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Coordinated Allocation of PV and Capacitors with Var Capability for Voltage Unbalance Mitigation in LV Distribution Grids

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Abstract**—The increased penetration of photovoltaic systems (PVs) and unbalanced loads in low-voltage (LV) distribution systems can adversely affect the overall performance of the utility grid (UG). These impacts include voltage unbalance, power losses, thermal overloading of lines, and various power quality issues. To mitigate voltage unbalance, reactive power control (RPC) techniques are employed by regulating PV inverters and capacitor banks. This study focuses on coordinating the sizing and placement of PVs with reactive power capability (Var) to reduce voltage unbalance and maintain acceptable limits for other power quality indices, particularly in unbalanced three-phase systems. During full load conditions, there is insufficient excess capacity available for reactive power injection or absorption by PV inverters. Therefore, to improve their reactive power capability, the inverters must be oversized relative to the nominal rating of the installed PV systems, which increases capital costs and harmonic levels within distribution networks. To address this, both PVs and capacitor banks are optimally allocated using a multi-objective grey wolf optimization (MOGWO) algorithm within the IEEE 123-bus unbalanced distribution system, using MATLAB and OpenDSS platforms. As a result of this proposed planning, voltage unbalance, power loss, and voltage deviation are significantly decreased by 19%, 34%, and 14% (under 100% overloading), respectively, along with a 215% increase in PV penetration levels. Furthermore, the proposed planning emphasizes that the combination of PVs and capacitor banks can effectively reduce voltage unbalance, which in turn reduces power losses and thermal line overloading.**

Keywords—Hosting Capacity, Voltage Unbalance, Reactive power capability, PVs, Capacitor Banks.

I. INTRODUCTION

Recently, the necessity for clean and sustainable energy sources has increased in low-voltage (LV) distribution systems. To accomplish such aims, renewable energy sources (RESs) especially photovoltaic systems (PVs) are introduced to reduce the adverse impacts of fossil fuels on the environment [1]. This makes a bulk of distribution generation (DG) units connected to the utility grid (UG) especially single-phase DG units in the presence of unbalanced loads. Which causes various adverse impacts on the power quality provided by the UG [2].

Hence, the increased penetration of PVs in the UG causes various influences. Common technical issues can be noticed in the distribution system operation, stability and reliability, and control. Most of these issues can be seen notably in unbalanced three-phase systems, which are mainly based on their placement and capacity. These influences may deteriorate the overall network performance involving voltage unbalance, power losses, thermal overloading of lines, and other power quality issues [3]. Therefore, the integration of PVs or DGs should be optimally coordinated to regulate the voltage and solve other power quality issues. This in turn enhances the hosting capacity (HC) of distribution systems. Various enhancement techniques are applied for voltage regulation especially reactive power control (RPC) [4] to mitigate the voltage unbalance index (VUI) during increased integration of PVs.

To alleviate the VUI, the authors in [5], [6] applied various RPC schemes using Flexible AC Transmission Systems (FACTs) based on power electronic devices such as static VAR compensators or passive filters. However, the necessity of accurate allocation is raised beside the increased level of harmonics and maintenance costs. Notably, modern PV inverters are designed with reactive power capability to regulate the voltage however their capacity should be larger than the nominal rate of installed PVs which increases the levels of harmonic and implemented cost [7]. In [8], [9], the PV inverters are regulated locally for injection/absorption of reactive power to reduce the voltage unbalance; however, centralized control and robust communication systems are required which are not available in old UG infrastructure. In [10], the capacity of PV inverters was optimally increased in the presence of capacitor banks to regulate the voltage and reduce the cost.

To address the gap in the literature, this paper applies the multi-objective grey wolf optimization (MOGWO) algorithm to optimally coordinate both the size and location of PVs and capacitor banks for voltage regulation, aiming to reduce voltage imbalance and resolve other power quality issues in the IEEE 123-bus unbalanced distribution system. This is achieved through co-simulation between MATLAB and OpenDSS platforms. The PVs are designed for reactive power injection and absorption. The proposed planning involves five operational zones, each with aggregated bulk generation of PVs and capacitor banks. Accurate specification of the optimal capacity allocation of PVs and capacitor banks across these five operational zones not only helps in mitigating voltage unbalance, power losses, and line overloads but also increases the HC of distribution systems while reducing the exchanged power through the UG.

II. PROBLEM DESCRIPTION

The increased penetration of PVs in unbalanced distribution systems causes adverse issues, such as voltage unbalance, power loss, thermal overloading on lines, and reverse power flow, especially in low load demand. In this regard, the common method for regulating voltage in unbalanced systems and solving these issues, while also increasing the HC of distribution systems to accommodate more PVs, is RPC. For this purpose, the reactive power capability of PV inverters can be used for reactive power

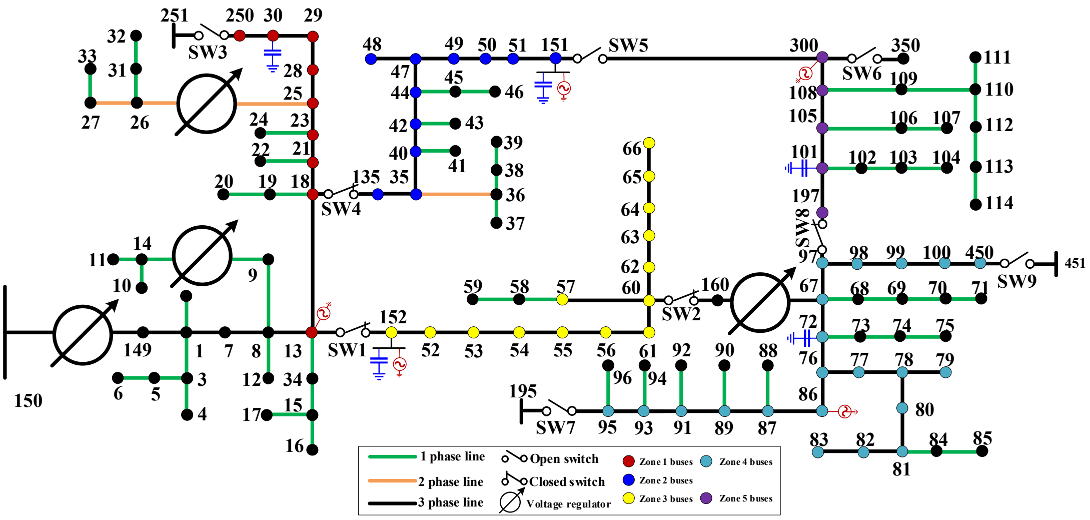


Fig. 1. Proposed planning structure of IEEE 123 bus distribution system.

injection/absorption in distribution systems. However, there is no spare capacity for reactive power injection/absorption from PV inverters during full-loaded conditions as these inverters are designed to operate at unity power factor. So, to enhance their reactive power capability and regulate the voltage, the capacity of inverters needs to be larger than the nominal rated of installed PVs which increases the capital cost and harmonic levels in distribution networks. Therefore, the capacitor banks and spare capacity of PV inverters can be used simultaneously to regulate the voltage, reduce the voltage unbalance and solve other problems. In this paper, the optimal planning of both PVs and capacitor banks is investigated in this work to reduce the voltage unbalance mainly which in turn reduces the power losses and thermal line overloading.

III. PROBLEM FORMULATION

To mitigate the voltage unbalance due to the increased penetration of unbalanced loads and PVs, optimal coordination (sizing and placement) of PVs and capacitor banks are proposed for an unbalanced three-phase system with reactive power capability. The main objectives are reducing the voltage unbalance and increasing the penetration of PVs with reactive power support which in turn improve other power quality indicators.

A. Unbalanced Distribution Systems

A typical IEEE 123-bus distribution system is applied to verify the proposed planning of PVs and capacitors, as depicted in Fig. 1 [11]. The structure of the proposed system is modified by dividing it into 5 operational zones, each zone has its candidates with unbalanced three-phase buses for PVs and capacitors selection, as depicted in Table I.

TABLE I. IEEE 123-BUS DISTRIBUTION SYSTEM STRUCTURE

	Candidate buses at each zone
Zone 1	[13 18 21 23 25 28 29 30 250]
Zone 2	[135 35 40 42 44 47 49 50 51 48 151]
Zone 3	[152 52 53 54 55 56 57 60 61 62 63 64 65 66]
Zone 4	[67 72 76 77 78 79 81 80 82 83 86 87 89 91 93 95 97 98 99 100 450]
Zone 5	[101 105 108 197 300]

B. Objective Function

The objective function is mathematically modelled involving three decision variables for minimizing the voltage unbalance and voltage deviation (VD), and maximizing the the accommodated PVs' capacity. The complete objective function can be formulated as shown in Eq. (1).

$$\min_{\theta}\{f_1, f_2, f_3\} \tag{1}$$

where θ is the vector of the decision variables which includes VUI, VD, and sizing of the bulk generation of PVs.

1) VUI formulation

To calculate the VUI percentage, the following equation can be used,

$$f_1 = VUI\ \% = \frac{Max.AVD}{V_i^{avg.}} * 100\% \tag{2}$$

where $Max.AVD$ is the maximum average voltage deviation far from the average voltage of three phases ($V_i^{avg.}$), i donets the bus number. Hence, both $Max.AVD$, and $V_i^{avg.}$can be demonstrated as follows,

$$Max.AV = max.\left\{ \begin{matrix} 3 \\ ph = 1 \end{matrix} \left|V_i^{avg}. - V_i^{ph}\right| \right. \tag{3}$$

$$V_i^{avg} = \frac{V_i^a + V_i^b + V_i^c}{3} \tag{4}$$

where V_i^{ph} is the actual voltage per phase (V_i^a, V_i^b, V_i^c). The AVD can be calculated using Eq. (5),

$$f_2 = AVD = \frac{\sum_{i=1}^{n} |V_n - V_i|}{n}\ (pu) \tag{5}$$

Here n is the total buses number, V_n donates the required voltage at bus i (1 pu.) and Vi gives the actual voltage at bus i.

2) Sizing of PVs and capacitor banks

The optimal placement and sizing of both PVs and capacitors are attained using the MOGWO algorithm which guarantees to maximize the capacity of PVs with reactive power capability along with minimizing the VUI ratio. So, f_3 can be formulated as follows,

$$f_3 = -\sum_{k=1}^{N_z} P_{PVs}^k \pm j \sum_{k=1}^{N_z} Q_{PVs}^k \tag{6}$$

where N_z is the number of zones, and P_{PVs}^k and Q_{PVs}^k are the generated active power, and injected/absorbed reactive power of PVs installed at each zone, respectively, in the presence of capacitor banks that injected reactive power ($Q_{Cap.}^k$) to the candidate bus. The negative sign in the second term of (6) indicates the leading power factor.

C. Constraints

1) Power Flow Balance Constraints

$$\sum_{i=1}^{N_L} S_{Load}^{i} + \sum_{l=1}^{N_{line}} S_{Loss}^{l} - \sum_{k=1}^{N_z} P_{PVs}^{k} \pm j \sum_{k=1}^{N_z} Q_{PVs}^{k} - j \sum_{k=1}^{N_z} Q_{Cap.}^{k} = S_{Grid} \tag{7}$$

where S_{Load}^{i} is the apparent power of load for bus i to the total number of loads (N_L), S_{Loss}^{l} declares the apparent power loss per line, and S_{Grid} is the exchanged active and reactive power from the UG.

2) Voltage Limits

$$V_i^{min} \leq V_i \leq V_i^{max} \tag{8}$$

where $\{ V_i^{min}, V_i^{max} \}$ equal $\{0.95\, pu, 1.05 \text{ pu} \}$, respectively. Further, the average and maximum VUI % at each zone don't exceed 1%, and 1.5%, respectively.

3) Constraints of PVs and capacitors

$$P_{PVS}^{min} \leq P_{PVs}^{k} \leq P_{PVS}^{max} \tag{9}$$

$$Q_{PVs}^{k} \leq \sqrt{S_{PVs}^{k} - (P_{PVs}^{k})^2} \tag{10}$$

Here, the generation limits of PVs are restricted from 10 kW to 1500 kW installed per zone. The injected/absorbed reactive power is restricted by generated power and bus voltage. The injected reactive power of capacitors is restricted between 10 kvar to 750 kvar installed per zone.

$$Q_{Cap.}^{min} \leq Q_{Cap.}^{k} \leq Q_{Cap.}^{max} \tag{11}$$

IV. RESULTS AND DISCUSSIONS

The proposed planning of PVs and capacitor banks is validated using co-simulation between OpenDSS and Matlab platforms in the IEEE123-bus unbalanced distribution system. The best capacity and placement of both PVs and capacitors at each zone is optimized using the MOGWO algorithm under the applied constraints. The simulation results of the proposed methodology are carried out using a Dell workstation desktop equipped with 32 GB RAM, and Intel(R) Xeon(R) W-2133&3.60GHz CPU. The total active and reactive powers of loads are 3490 kW and 1920 kvar, respectively. The active and reactive power losses at nominal loading are 95.98 kW, and 19.25 kvar, respectively. Additionally, the lower and upper voltages are 0.979 pu, and 1.05 pu, respectively. To demonstrate the effectiveness of the proposed planning, the following cases are investigated using snapshot and daily simulation states,

- ***Case 1:*** is simulated without considering either PVs or capacitor banks.
- ***Case 2:*** is simulated using PVs with the reactive power capability only.
- ***Case 3:*** is simulated using PVs with the reactive power capability and capacitor banks.

The proposed planning of the integrated PVs and capacitors used in Case 2 and Case 3, is given in Table II.

TABLE III. BEST LOCATION OF PVS AND CAPACITORS.

	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5
PV Location	13	151	152	86	300
Capacitor's location, 3Ph, Conn. Delta	30	151	152	72	101

A. Snapshot results at nominal loading

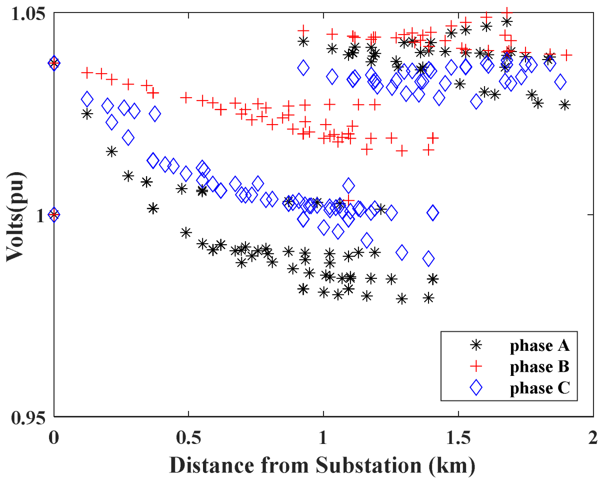
The snapshot results of the three cases are concluded in Table III and compared to results in Ref. [12]. Case 3 exhibits the best results of lower and upper voltages are 0.9887 pu, and 1.0361 pu, respectively, compared to other cases with a 34.2% loss reduction compared to Case 1. The lowest VUI% (1.0677%) and AVD are obtained in Case 3 with approximately 7.5 MW of PVs compared to 1.2469% and 6.2 MW of PVs in Case 2, and 1.3242% in Case 1, respectively. Table III shows the superiority of implementing a combination of PVs with reactive power capability and capacitor banks in terms of voltage unbalance, voltage deviation, integrated PV capacity, and active and reactive power losses, compared to other cases. To indicate thermal overloading of lines, Table A, Table B, and Table C in Appendix A, illustrate the overloaded lines in Case 1, Case 2 and Case 3, respectively. By comparing between results, it is clear that the overload ratio of lines and current unbalance are decreased in Case 3. Further, Fig. 2(b) depicts the enhanced voltage profiles per phase vs. distance from the substation in Case 3, compared to Fig. 2(a) for Case 1. In [12], the results are promised however there are no limits for integrating DGs which is not suitable in grid-connected mode. It should be a reserve power from UG /UG and energy storage systems to supply the base power of distribution systems to deal with the uncertain conditions of DGs. So, in this article, the penetration level of PVs does not exceed 215% with the capability for increasing to higher than 500% but other factors should be considered such as line ampacity and the reserve capacity of base power.

B. Daily simulation

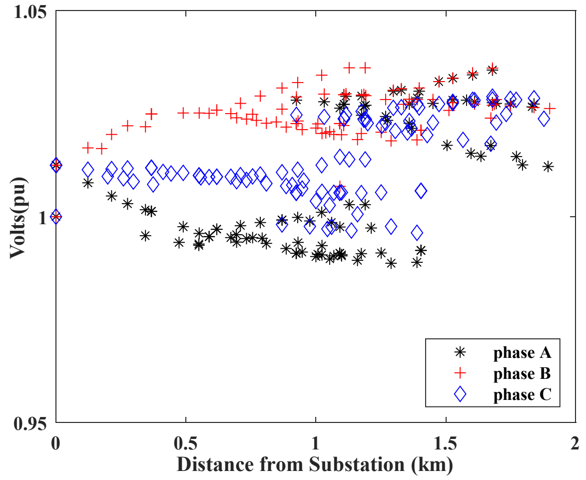
In the daily simulation, the stochastic generation of PVs and load consumption pattern per day curves are used, as depicted in Fig. 3 (a, b), respectively. Table IV gives the summary of the daily simulation results of three cases which shows the superiority of the combination of PVs with reactive power capability and capacitor banks in Case 3 to enhance the overall performance regarding voltage unbalance, voltage deviation, integrated PV capacity, and active and reactive power losses, compared to other cases. This is noticed in Fig.4 and Fig.5 that Case 3 obtained the lowest average VUI% and AVD% per day overall operational zones which are 0.734%, and 1.51%, respectively.

TABLE II. SNAPSHOT RESULTS AT NOMINAL LOADING.

	Case 1	Case 2	Case 3	Ref.[12]
Max pu. Voltage	1.05	1.0436	1.0361	1.0436
Min pu. Voltage	0.979	0.99219	0.9887	0.9825
Total Active Power imported from UG (MW)	3.61531	2.70585	2.51573	-
Total Reactive Power imported from UG (Mvar)	1.31156	-0.598353	-1.00383	-
Total Active Losses	95.98 kW, (2.655 %)	76.70 kW, (2.835 %)	63.12 kW, (2.509 %)	72.58 kW
% loss reduction	-	20%	34.2%	24.4%
Total Reactive Losses (Mvar)	0.192509	0.153635	0.126002	-
Total Avg. VUI%	1.3242%	1.2469 %	1.0677 %	2.576
Total installed PV capacity	0 kW	6230 kW	7495 kW	9 DGs with 17 MW
Penetration level%	0%	178.5%	215%	500%
Total capacitor bank capacity	0 kvar	0 kvar	3350 kvar	0 kvar



a) Case 1



b) Case 3

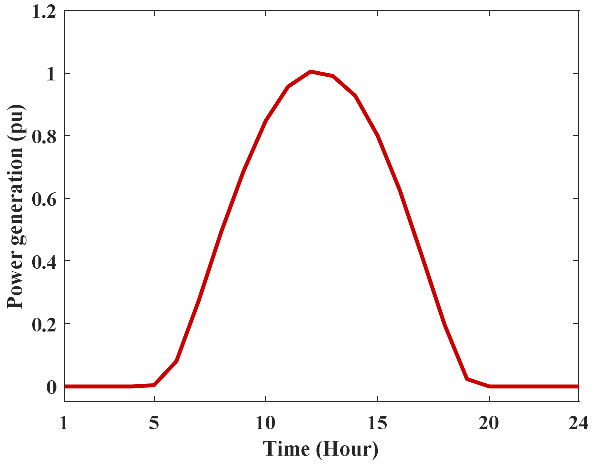
Fig. 2. Voltage profile vs distance from substation

TABLE IV. SUMMARY OF DAILY SIMULATION RESULTS.

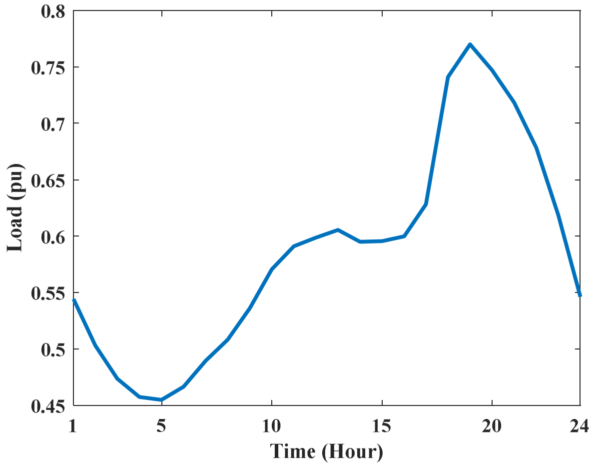
		Zone 1	Zone 2	Zone 3	Zone 4	Zone 5
Case 1	**VD**	Total AVD%= 1.75, Max. VD%= 3.85 at bus #83 , Min. VD%= 0.008 at bus #66				
	Voltage unbalance	Total VUI%=0.94, Max. VUI %=1.55 at bus#66, Min. VUI %= 0.239 at bus #93				
Case 2	**PV Capacity, 3 Ph, kW**	**1500**	**1500**	**1500**	**230**	**1500**
	PV Location	13	151	152	86	300
	Power factor	1	0.467	0.514	-0.337	0.178
	VD	Total AVD%= 1.51, Max. VD%= 4.57 at bus #300 , Min. VD%= 0.004 at bus #135				
	Voltage unbalance	Total VUI%=0.825, Max. VUI %=1.4 at bus#30&250, Min. VUI %= 0.25 at bus #105				
Case 3	**PV Capacity, 3 Ph, kW**	**1500**	**1495**	**1500**	**1500**	**1500**
	Power factor	1	-0.278	0.715	1	-0.296
	Capacitor's location, 3Ph, Conn. Delta	30	151	152	72	101
	Capacitor's capacity, kvar	**730**	**750**	**750**	**371**	**750**
	VD	Total AVD%= 1.51, Max. VD%= 3.75 at bus #83, Min. VD%= 0.009 at bus #42				
	Voltage unbalance	Total VUI%=0.734, Max. VUI %=1.34 at bus#30&250, Min. VUI %= 0.16 at bus #105				

V. CONCLUSION

The rising presence of PVs and unbalanced loads in LV distribution networks poses challenges to overall UG performance, leading to issues such as voltage imbalance, power losses, and thermal overloads on lines. To alleviate voltage imbalances, reactive power control methods are employed, including the management of PV inverters and capacitor banks. This study focuses on coordinating the optimal sizing and placement of PVs equipped with reactive power capability to minimize voltage unbalances and sustain acceptable levels of other power quality parameters, particularly in unbalanced three-phase systems. However, under full load conditions, PV inverters may lack excess capacity for reactive power exchange, necessitating larger



a) PV generation curve.



b) Load consumption curve.

Fig. 3. PV generation and load consumption curves.

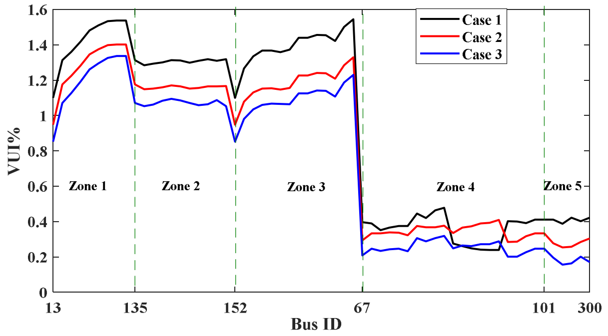


Fig. 4 Average VUI% per day.

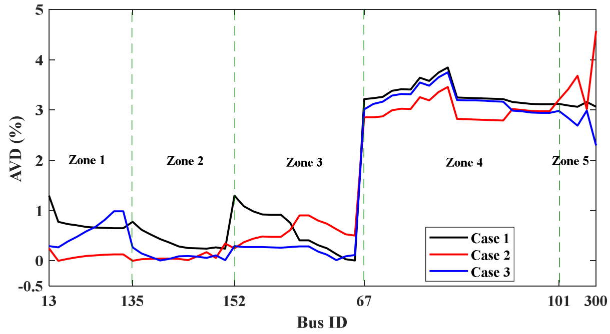


Fig. 5 Average AVD% per day.

sizes than the nominal rating of installed PV systems. This results in increased capital expenditure and higher harmonic levels in distribution networks. To address these challenges, a MOGWO algorithm is utilized to optimally allocate both PVs and capacitor banks within an IEEE 123-bus unbalanced distribution system, employing MATLAB and OpenDSS platforms. Consequently, voltage unbalance, power loss and voltage deviation are reduced by 19%, 34%, and 14% (respectively) under 100% overloading conditions, along with a 215% penetration level of PVs. This proposed planning approach emphasizes the effectiveness of combining PVs and capacitor banks in mitigating voltage imbalances, subsequently reducing power losses and thermal line overloads.

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APPENDIX A

TABLE (A) OVERLOAD ON LINES IN CASE 1.

Element	I1	Amps Over	kVA Over	%Normal	%Emergency	I2	%I2/I1	I0	%I0/I1
Line.L115	514.46	231.46	2225.37	157.9	105.2	70.7	13.7	58.9	11.4
Line.L3	490.08	213.38	1938.21	153.3	102.2	70.2	14.3	58.2	11.9
Line.L7	487.06	204.27	1833.17	151.1	100.7	67.2	13.8	55.3	11.4
Line.L10	468.75	158.08	1360.22	139.5	93	54.6	11.7	43	9.2

TABLE (B) OVERLOAD ON LINES IN CASE 2.

Element	I1	Amps Over	kVA Over	%Normal	%Emergency	I2	%I2/I1	I0	%I0/I1
Line.L115	377.53	75.5	523.07	118.9	79.2	71.9	19	58.4	15.5
Line.L3	358.83	59.75	392.71	114.9	76.6	71.7	20	57.7	16.1
Line.L7	356.57	51.96	339.02	113	75.3	68.7	19.3	54.7	15.3
Line.L10	343.4	14.02	88.02	103.5	69	55.9	16.3	42.6	12.4

TABLE (C) OVERLOAD ON LINES IN CASE 3.

Element	I1	Amps Over	kVA Over	%Normal	%Emergency	I2	%I2/I1	I0	%I0/I1
Line.L115	371.27	53.44	361.88	113.4	75.6	71.1	19.2	55.5	15
Line.L3	355.48	38.99	252.72	109.7	73.2	70.6	19.9	54.6	15.4
Line.L7	353.61	31.91	205.78	108	72	67.6	19.1	51.6	14.6