickly predict power-flow behavior and to be able to adaptively control the system..

D. Energy Storage and Hybrid Compensation

The battery energy storage systems provide a supplemental ability to capacitor banks. Although capacitors are very suitable in stead-state reactive power compensation, storage systems are capable of injecting or absorbing both active and reactive power very rapidly. Hybrid volt/VAR controllers are able to coordinate capacitor bank switching with storage dispatch and distributed generation inverter setpoints.[11]

X. CONCLUSION

The paper has provided a systematized study of the capacitor banks in the regulation of distribution power system voltage. Theoretical backgrounds, mathematical models, configurations of capacitor banks, and a quantitative analysis using the IEEE 33-bus radial distribution system benchmark were covered.

The outcomes of the simulation indicate the effectiveness of capacitor banks in improving voltage shapes, lowering losses and increasing power factor. A voltage sensitivity analysis based on optimal placement attains a 29.78% reduction in the total real power losses and eliminates all under-voltage violations in the IEEE 33-bus system. The power factor of the system is increased to a range of 0.9680 p.u. to 0.9680 p.u. as opposed to the previous 0.9038 p.u. to 0.9680 p.u. The relative examination among uncompensated, uniformly located, and optimally placed capacitor banks highlights the significance of optimization in the planning of reactive power.

The distribution of similar total reactive power capacity at optimal instead of uniformly distributed locations results in better loss reduction and total elimination of under-voltage violations. Although more advanced devices like SVC and STATCOM provide better dynamic performance, they have a higher cost of capital and thus capacitor banks are preferred technology in many applications requiring reactive compensation at the distribution level. In the future, the integration of smart grids, coordination with inverter-based distributed generation, and adaptive control based on artificial intelligence are promising directions in the further extension of the effectiveness of capacitor banks in contemporary power systems.

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VIII. Single Line Diagrams – All Simulation Scenarios

The table below presents the engineering Single Line Diagrams (SLDs) for all three simulation scenarios on the IEEE 33-Bus radial distribution system. Bus voltage levels, feeder segments, circuit breakers, and capacitor bank installations are shown for each scenario, directly corresponding to the simulation readings in Tables II and III.

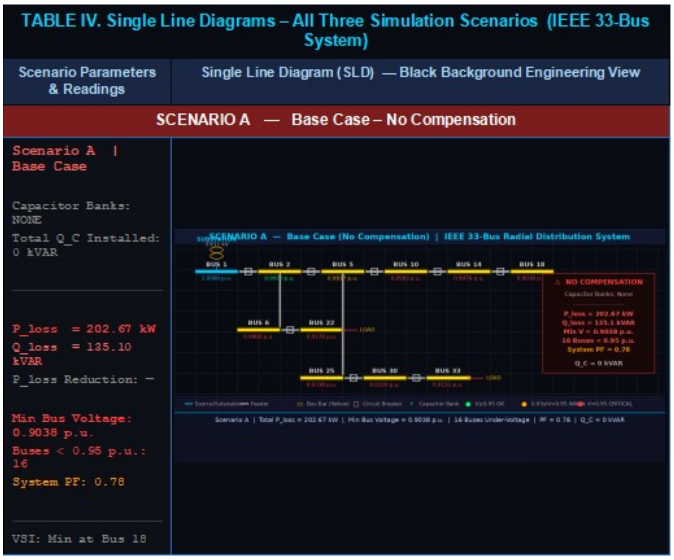


TABLE IV. Single Line Diagrams – All Three Simulation Scenarios (IEEE 33-Bus System)

Scenario Parameters & Readings	Single Line Diagram (SLD) — Black Background Engineering View

SCENARIO A — Base Case – No Compensation

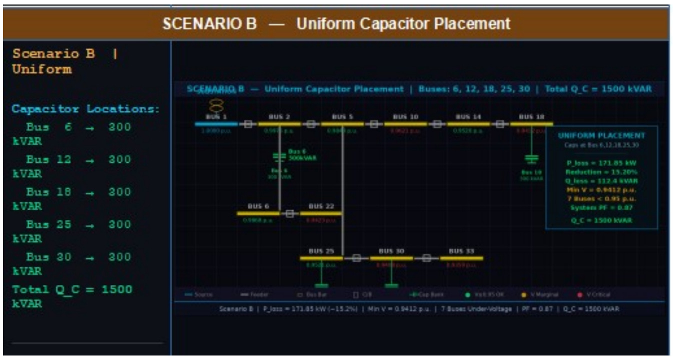
Scenario A | Base Case

Capacitor Banks: NONE
Total Q_C Installed: 0 kVAR

P_loss = 202.67 kW
Q_loss = 135.10 kVAR
P_loss Reduction: —

Min Bus Voltage: 0.9038 p.u.
Buses < 0.95 p.u.: 16
System PF: 0.78

VSI: Min at Bus 18



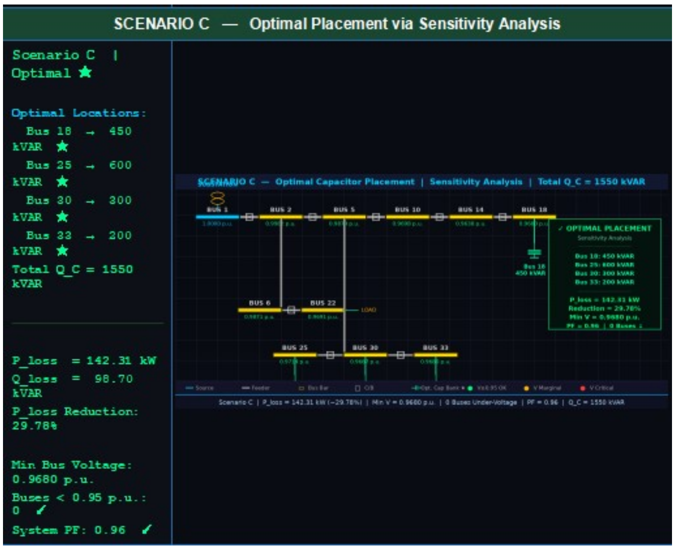
SCENARIO B — Uniform Capacitor Placement

Scenario B | Uniform

Capacitor Locations:
Bus 6 → 300 kVAR
Bus 12 → 300 kVAR
Bus 18 → 300 kVAR
Bus 25 → 300 kVAR
Bus 30 → 300 kVAR
Total Q_C = 1500 kVAR

P_loss = 171.85 kW
Q_loss = 112.40 kVAR
P_loss Reduction: 15.20%

Min Bus Voltage: 0.9412 p.u.
Buses < 0.95 p.u.: 7
System PF: 0.87



SCENARIO C — Optimal Placement via Sensitivity Analysis

Scenario C | Optimal ★

Optimal Locations:
Bus 18 → 450 kVAR ★
Bus 25 → 600 kVAR ★
Bus 30 → 300 kVAR ★
Bus 33 → 200 kVAR ★
Total Q_C = 1550 kVAR

P_loss = 142.31 kW
Q_loss = 98.70 kVAR
P_loss Reduction: 29.78%

Min Bus Voltage: 0.9680 p.u.
Buses < 0.95 p.u.: 0 ✓
System PF: 0.96 ✓

Figure 1: Engineering SLDs — Scenario A (Base Case) | Scenario B (Uniform) | Scenario C (Optimal). Color coding: Cyan=Source, Yellow=Bus Bar, Green=Capacitor Bank, Red=Under-voltage, Green text=Compliant voltage.