Analysis on the Influence of the Distributed Photovoltaic on the Line Loss of Distribution System

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Abstract. Based on the radiation single loop distribution network, a uniform distributed constant power load model is established. Based on the basic principle of loss, formula reasoning is carried out to calculate the influence of the location, penetration levels and power factor angle of photovoltaic on the line loss under different load distribution. Then, the line loss of a typical model of IEEE distribution network with distributed photovoltaic is simulated. Finally, the theoretical calculation of line loss of a typical line affected by photovoltaic mentioned in the background is carried out, confirming that the change of line loss rate of this line is caused by photovoltaic.

1. Introduction

Since 2005, the scale of the photovoltaic industry has been expanding rapidly. In the past two years, with new preferential government policy and the project of photovoltaic poverty alleviation, the distributed photovoltaic which mainly consists of commercial and industrial roof photovoltaic and household photovoltaic has risen rapidly.

For example, a 10kV line with a 4.5MW rooftop photovoltaic near the end, has been grid-connected since August, and photovoltaic power generation accounts for 40% of the line's total power supply. The line loss rate of the line in the three months from May to July is 8%. Since August, the load power consumption is at the peak period, and the total power supply of the line has increased, but the line loss rate has decreased significantly. Therefore, it is necessary to make further analysis on whether the line loss rate will definitely be declined with distributed photovoltaic, as well as its impact mode and effect.

2. Circuit modelling with distributed photovoltaic

The connection mode of distribution system is mostly radial chain connection. The loss power $P_{LS}$ is calculated as:

$$P_{LS} = 3 \int_0^1 (I_1 - (I_1 - I_2)x)^2 R \, dx = (I_1^2 + I_1I_2 + I_2^2) R$$  \hspace{1cm} (1)

Where $I_1$ is current of the head of line, $I_2$ is current of the end of line, and $R$ is the resistance per unit length.

A distributed photovoltaic is supposed to be connected in $x_1$ with input current $I_{PV}$, as shown in figure 4. Therefore, the current flowing through the circuit should be subtracted from the original input current, that is, from 0 to $x_1$ the current will be reduced. The loss power $P'_{LS}$ is calculated as:

$$P'_{LS} = (I_1^2 + I_1I_2 + I_2^2) + 3x_1\{(x_1 - 2)l_2I_{PV} - x_1I_2I_{PV}\} \cos(\varphi_{PV} - \varphi_{id}) + I_{PV}^2 R$$  \hspace{1cm} (2)
Where \( \varphi_{py} \) is the power factor angle of is distributed photovoltaic, and \( \varphi_{id} \) is the power factor angle of line load.

To discuss the effect of the above variables on line loss better, the following definition is made:

\[
\Delta \varphi = \varphi_{PHOTOVOLTAIC} - \varphi_{id}; \quad d = \frac{I_{PHOTOVOLTAIC}}{I_1}; \quad \lambda = \frac{I_2}{I_1}.
\]

The relative reduction of line loss with distributed photovoltaic is obtained as:

\[
\Delta P_{LS} = \frac{(P_{LS}-P_{LS}^0)}{P_{LS}} = \frac{3dx_1}{1+\lambda+\lambda^2} \left\{ \left[ (2-x_1) + \lambda x_1 \right] \cos \Delta \varphi - d \right\} (3)
\]

In Multiple schemes of loading distributing \( \lambda = 0, 1/2 \), power factor angle difference \( \Delta \varphi = 0, \pi/6, \pi/2 \), and penetration levels scaling from 10% to 100%, the reduction of line loss of the distribution system are calculated with the change of photovoltaic location (x space \((0, 1))

![Figure 1. Reduction of line loss when \( \lambda = 0, \Delta \varphi = 0 \) and \( \lambda = 0, \Delta \varphi = \pi/6 \)]

It can be seen from the curves of Fig.1 that the reduction of line loss of distribution system presents a quadratic function relation with photovoltaic location. When the photovoltaic capacity is small (e.g., the proportion of access is between 10% and 40%), the closer the photovoltaic is to the load end, the greater the line loss reduction. When the photovoltaic capacity is large (e.g. the proportion of access is more than 60%), the optimal access position of photovoltaic is usually in the middle or end of the line, and the specific location is closely related to capacity and power factor.

When the proportion of photovoltaic capacity increases from 10% to 50%, the loss reduction gradually increases, while after exceeding 60%, the loss reduction gradually decreases as the location is nearer to the end of line. Especially when the proportion of photovoltaic capacity is greater than 90%, the loss decreases to a negative value, that is to say, photovoltaic increases the loss of distribution network instead. Therefore, in a certain range, the larger the photovoltaic capacity is, the greater the reduction of the line loss of the distribution system will be. Optimal access capacity is closely related to location and power factor.

By comparing curves of Figure 1, it can be found that when the photovoltaic injection current is in the same phase with the load current, the loss decreases more significantly, and the maximum reduction can reach 80%. However, the larger the phase Angle difference between photovoltaic and load is, the smaller the loss is, and even the line loss will increase.

Under the above conditions, the load distribution is changed to \( \lambda = 1/2 \), that is, half the load of the whole line concentrate on the end. The simulation results are shown in Fig.2.
The line loss reduction of distribution system is still in a quadratic function relation with the photovoltaic location, and it is basically in an increasing region. In other words, the farther the location is, the closer it is to the load center, the greater the line loss reduction.

There is also a certain optimal capacity of photovoltaic. Under this, the larger the capacity, the larger the line loss reduction, and the smaller the amount if it exceeds the optimal capacity. Compared with the previous situation, the optimal capacity of photovoltaic has been improved. For example, when \( d > 90\% \), the loss of distribution network still decreases significantly.

By comparing curves of Fig. 2, it can be seen that when there is a phase angle difference between photovoltaic and load, the line loss decreases less.

The extreme case of \( \Delta \phi = \pi/2 \) is calculated and the results are shown in Fig. 3. At this point, the line loss reduction of distribution system is negatively linear with the photovoltaic location. The line loss reduction is negative for any load distribution, different photovoltaic capacity and location. That is to say, the photovoltaic will lead to an increase in the line loss of distribution network, which should be avoided in the actual situation.

3. Example simulation analysis

The longest chain branch is selected from the IEEE 37 node model as the research object of the simulation scheme. The branch structure is shown in Fig. 4 and the load of each node is equal. That is to say \( \lambda = 0 \).
In Multiple schemes of power factor angle difference $\Delta \varphi = 0, \pi/2$, and penetration levels scaling from 10% to 100%, the reduction of line loss of the distribution system are calculated with the change of photovoltaic location ($x$ space $(0, 1)$).

![Figure 4. Reduction of line loss when $\lambda = 0$, $\Delta \varphi = 0$ and $\lambda = 0$, $\Delta \varphi = \pi/2$](image)

It can be seen from the curves of Fig.4 that the reduction of line loss of distribution system presents a quadratic function relation with photovoltaic location. When photovoltaic capacity is relatively small ($d=10\%, 40\%$), reduction of line loss is the largest with photovoltaic at the end node of 741. When photovoltaic capacity is relatively high ($d=80\%, 100\%$), the best location is at the node of 733. The diminution amount is negative under different access ratio, when the $\Delta \varphi = \pi/2$. In particular, when the photovoltaic capacity is 100%, the line loss increases by nearly 50% with photovoltaic at the node of 741.

The line loss is calculated for the 10kV line which is mentioned in the background under two schemes. The results are shown in Table 1.

| Photovoltaic power | Location | Electric energy production (million kWh) | Line loss (million kWh) | Theoretical line loss rate | Statistic line loss rate |
|--------------------|----------|----------------------------------------|-------------------------|---------------------------|-------------------------|
| Aug.               | Transformer exit | 1087515 | 632445 | 79978.14 | 4.65% | 5.32% |
| Sep.               | Photovoltaic | 1598818 | 899367 | 137899.8 | 5.52% | 6.27% |
| Oct.               | 982735 | 705865 | 73454.1 | 4.35% | 5% |
| equivalent generating | Aug. | 1719960 | 156819.9 | 9.12% |
| Sep.               | 2498185 | 275799.6 | 11.04% |
| Oct.               | 1688600 | 166941.1 | 9.89% |

According to the actual situation, the theoretical line loss rate from August to October is calculated as 4.65%, 5.52% and 4.35%, about 0.8 percentage points lower than the statistical line loss rate. This is mainly due to the management of line loss. In scheme 2, the generation capacity of photovoltaic is equivalent to that of public variable export, which means that all power supply of the line is assumed to come from the transformer station. The theoretical line loss rate from August to October is 9.12%, 11.04% and 9.89%. The results of the two schemes prove that the photovoltaic power from August caused the significant reduction of line loss.

4. Summary

Based on above analysis, the following conclusions can be drawn:

1. Distributed photovoltaic is bound to affect the power flow distribution system. The change depends on the load distribution characteristics, photovoltaic capacity, location and power factor. Thus, the photovoltaic access scheme and photovoltaic operation mode should be reasonably arranged;
Presently, the capacity of distributed photovoltaic is small, which can be connected to the distribution system to supply power nearby and reduce power transmission, thus reducing line loss. When the proportion of access capacity reaches more than 100%, the power flow will be reversed, which may lead to the increase of power grid line loss.

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