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A Fast Rule For Improving Three-phase Voltage Imbalance in Distribution Feeders

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***Abstract*—This paper proposes a fast rule to improve three-phase voltage imbalance in distribution feeders. In practice, the three-phase voltage of distribution feeders is unbalanced for a long time. Unbalanced three-phase voltage will affect the efficiency and safety of electrical equipment. The fast rule proposed in this paper can be used to improve the three-phase voltage imbalance on distribution feeders via the renewable energy generation systems connected to the distribution feeders. The fast rule is easy to use and can also increases the application benefits of renewable energy power generation systems.**

***Keywords*—**Fast rule, distribution feeder, voltage imbalance.

I. INTRODUCTION

Distribution systems are downstream of the entire power system. They supply electricity to a wide range of medium-voltage and low-voltage customers. A distribution system is composed of transformers, distribution feeders, switches and protection equipment. The transformers are used to convert high voltage on the primary side to low voltage on the secondary side, and the distribution feeders are used to supply electric power to their loads. Distribution feeders have a three-phase structure and supply three-phase electric power to three-phase loads. Unfortunately, single-phase loads also exist in distribution systems. Since distribution feeders supply power to single-phase and three-phase loads simultaneously, the three-phase currents are inconsistent, resulting in unbalanced three-phase voltages.

Literature [1-3] has shown that three-phase unbalanced voltage will reduce the torque of motors, increase the power loss of feeders, and interfere with the function of protection equipment. Therefore, the three-phase voltage imbalance problem of distribution feeders must be improved, otherwise the economic losses will be huge.

At present, distribution system operators generally use reactive power compensation equipment or on-load tap-changers to improve the three-phase voltage imbalance problem of distribution feeders [4-6]. Although these devices can effectively reduce the three-phase voltage imbalance of distribution feeders, they are expensive and have short service life, resulting in high operating costs of the distribution system.

In the past 20 years, governments around the world have actively promoted renewable energy power generation policies and encouraged small wind power generation systems, solar power generation systems, hydroelectric power generation systems and biomass power generation systems to be connected to the distribution systems [7,8]. Some small renewable energy power generation systems (REPGSs) are single-phase power generation equipment. If they can be properly arranged and connected to each phase of the distribution feeders, the three-phase voltage imbalance of the distribution systems can be improved.

This paper proposes a quick rule for reducing three-phase voltage imbalance in distribution feeders. This quick rule can help distribution system operators properly arrange the connecting phases of small REPGS to reduce the degree of three-phase voltage imbalance on distribution feeders. There is no need to use reactive power compensation equipment or on-load voltage regulation, which can reduce the operating cost of the power distribution system.

II. DESCRIPTION OF SYSTEM STRUCTURE

Fig. 1 shows the simplified structure of a distribution system, which is used as an example system in this paper. The example system includes a three-phase transformer, a circuit breaker, a distribution feeder, 6 buses, 6 loads and a REPGS. The component parameters of the example system are shown in Table I, and the load parameters are shown in Table II.

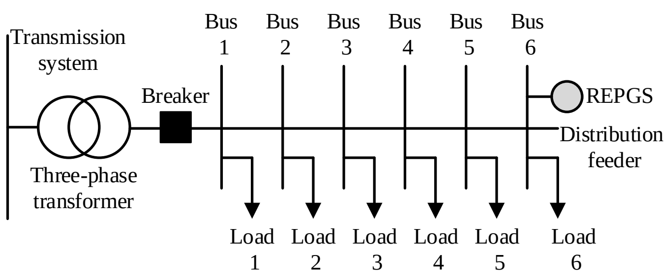

Fig. 1. The structure of the sample system employed in this paper.

The length of the distribution feeder is 1000 m, and the power supply structure is a three-phase three-wire scheme, so there are three phases A, B, and C. There are 6 buses on the distribution feeder, which are spaced 200 m apart from each other. The load of each bus is 150k W. The load of phase A is 40k W, the load of phase B is 50k W, and the load of phase C is 60k W.

The maximum power generation capacity of the REPGS is 100k W. Assuming that the connection position is at bus 6. The connected phase of the REPGS depend on the research scenarios.

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TABLE I. The Parameters of Each Component in the Example System

Component Name	Parameters
Three-phase transformer	Rating capacity : 25M VA Winding connection : Delta – Grounded wye Rating voltage : 69k/11.4k V Winding impedance : 0.0196+j0.028 pu
Distribution feeder	Length : 1000 m Cross-sectional area : 477 MCM Impedance : 0.131+j0.405 Ω
Bus	Three-phase structure (phase A, B, C)
REPGS	Power generation capacity: 100k W Output voltage: 11.4k V

TABLE II. The Load Parameters of Each Bus in the Example System

Bus No.	Load		
	Phase A (kW)	Phase B (kW)	Phase C (kW)
1	40	50	60
	0	0	0
2	40	50	60
	0	0	0
3	40	50	60
	0	0	0
4	40	50	60
	0	0	0
5	40	50	60
	0	0	0
6	40	50	60
	0	0	0

III. THE FAST RULE

In this research, it is assumed that the connecting bus of this REPGS cannot be changed, but the connecting phase can be changed.

In order to make the three-phase voltage of a distribution feeder as balanced as possible, the load distribution of the three phases of the distribution feeder should be as equal as possible to each other, that is, the difference between each other should be as close to zero as possible.

To achieve the above goal, this paper develops a fast rule and the algorithm is as shown in (1) to (7). The (1) to (3) are used to calculate the total load of each phase of a distribution feeder, the (4) to (6) are used to calculate the total power generation of REPGSs connected to each phase of the distribution feeder, the (7) is used to calculate the load difference of the three phases of the distribution feeder, where n is the number of buses on the distribution feeder, m is the number of each bus, S_{TL} is the total load, and S_{TG} is the total power generation of REPGSs, S_L is the load of each bus, and S_G is the power generation of REPGS of each bus, ΔS is the difference between the total load of the distribution feeder and the total power generation of REPGSs connected to the distribution feeder, and Max. and Min. represent obtaining the maximum and minimum values, respectively. When ΔS is zero, it means that the load distribution of the three phases of the distribution feeder is completely equal, so its three-phase voltage is also completely balanced.

$$S_{TL,A}=\sum_{m=1}^{n}\left|S_{Lm,A}\right|=\sum_{m=1}^{n}\sqrt{P_{Lm,A}^2+Q_{Lm,A}^2} \quad (1)$$

$$S_{TL,B}=\sum_{m=1}^{n}\left|S_{Lm,B}\right|=\sum_{m=1}^{n}\sqrt{P_{Lm,B}^2+Q_{Lm,B}^2} \quad (2)$$

$$S_{TL,C}=\sum_{m=1}^{n}\left|S_{Lm,C}\right|=\sum_{m=1}^{n}\sqrt{P_{Lm,C}^2+Q_{Lm,C}^2} \quad (3)$$

$$S_{TG,A}=\sum_{m=1}^{n}\left|S_{Gm,A}\right|=\sum_{m=1}^{n}\sqrt{P_{Gm,A}^2+Q_{Gm,A}^2} \quad (4)$$

$$S_{TG,B}=\sum_{m=1}^{n}\left|S_{Gm,B}\right|=\sum_{m=1}^{n}\sqrt{P_{Gm,B}^2+Q_{Gm,B}^2} \quad (5)$$

$$S_{TG,C}=\sum_{m=1}^{n}\left|S_{Gm,C}\right|=\sum_{m=1}^{n}\sqrt{P_{Gm,C}^2+Q_{Gm,C}^2} \quad (6)$$

$$\begin{aligned}\Delta S=&\text{Max.}(\left|S_{TL,A}\right|-\left|S_{Gm,A}\right|,\left|S_{TL,B}\right|-\left|S_{Gm,B}\right|,\left|S_{TL,C}\right|-\left|S_{Gm,C}\right|)\\&-\text{Min.}(\left|S_{TL,A}\right|-\left|S_{Gm,A}\right|,\left|S_{TL,B}\right|-\left|S_{Gm,B}\right|,\left|S_{TL,C}\right|-\left|S_{Gm,C}\right|)\end{aligned} \quad (7)$$

IV. RESULTS

In order to verify the validity of the fast rule, 4 simulation scenarios have been carried out by the research. The definitions of the 4 simulation scenarios are described as follows.

Scenario_0: No REPGS connected with the distribution feeder of the example system.

Scenario_A: A REPGS connected with the phase A of the bus 6 of the distribution feeder of the example system and output 100k W of active power.

Scenario_B: A REPGS connected with the phase B of the bus 6 of the distribution feeder of the example system and output 100k W of active power.

Scenario_C: A REPGS connected with the phase C of the bus 6 of the distribution feeder of the example system and output 100k W of active power.

Scenario_0 was used to demonstrate the original unbalanced situation of the three-phase voltage of the distribution feeder of the example system. Scenario_A, Scenario_B and Scenario_C were used to demonstrate the impact on the three-phase voltage imbalance of the distribution feeder when a REPGS outputs electric power to the phase A, B and C of the distribution feeder of the example system, respectively.

Simulation results include the voltage profiles and voltage unbalanced ratios (VURs) of the four scenarios have been

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obtained by the research. The definition of the VUR is shown in (8). The simulation results are described in detail as follows

$$VUR=\frac{\left(Max.\left(|V_A|,|V_B|,|V_C|\right)-Min.\left(|V_A|,|V_B|,|V_C|\right)\right)}{\frac{\left(|V_A|+|V_B|+|V_C|\right)}{3}} \quad (8)$$

Where the V_A, V_B and V_C are the phase voltages of a bus on the distribution feeder of the example system.

A. Scenario_0

The voltage profiles of the distribution feeder of the example system in scenario_0 are shown in Fig. 2.

The distribution feeder of the example system has three feeders, namely phase A, B and C. The loads on the three feeders are not equal to each other, causing the example system to operate in an unbalanced state because the load of feeder A is the lightest, only 240k W, and the load of feeder C is the heaviest, reaching 360k W. Fig. 2 shows that the voltage profile of feeder A is the highest, feeder B is the second, and feeder C is the lowest.

The VURs of the distribution feeder of the example system in scenario_0 are shown in Fig. 3. The simulation results show that the VUR of the feeder is larger toward the end, which means that as the length of the feeder increases, the imbalance will become more serious.

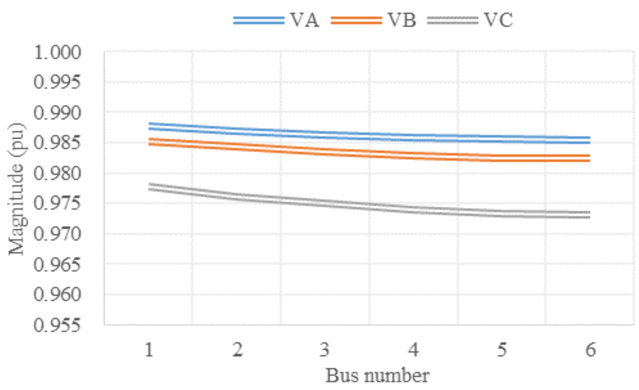

Fig. 2. The voltage profiles of the distribution feeder of the example system in scenario_0.

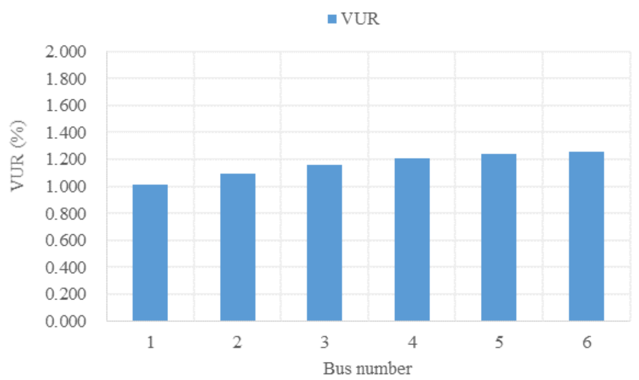

Fig. 3. The VURs of the distribution feeder of the example system in scenario_0.

B. Scenario_A

In this simulation scenario, a REPGS was connected to phase A of bus 6 of the distribution feeder and outputs 100k W of active power. At this time, the load of feeder A was only 140k W, which was less than the original 240k W, so the operation of the example system was inevitably become more unbalanced.

The simulation results of this scenario show that the voltage profile of feeder A becomes higher, and the difference with the voltage profile of feeders B and C becomes larger, as shown in Fig. 4. Because of this, the VURs of the distribution feeder become larger, as shown in Fig. 5.

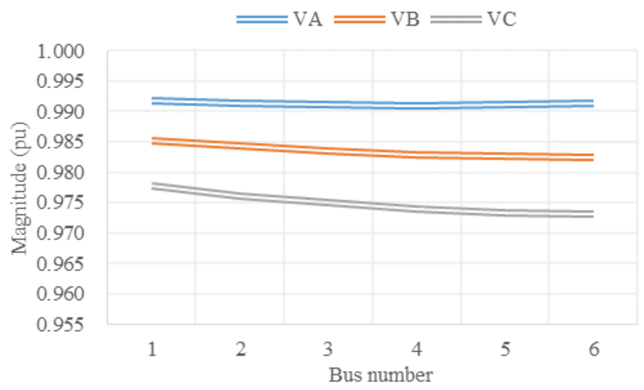

Fig. 4. The voltage profiles of the distribution feeder of the example system in Scenario_A.

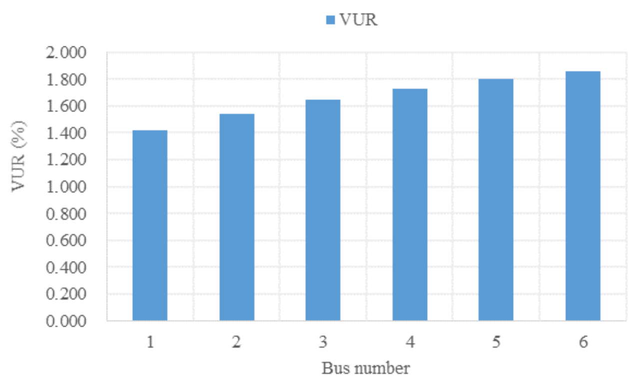

Fig. 5. The VURs of the distribution feeder of the example system in Scenario_A.

C. Scenario_B

In this simulation scenario, the REPGS's connection phase was changed from A to B, and it outputs 100k W of active power to the feeder B, so the load on the feeder B dropped from 300k W to 200k W. At this time, the load of feeder B was smaller than feeder A, so its voltage profile was higher than feeder A, as shown in Fig. 6. Even so, the example system was still operating in an unbalanced state, but the degree of imbalance was smaller than that of scenario_A, but larger than scenario_0, as shown in Fig. 7. In addition, the simulation results show that different connection phase of a REPGS have different effect on the imbalance of a distribution system.

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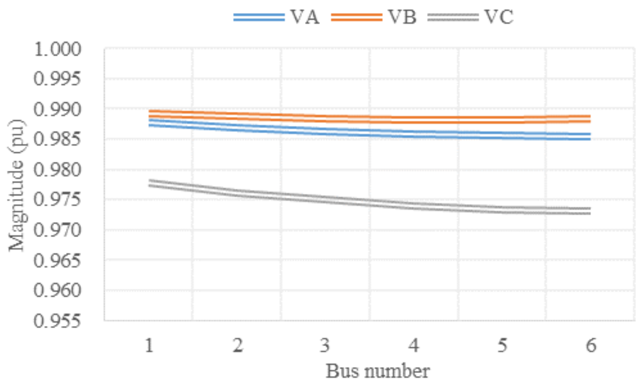

Fig. 6. The voltage profiles of the distribution feeder of the example system in Scenario_B.

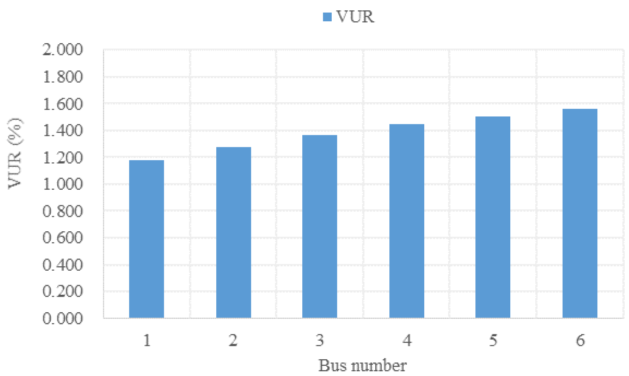

Fig. 7. The VURs of the distribution feeder of the example system in Scenario_B.

D. Scenario_C

In this simulation scenario, the REPGS's connection phase was changed from B to C, and it outputs 100k W of active power to the feeder B, so the load on the feeder C dropped from 360k W to 260k W. Although the load of feeder C was still greater than that of feeders A and B, the difference between them had become smaller, so the imbalance of the example system had also become lighter. Fig. 8 shows the voltage profiles of the distribution feeder of the example system, where the voltage profile of feeder C is clearly improved. Fig. 9 shows the VURs of the distribution feeders of the example system, which are significantly smaller than the VURs of the other three scenarios. The simulation results of the scenario_C show that if the connection phase of a REPGS can be appropriately selected, it will improve the imbalance of a distribution system. On the contrary, if the connection phase is inappropriately selected, it will aggravate the imbalance of a distribution system.

V. DISCUSSION

How to select the connection phases of REPGS is a challenge for distribution system operators. The fast rule proposed in Section II of this paper can assist distribution system operators. According to (1) to (3), the values of $S_{TL,A}$, $S_{TL,B}$ and $S_{TL,C}$ can be obtained as follows.

$$S_{TL,A} = 40+40+40+40+40+40 = 240k\ W$$

$$S_{TL,B} = 50+50+50+50+50+50 = 300k\ W$$

$$S_{TL,C} = 60+60+60+60+60+60 = 360k\ W$$

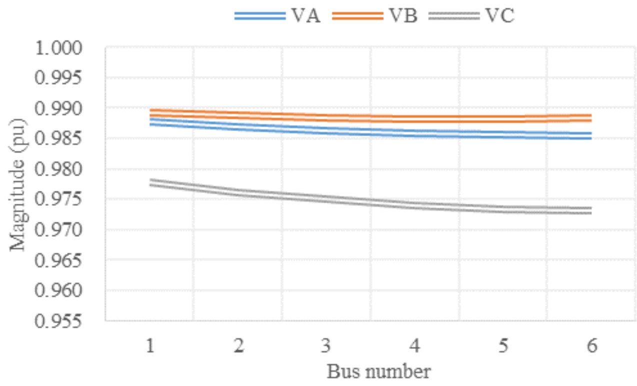

Fig. 8. The voltage profiles of the distribution feeder of the example system in Scenario_C.

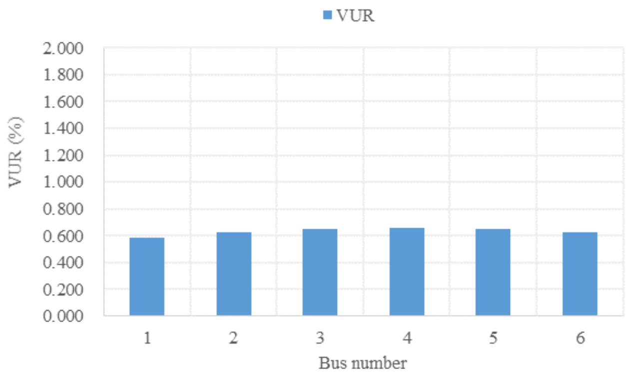

Fig. 9. The VURs of the distribution feeder of the example system in Scenario_C.

Assuming that the REPGS is connected to phase A of the bus 6 of the distribution feeder, according to (4) to (6), the values of $S_{TG,A}$, $S_{TG,B}$ and $S_{TG,C}$ can be obtained as follows.

$$S_{TG,A} = 0+0+0+0+0+100 = 100kW$$

$$S_{TG,B} = 0+0+0+0+0+0 = 0kW$$

$$S_{TG,C} = 0+0+0+0+0+0 = 0kW$$

At this time, the load difference value can be obtained according to (7) as follows.

$$\Delta S_A = \text{Max.}(240-100, 300-0, 360-0) - \text{Min.}(240-100, 300-0, 360-0)$$
$$= 360-140 = 220k\ W$$

Assuming that the REPGS is connected to phases B or C of the bus 6 of the distribution feeder, the load difference values can be obtained according to (7) as follows.

$$\Delta S_B = \text{Max.}(240-0, 300-100, 360-0) - \text{Min.}(240-0, 300-100, 360-0)$$
$$= 360-200 = 160k\ W$$

$$\Delta S_C = \text{Max.}(240-0, 300-0, 360-100) - \text{Min.}(240-0, 300-0, 360-100)$$
$$= 300-240 = 60k\ W$$

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Comparing ΔS_A, ΔS_B and ΔS_C, it can be found that ΔS_C has the smallest value, so this solution shows that connecting the REPGS to the phase C of bus 6 of the distribution feeder will be the most beneficial to the operation of the example system.

VI. CONCLUSIONS

In recent years, in order to protect the environment, governments around the world have actively encouraged people to install small REPGSs. These small REPGSs may be single-phase power generation systems. When they operate in parallel with distribution systems, they will have an impact on the three-phase unbalance problems of the distribution systems. Therefore, how to respond to this challenge has become an important issue. The fast rule proposed in this paper can allow distribution system operators to quickly find the optimal connection phases of REPGSs in a distribution system, so that the REPGSs can help reduce the three-phase unbalance situations of the distribution system. In this way, it not only helps to improve the safety of distribution system operation, but also increases the application benefits of REPGSs.

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