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Compensation to Fulfill Voltage Drop Security in Medium Voltage Feeders

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ABSTRACT

Increasing the load or expanding the feeder can increase the voltage drop. In addition, the greater the flow of reactive power on the line, the worse the voltage drop. On the other hand, the voltage must meet certain safety limits, and one way to correct the voltage drop is to apply for compensation. However, calculating the voltage drop through the power flow and the measurement methods is difficult to apply because it is necessary to determine the value of the amount of load on each node. This paper will propose a simple method that is convenient to apply to determine the compensation needed to maintain voltage quality in medium voltage feeders. The methodology used is a current source approach that functions as a variable. Then the current flow along the channel is assumed as a linear function so that the load center point is obtained according to the feeder configuration and load capacity. The simulation results on the 21-node feeder assuming a power factor of 0.8, show that the voltage drop improvement is quite effective with compensation. For example, at a 150 A current source, with 30 A compensation, the voltage drop can be increased from 4.45% to 3.98%. Furthermore, by applying for compensation, it is possible to expand the load to a source current of 165 A with a compensating current of 80 A.

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1. INTRODUCTION

One of the problems in the medium voltage feeder is the voltage drop that can exceed the allowable voltage security limit due to load growth or feeder expantion. The load growth will increase the current flowing in the feeder segments, thereby increasing the voltage drop at each node. Meanwhile, the feeder expantion will increase the impedance of the line, which can also worsen the voltage quality on the user side. Generally, the load characteristics of the medium feeder have a poor power factor due to a low power factor, such as electric motors and reduction furnaces. This poor power factor will cause reactive current to flow in the feeder so that it has adversely impact on the voltage drop. On the other hand, the reactive power flow caused by this reactive current cannot be absorbed by the load, but this reactive power only circulating in the network. This decrease in reactive power will reduce reactive current flow so that the voltage drop is corrected. In other words, reactive power compensation can improve the voltage drop on the medium feeder.

To improve the quality of electricity, especially the voltage quality, the study of voltage drop is still relevant recently. The theoretical basis for voltage drop in a line and feeder has been well presented in [1]-[6]. The formulations for calculating the voltage drop are well presented in [1]-[5]. A simple formulation has been implemented to determine the voltage drop across the feeder with a small error rate and very effectively applied to the distribution network [6].

The study of calculating the voltage drop has been proposed by [7]-[10]. The voltage drop calculation based on the study of power flow for rural areas has been well formulated by [7]. Parameter modeling in determining the voltage drop in the distribution network has been successfully tested by [8]. Furthermore, the calculation and design in determining the voltage drop applied to the feeder in rural areas have been formulated by [9][10]. In addition, determining the voltage drop is a problem that needs serious attention in assessing the quality of electricity. References [11][15] have proposed determining the voltage drop to monitor the voltage. Calculating the voltage drop across a simple medium feeder with data on the incoming current to the feeder has been well-formed by [11]-[14]. The measurement method is presented by [15] to look at the effect of the quality of the voltage power profile.

The load growth will increase the load on the feeder, and this will result in poor voltage quality. Adding uncontrolled feeder loads will make the situation worse. In this case, the voltage security limit may be violated. It is necessary to control the voltage so that the voltage is always subject to its security limits. Voltage control via a Distribution Generator using a transformer tap change is presented in [16]-[26]. Having a Distribution Generator injected into the medium voltage network at a bad voltage point can correct the voltage drop, especially at that point. At the same time, reference [27][28] has presented voltage regulation in a radial system through reactive power injection and proper placement of the Distribution Generator.

The voltage improvement on the medium feeder can be made by installing a compensation device. In this case, the reactive current is attempted to be compensated by the current generated by the capacitor. Compensation studies to improve the voltage in the feeder have been proposed by [29]-[40]. Ideally, the voltage drop across the feeder must meet its security. Compensation is required in feeders with poor voltage drop, either due to the addition of feeder length or load growth. The voltage improvement due to this has been suggested by [29][34]. Compensation using the battery for the trolley bus supply system has been successfully discussed by [35]-[38]. The effect of the location of the capacitor in the feeder on loss savings has been well presented by [39]-[40].

The voltage drop on the consumer nodes must be ensured to meet security. It is the power company's responsibility to maintain the quality of its services. In a medium-voltage network system consisting of many medium feeders, it will be an issue if the voltage determination uses the measurement method because many measuring instruments are needed in addition to sampling measurements for each hour. On the other hand, compensation can improve the voltage drop. It needs to be calculated carefully to determine the effect of compensation on the voltage drop. Characteristics of a horse saddle, the voltage drop will drop to the optimal compensation (less compensation), and after that, the voltage drop will rise again (overcompensation). This paper presents the calculation of the compensation needed to meet voltage security if the medium feeder has a poor voltage drop. This method is expected to know the amount of compensation to the maximum compensation in repairing the poor voltage drop on the feeder medium.

From the literature studies, the voltage drop improvement at the feeder has been made with a tap-changer of a transformer, distributed generator, and compensation. In terms of compensation, it has succeeded in increasing the voltage according to the desired compensation without considering the voltage security limit. This article aims to fix the bad voltage in the feeder with minimal compensation; the bad voltage will be raised to the minimum safety limit. This effort should be made so that the cost of compensation can be kept as low as possible.

It has been explained that compensation can improve the voltage, but calculating the voltage drop on the feeder is complicated, both through the power flow and measurement methods. The power flow method requires data for all loads, while the measurement method requires measuring instruments at each load point. The contribution of this paper proposes a simple calculation method to determine the voltage drop, both with and without compensators, based on the input current approach from the feeder. The current flow along the feeder is modeled as a linear function so that the load center point can be determined according to the feeder configuration and load capacity. Then the voltage drop is calculated after the load center point is obtained.

2. METHOD

2.1. Voltage Drop Calculation

Generally, the reactive power flow in the line is due to the reactive power requirement at the load. Compensation must be placed on the load side to reduce the voltage drop in the segment line (line) so that the supply side no longer sends reactive power. This compensator will reduce the amount of current sent from the supply side. The reduction in voltage drop by this compensation is modeled in Fig. 1. In medium voltage networks, the effect of ground capacitance is very small and can be neglected. The Fig. 1 is an equivalent circuit of the line loaded with an amount of reactive power. The current flow to the circuit is i_s, the current flow to the load is i_b, and the current produced by compensation is i_C. The impedance of the line causes a voltage drop, so that has occurred voltage difference between V_1 and V_2.

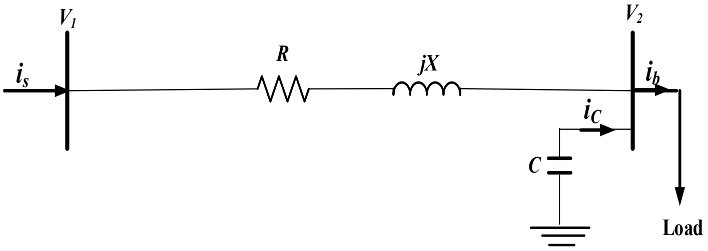

Fig. 1. Equivalent circuit of segment line with compensation

If the condition is uncompensated, then,

$$i'_s = i_b \tag{1}$$

Where i'_s is the current on the sending side, i_b is the current on the receiving side (load). Suppose the load current is,

$$i_b = i_a + ji_r \tag{2}$$

Where i_a is the active load current, i_r is the reactive load current. Then the magnitude of the sending current is,

$$I'_s = I_b = \sqrt{i_a^2 + i_r^2} \tag{3}$$

So, the voltage drop is,

$$\Delta V = I'_s Z \tag{4}$$

Where ΔV is the voltage drop, I_s is the current on the sending side and Z is the line-impedance. If there is compensation of I_C, then the sending current to be,

$$i_s = i'_s - i_c = i_a + j(i_r - i_c) \tag{5}$$

Or,

$$I_s = \sqrt{i_a^2 + (i_r - i_c)^2} \tag{6}$$

Now suppose the current passing through the line is,

$$i = I(\mathrm{Cos}\varphi + \mathrm{jSin}\varphi) \tag{7}$$

And voltage drop based on [6] is,

$$\Delta \mathrm{V} = \mathrm{Iz}\sqrt{1 + f_z^2} \tag{8}$$

Where I is the current and,

$$f_z = \frac{b}{a} \tag{9}$$

$$z = a{=}a_1 + a_2 = R\ \mathrm{Cos}\ \varphi + X\ \mathrm{Sin}\ \varphi \tag{10}$$

$$b{=}b_1 - b_2 = X\ \mathrm{Cos}\ \varphi - R\ \mathrm{Sin}\ \varphi \tag{11}$$

Furthermore, the calculation of the voltage drop represented by (8) can be shown through the phasor diagram in Fig. 2. The dotted line represents the phasor diagram before compensation, and the solid line represents the phasor diagram after compensation. In this Fig. 2, it can be seen that the voltage drop is due to the compensation current I_c. After compensation, the voltage drop decrease from $\Delta V'$ to ΔV. It is caused by the voltage phasor angle that reduces from δ' toi δ so that the voltage magnitude of V_1 becomes smaller.

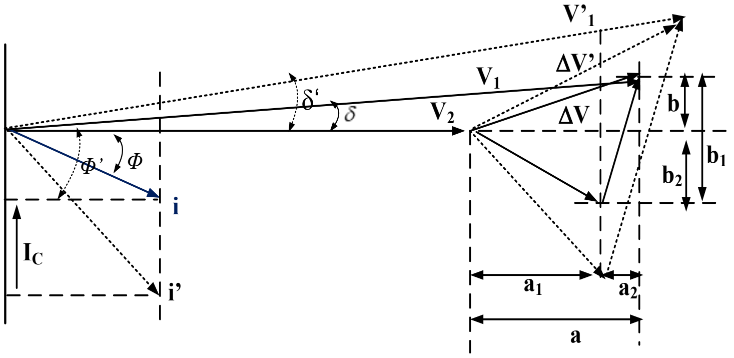

Fig. 2. Phasor diagram before and after the compensation

From Fig. 2, the voltage drop is obtained after compensation,

$$\Delta V = |V_1 - V_2| \tag{12}$$

If the factor $f_z = 0$, then $b = 0$ or the voltage V_1 and V_2 are one phase ($\delta = 0$) and fulfill the following equation 13.

$$\frac{R}{X} = \frac{f_d}{\sqrt{1 - f_d^2}} \tag{13}$$

For the value $\delta \leq 4^o$, the phase angle difference can be neglected, so the value of $f_z \approx 0$ and the value of the voltage drop in (8) becomes simpler, namely:

$$\Delta V = Iz \tag{14}$$

2.2. Compensation on Medium Voltage Feeder

Consider a medium voltage feeder in Fig. 3, where Lm is the span length for the Main Feeder and L_c is the span length for the Lateral Feeder. While n is the number of nodes in the main feeder, GI is the Bulk Substation and GD is the Distribution Substation.

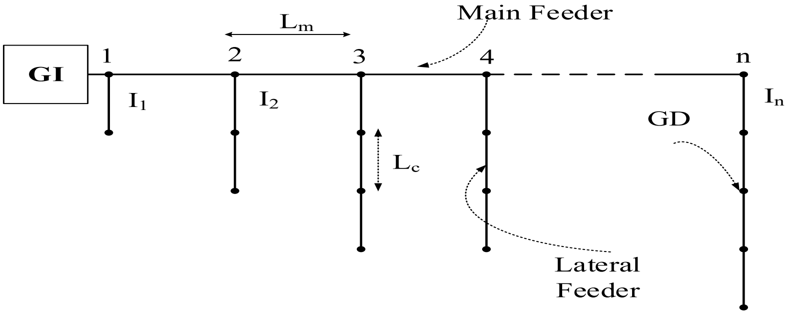

Fig. 3. Medium voltage feeder

From Fig. 3, the lengths of the main and lateral feeders respectively are,

$$TL_M = (n-1)L_m \tag{15}$$

$$TL_C = \sum_{i=1}^{n} m_i L_c \tag{16}$$

Where m_i is the number of GD in the $i-th$ lateral.

2.3. Voltage Drop in Medium Feeder

Suppose in Fig. 3, the impedance of each gate length is Zm and the current flowing at node-i is Ii, then the voltage drop across node-i is,

$$\Delta V_k = \sum_{j=1}^{k-1} Z_m \sum_{i=j+1}^{n} I_i \tag{17}$$

While the current at node-I is,

$$I_i = I(1 + c(i - 1)) \tag{18}$$

Where c is the current density, $c = 0$ is the average feeder loading, $c > 0$ is the higher current density to the end of the feeder and $c < 0$ is the higher current density to the feeder base. c based on [6] is,

$$c = \frac{\sum_{i=1}^{n-1}\left(\frac{I_{i+1}}{I_i} - 1\right)}{\sum_{i=1}^{n-1} i} = \frac{\sum_{i=1}^{n-1}(A_{i+1} - 1)}{\sum_{i=1}^{n-1} i} \tag{19}$$

Where A_{i+1} is the ratio of I_{i+1} to I_1. To determine the voltage-drop at the end of the feeder from Fig. 3, it can be modeled as a feeder with a concentrated load at a distance s and the voltage drop is,

$$\Delta V_n = sZ_{Tm}I_T \tag{20}$$

Where ZTm is the total impedance of the feeder, I_T is the source current and s are,

$$s = \frac{1}{n-1} \frac{\sum_{j=1}^{n-1}\sum_{i=j+1}^{n}\{1 + c(i-1)\}}{\sum_{i=1}^{n}\{1 + c(i-1)\}} \tag{21}$$

The value $s = 1/2$ for $c = 0$ and $s = 2/3$ for $c = 1$.

3. ALGORITHM

The step-by-step calculation of the voltage drop from the proposed method will follow the procedures in Fig. 4. After all feeder data is entered, the voltage drop is calculated for each feeder at the selected nodes. Read the current source data and calculate voltage drop each selected node, both with and without compensator. The calculation is repeated for other source current values. After calculating the voltage drop for this feeder, then a calculation is repeated for the other feeders until all feeders have been calculated its voltage drop. Write all calculation results and finish.

4. SIMULATION

4.1. First Simulation

For validating the proposed method, it is tested through comparison with other methods. Test data is from [9] for Network N1. Table 1 is the comparison results of the voltage drop for three load variations, $\boldsymbol{L_1}$, $\boldsymbol{L_2}$ and $\boldsymbol{L_3}$. The two methods (Monte Carlo Simulation and Loss of diversity - cascaded sections) give not significantly different results.

Table 1. Results for Network N1: Voltage drop comparation

Method	Load	Volt Drop to End of Feeder [%]
Monte Carlo Simulation (base case)	L_1	4.30
	L_2	3.72
	L_3	3.18
Loss of diversity - cascaded sections	L_1	4.16
	L_2	3.79
	L_3	3.17
Proposed Method	L_1	4.26
	L_2	3.74
	L_3	3.19

The Tabel 1 shows the comperation among three methods with the similar results. Compared to the proposed method, it also provides results close to the Monte Carlo Simulation.

4.2. Second Simulation

The method has been applied to the large medium feeder. The simulation was undertaken on the case of the 21 nodes feeder in [10], which is the feeder in Fig. 4. There are three types of loads, namely:

a) Dot capacity : 240 kVA
b) Cross capacity :180 kVA
c) Vie capacity : 160 kVA

This Fig. 5 consists of the main feeder with five nodes and eight lateral feeders that are connected to nodes 1,2,3, and 4. The system of the feeder is a radial system that is supplied by a current of I_T. The amount of I_T can be determined by measurement from the Ampermeter A.

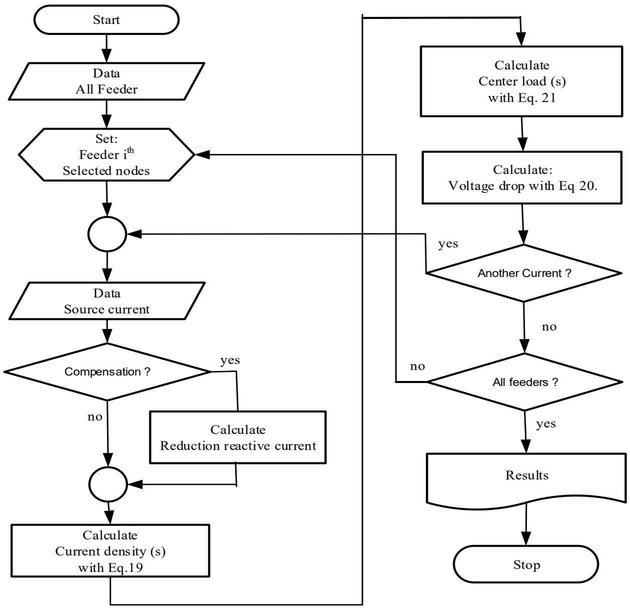

Fig. 4. Voltage drop calculation

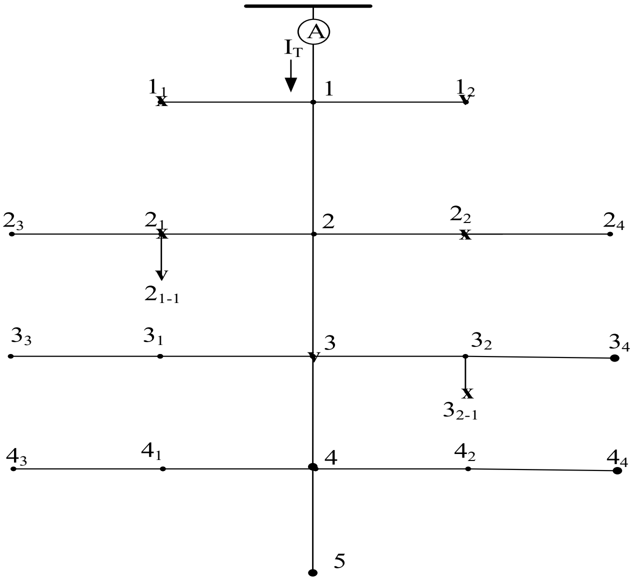

Fig. 5. The 21-node feeder

The results of calculating the voltage drop from the proposed method are shown in Fig. 6. The source current is 135 A with a power factor of 0.8 lagging. The result of the calculation of the voltage drop without compensation is that the three largest voltage drops fall on Node 43 (4.00%), Node 44 (3.80%), and Node 5 (3.80%), respectively. For a source current more than 135 A, the voltage drop at Node 43 is more than 4.00%. To maintain a voltage drop of 4.00% on Node 43, compensation needs to be done.

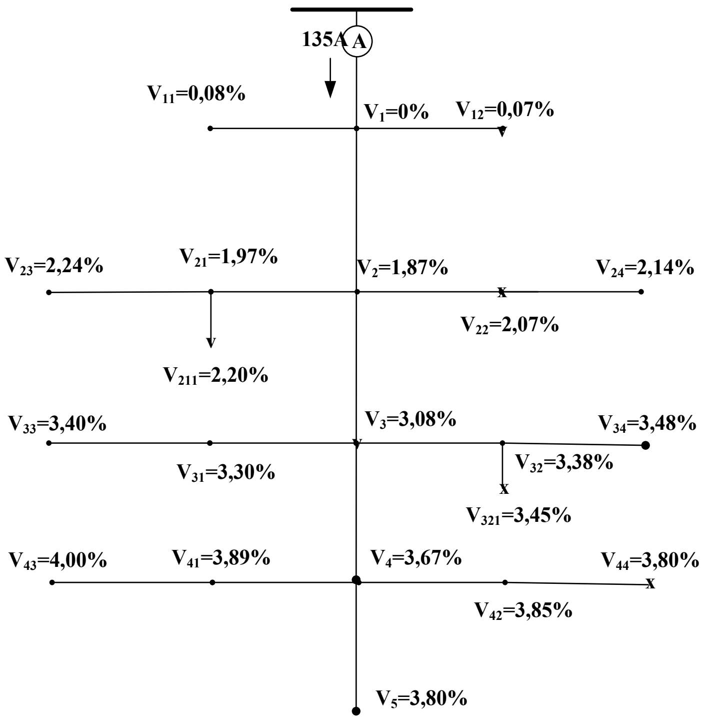

Fig. 6. The voltage-drop for each node for a source current of 135 A

Complete results for maintaining a voltage drop of 4.00% at Node 43 are presented in Table 2. Compensation is required when the source current is greater than 135 A. For example, when a source current of the feeder achieves 140 A. The compensation current of 10 A is required to reduce the voltage from 4.15% (before compensation) to 3.98%. However, compensation is limited to a source current of 165 A with a compensation current of 80 A. For source currents more significant than 165 A, the voltage at Node 43 will be greater than 4.00 % even though it has been compensated optimally.

Table 2. Voltage drop of the three nodes vs input current

No	**Source Current (A)**	**Voltage Drop Before Compensation**			**Compensation Current (A)**	**Voltage Drop After Compensation**		
		N5 (%)	**N43 (%)**	**N44 (%)**		**N5 (%)**	**N43 (%)**	**N44 (%)**
1	120	3.37	3.56	3.51	0	3.37	3.56	3.51
2	125	3.51	3.71	3.66	0	3.51	3.71	3.66
3	130	3.66	3.85	3.80	0	3.66	3.85	3.80
4	**135**	**3.80**	**4.00**	**3.80**	**0**	**3.80**	**4.00**	**3.95**
5	140	3.94	4.15	3.77	10	3.77	3.98	3.92
6	145	4.08	4.30	3.77	20	3.77	3.97	3.92
7	150	4.22	4.45	3.77	30	3.77	3.98	3.92
8	155	4.36	4.59	3.79	40	3.79	4.00	3.94
9	160	4.50	4.74	3.74	60	3.74	3.94	3.89
10	165	4.64	4.89	3.75	80	3.75	3.95	3.90
11	**170**	**4.78**	**5.04**	**3.83**	**90**	**3.840**	**4.045**	**3.991**
12	175	4.92	5.19	3.91	100	3.83	4.03	3.98
13	180	4.92	5.34	3.97	110	3.832	4.037	3.982

5. DISCUSSION

The problem of voltage drop in the feeder is a matter that obtains serious attention. It is because it is very closely related to line losses. The smaller the voltage drop, the smaller the losses will be. Reducing the voltage drop can be done by compensating for the reactive current flowing in the network. The compensation capacity does not surpass the maximum compensation. It is because when over-compensation requires a large capacitor, the voltage drop is the same as compensation which requires a smaller capacitor. The voltage drop decreases to optimal compensation when under compensation. Meanwhile, in overcompensation, the voltage drops when the compensation is larger.

The proposed method has been able to calculate the compensation required to maintain the voltage drop to meet the security standards. The simulation results on the feeder in Fig. 5 show that the voltage drop will be higher as the source current increases. The simulation compares the calculation results between before and after compensations for the current I_T variations shown in Table 1. Voltage drops are calculated for nodes with the large voltage drop, namely nodes N_5, N_{43} and N_{44}.

The calculation results for the source current of 135 A are shown in Fig. 6, where the largest voltage drop decreases on node 43 by 4.00%. Source current up to 135 A is not compensated because the voltage drop at Node 43 is less than 4.00 %. If the voltage drop security limit is maintained at 4.00%, compensation is needed for a source current greater than 135 A. The calculation results show that the voltage control through compensation is only limited to a source current of 165 A. For example, when a source current of 150 A. The compensation current of 30 A is required to reduce the voltage drop from 4.45% (before compensation) to 3.98% (after compensation). In this control, the compensation current is assumed to increase with each step of 10 A. For source currents greater than 165 A, the voltage drop is always greater than 4.00%, even though it has been optimally compensated. Table 1 shows the source current of 170 A before compensating for the voltage drop at Node 43 is 5.04%, and after being compensated for 100 A, the voltage drop is still greater than 4.00%, which is 4.03%. As for the compensation current of 90 A and 110 A, the voltage drop at Node 43 will be even bigger.

6. CONCLUSION

A method for controlling the voltage drop across a medium-voltage feeder has been discussed in this paper. The methodology is based on the source current entering the feeder, so the calculations are effective and easy to implement. Compensation distributed to the loads will reduce the reactive current in each lateral feeder and the current entering the feeder (source current). This compensation will improve the voltage drop at each node in the feeder. So, through this method, only the source current data is needed after being compensated to determine the voltage drop.

The calculation results from the simulation show that the source current rises to 135 A; no compensation is needed because the highest voltage drop at Node 43 is still smaller than 4.00%. Compensation is only adequate until the source current is 165 A. The compensation is no longer effective for source currents greater than 165 A. This compensation can be seen for the source current of 170 A; the voltage drop is always greater than 4.00%, even though it is optimally compensated.

In this simulation, without compensation, the increase in load is limited to a source current of 135 A (if the maximum voltage drop security criterion is 4.00 %). Meanwhile, applying load compensation can increase again until the source current is 165 A with a compensation current of 80 A. This method is a compensation advantage. In addition to controlling the voltage drop, it can also increase the load. The increase in load in this simulation is from 135 A (before compensation) to 165 A (after compensation). In this case, the increase in source current is quite significant, namely 30 A.

For further study, the developed method can be extended to optimize the compensation for the feeders of low-voltage distribution. Furthermore, the formulation of the proposed method can be further developed to calculate the compensation for electric power systems in general. However, the application of the proposed method to high-voltage power systems will be limited by the availability of capacitors.

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