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VOLTAGE AND POWER LOSS CONTROL IN DISTRIBUTION SYSTEM USING UPFC

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Abstract: *A simplified loop distribution system is taken as the object and the main reasons leading to the power loss in the feeder are analysed in this paper. According to the natural power distribution theory of the loop systems, the minimum power distribution in the loop power system is deduced through the extremism method. Thinking about the power control function of the unified power flow controller, the control system for the series side of the unified power flow controller is designed based on the voltage control method. This control system insets a series voltage into the controller line and produces a power, which in the same direction with the power of the controlled line and equals to the loop power of the loop system in quantity, and the power loss is decreased by eliminating the loop power in the distribution system. Digital simulations in the loop distribution systems configured by two feeders with different resistance and reactance proportion are made and the results verified the function of UPFC designed in this paper for reducing the power loss of the distribution system.*

Keywords: *Loop distribution system, Power loss, Unified power flow controller, Power distribution, Simulation***.**

1. Introduction

With the increasing demand for electricity, power loss is also growing if no technical measures are taken to reduce the line loss rate. At present, there are two main ways to reduce the line loss in the distribution network at home and abroad: one is the transformation of grid structure itself, such as the transformation of network connection, improving the voltage level, shortening the length of distribution lines, increasing the wire cross section, reducing or replacing the distribution transformers that with high energy consumption, but these methods generally need vast initial investment and are difficult to implement [1]. The other is the use of appropriate control devices, such as the rational allocation of reactive power compensation device to reduce the reactive power flow in the distribution network, thereby reducing the line losses of distribution network and increasing the voltage level of distribution network [2][3].

With the development of various renewable energy sources in a distributed way to access the distribution network, there is an increasing demand for the flexible control of distribution networks, various flexible AC transmission technologies (FACTS, flexible AC transmission technology systems) have been gradually introduced into the flexible control of the distribution networks [4-7]. Unified Power Flow Controller (UPFC) is one of the most powerful devices among the FACTS family, it is famous for quickly, flexibly and independently changing the line impedance, transmission angle and other parameters of the power system to adjust the bus voltage, active and reactive power flow and system oscillation damping. But it has not been promoted the use within the transmission network because of its complex structure and high cost. In the distribution network, the voltage is low and the power is small so that UPFC can display a very good function [8][9]. In this paper, we make use of functions of UPFC on the system voltage and power flow control, with the voltage control method to inject a series voltage into the distribution system whose power direction is made the same as the controlled lines' and size is equal to the cycle power, thus reducing the line losses in the distribution network.

2. Simplified model of distribution network

Taking account of the long transmission lines and multi-load nodes, the distribution network is often designed as a loop in order to ensure the reliability of power supply

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but usually operated in the radiation way. For convenient illustration, a simplified distribution system model is adopted as an example in this paper [9], as showed in Figure 1.

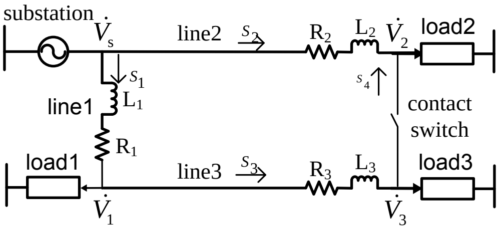


Figure 1. Simplified distribution system model

In Figure 1, two lines are led from substation. The first line supplies power to load 1 and load 3 by line 1 and line 3 respectively, and the second one line 2 supplies the load 2 directly. To ensure the reliability of power supply, a switch is set between the end of line 3 and line 2. Under normal circumstances, the switch is off. When it is on, the grid in Figure 1 forms a loop. Substation terminal bus voltage is $\dot{V}_S$. The node voltage of load 1 is $\dot{V}_1$, load 2 $\dot{V}_2$ and load 3 $\dot{V}_3$. The resistance and reactance of line 1, line 2 and line 3 are R_1, L_1, R_2, L_2, R_3, L_3 respectively and the power flow of which are S_1, S_2, S_3.

To facilitate the analysis, the load uses constant power model. The load 1 is expressed as S_{L1}, load 2 as load S_{L2}, load 3 as S_{L3} so that the Figure1 can be equivalent to Figure 2.

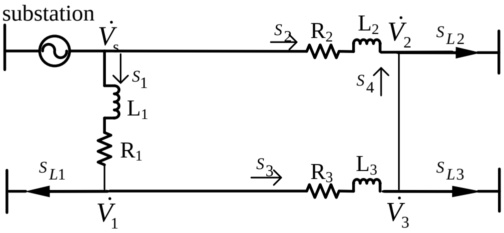


Figure 2. Equivalent model of distribution network

3. Line loss on the distribution network

According to the principle of natural power distribution that the power is inversely proportional to the impedance in the loop network, the power distribution of each paragraph in the grid of Figure 2 is shown as Eqn (1),

$$\begin{cases} S_1 = (\overset{*}{Z}_2 \dot{I}_{L2} + \overset{*}{Z}_2 \dot{I}_{L3} + (\overset{*}{Z}_2 + \overset{*}{Z}_3)\dot{I}_{L1}) / \overset{*}{Z}_\Sigma \\ S_2 = ((\overset{*}{Z}_1 + \overset{*}{Z}_3)\dot{I}_{L2} + (\overset{*}{Z}_1 + \overset{*}{Z}_3)\dot{I}_{L3} + \overset{*}{Z}_1 \dot{I}_{L1}) / \overset{*}{Z}_\Sigma \\ S_3 = (\overset{*}{Z}_2 \dot{I}_{L2} + \overset{*}{Z}_2 \dot{I}_{L3} - \overset{*}{Z}_1 \dot{I}_{L1}) / \overset{*}{Z}_\Sigma \\ S_4 = (\overset{*}{Z}_2 \dot{I}_{L2} - (\overset{*}{Z}_1 + \overset{*}{Z}_3)\dot{I}_{L3} - \overset{*}{Z}_1 \dot{I}_{L1}) / \overset{*}{Z}_\Sigma \end{cases} \tag{1}$$

where $\overset{*}{Z}_\Sigma = \overset{*}{Z}_1 + \overset{*}{Z}_2 + \overset{*}{Z}_3$ is the loop impedance in Figure 2.

For convenient analysis, we assume that the power flow in Figure 2 is counterclockwise. According to the Kirchhoff's current law, the relationship between power distribution and load power is shown by Eqn (2),

$$\begin{cases} S_3 = S_1 - S_{L1} \\ S_4 = S_3 - S_{L3} \\ S_2 = S_4 - S_{L2} \end{cases} \tag{2}$$

By Eqn (1) and (2), the total line loss of loop network shown in Figure 2 can be derived as

$$\begin{aligned} P_L &= \sum_{i=1}^{3} (P_i^2 + Q_i^2) R_i / V^2 \\ &= ((P_1^2 + Q_1^2)R_1 + (P_2^2 + Q_2^2)R_2 + (P_3^2 + Q_3^2)R_3) / V^2 \\ &= ((P_1^2 + Q_1^2)R_1 + ((P_1 - P_{L1} - P_{L2} - P_{L3})^2 \\ &\quad + (Q_1 - Q_{L1} - Q_{L2} - Q_{L3})^2)R_2) / V^2 \\ &\quad + ((P_1 - P_{L1})^2 + (Q_1 - Q_{L1})^2)R_3 / V^2 \end{aligned} \tag{3}$$

To minimize the system loss, the Eqn (3) are done the partial derivative for the active power and reactive power of each line, and make them be equal to zero, as shown in Eqn (4)

$$\begin{cases} \dfrac{\partial P_L}{\partial P_1} = \dfrac{2P_1}{V^2} R_1 + \dfrac{2(P_1 - P_{L1} - P_{L2} - P_{L3})}{V^2} R_2 \\ + \dfrac{2(P_1 - P_{L1})}{V^2} R_3 = 0 \\ \dfrac{\partial Q_L}{\partial Q_1} = \dfrac{2Q_1}{V^2} R_1 + \dfrac{2(Q_1 - Q_{L1} - Q_{L2} - Q_{L3})}{V^2} R_2 \\ + \dfrac{2(Q_1 - Q_{L1})}{V^2} R_3 = 0 \end{cases} \tag{4}$$

The solution of Eqn (4) is

$$\begin{cases} P_{1\min} = \dfrac{(P_{L1} + P_{L2} + P_{L3})R_2 + P_{L1}R_3}{R_1 + R_2 + R_3} \\ = \dfrac{(P_{L1} + P_{L2} + P_{L3})R_2 + P_{L1}R_3}{R_\Sigma} \\ Q_{1\min} = \dfrac{(Q_{L1} + Q_{L2} + Q_{L3})R_2 + Q_{L1}R_3}{R_1 + R_2 + R_3} \\ = \dfrac{(Q_{L1} + Q_{L2} + Q_{L3})R_2 + Q_{L1}R_3}{R_\Sigma} \end{cases} \tag{5}$$

where $R_\Sigma = R_1 + R_2 + R_3$.

Eqn (5) shows that when the power in the loop network is inversely proportional to the line resistance, the line loss in Figure 2 is minimum and the power distributed in the loop is the most economic. However, only when the ratio of resistance R and inductance L in each line meets equation that $R_1/L_1 = R_2/L_2 = R_3/L_3$, the natural power distributed in the loop network is equal to the economic power.

Normally, the distribution lines extend very long, even a feeder can be nearly 30km. The whole line is usually not constructed at one time, so the ratio of resistance R and inductance L of each line is not equal in each section. Therefore, the radial distribution network will have circulation power flow when operated in closed loop and the power flow is independent of the load. The larger the difference of the ratio of resistance R and inductance L on each line is, the greater the circulation power flow will be and this will result in greater power loss. If a voltage $\Delta\dot{E}$ injected into the line 1 produces the power S_{loop}, which has the same direction as S_1, and satisfy the following equation

$$S_1 + S_{loop} = S_{1\min} = P_{1\min} + jQ_{1\min} \qquad (6)$$

then the power distribution can meet the requirements of economy distribution and achieve the minimum power loss.

4. UPFC controller design

The UPFC is installed at the sender of the line 1, as shown in Figure 3. For convenient, we only use two loads here, but the conclusion is also suitable for the multi-loads cases.

The series side of UPFC injects a voltage $V_{se}\angle\theta_{se}$ into the system with the amplitude and phase both controllable. Its interaction with the current $\dot{I}_1$ of line1 produces S_{se}, which is also controllable both in magnitude and direction. From the Eqn (6) we can see that, to make the power loss in the loop network in Figure 3 minimum, S_{se} must satisfy the relationship in the Eqn (7)

$$S_{se} = S_{1\min} - S_1 = (P_{1\min} - P_1) + j(Q_{1\min} - Q_1) \qquad (7)$$

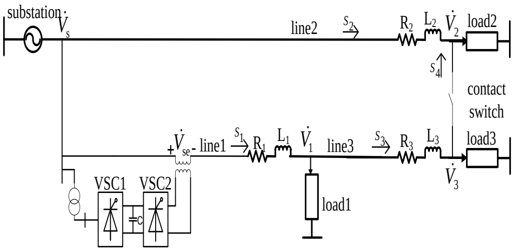


Figure 3. Block diagram of UPFC access to the distribution network

That is

$$\begin{cases} P_{se} = P_{1\min} - P_1 \\ Q_{se} = Q_{1\min} - Q_1 \end{cases} \qquad (8)$$

From $\overset{*}{S}_{se} = \dot{V}_{se}V_N / Z_\Sigma$, to make the line loss minimum, the injected voltage by the series side of UPFC should be

$$\begin{aligned} \dot{V}_{se} &= \overset{*}{S}_{se} Z_\Sigma / V_N \\ &= ((P_{se}R_\Sigma + Q_{se}X_\Sigma) + j(P_{se}X_\Sigma - Q_{se}R_\Sigma))/V_N \end{aligned} \qquad (9)$$

where $R_\Sigma = R_1 + R_2 + R_3$, $X_\Sigma = X_1 + X_2 + X_3$.

As in the distribution lines there is $R >> X$, the Eqn (9) can be approximately written as

$$\dot{V}_{se} = (P_{se}R_\Sigma - jQ_{se}R_\Sigma) / V_N \qquad (10)$$

From Eqn (10) we can see that the real part is only related to active power and the imaginary part is only related to reactive power, so Eqn (10) can be rewritten as

$$\begin{cases} \dot{V}_{sed} = P_{se}R_\Sigma / V_N \\ \dot{V}_{seq} = Q_{se}R_\Sigma / V_N \end{cases} \qquad (11)$$

Taking (8) into (10) will get

$$\begin{cases} \dot{V}_{sed} = (P_{1\min} - P_1)R_\Sigma / V_N \\ \dot{V}_{seq} = (Q_{1\min} - Q_1)R_\Sigma / V_N \end{cases} \qquad (12)$$

Taking (5) into (12), we can obtain the reference voltage injected into line 1 by the series side of UPFC. Thus the control system of UPFC will be got as shown in Figure 4,

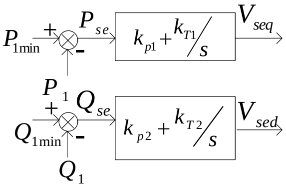


Figure 4. Block diagram of the series side of UPFC

According to the detected real-time power P_1 and Q_1 and the expected power $P_{1\min}$ and $Q_{1\min}$ of line 1 that can make the line loss minimum, the power reference P_{se} and Q_{se} injected into the system by the series side of UPFC will be obtained. From Eqn (11), the quadrate component of the injected voltage by the series side of UPFC, $\dot{V}_{sed}$, is proportional to the active power P_{se} and the direct component of the injected voltage is proportional to the reactive power, so the series side of UPFC can directly adopt the PI controller shown in Figure 4, where k_{p1}, k_{T1}, k_{p2}, k_{T2} are proportional integral control coefficients of active and reactive power respectively. Then obtained V_{sed} and V_{seq} are divided by the turns ratio of the series coupling transformer and then the results of which are taken as the voltage reference of the AC side of the converter VSC2 in the series side of UPFC, so that UPFC can control the line loss of loop network.

5. Simulations

The simulation model is shown in Figure 5, and the PSCAD/EMTDC is adopted. The substation supplies the power to load 1 and load 2 by line 1 and line 2 respectively. The ends of the two lines are connected to form the loop network by the switch. The power of substation is 15kVA, the power factor is 0.85, the bus voltage is 800V, the impedance of line 1 is $Z_1 = (20.7 + j1.06)\Omega$, the impedance of line 2 is $Z_2 = (16.7 + j1.62)\Omega$, load 1 is $Z_{L1} = (125 + j95)\Omega$ and load 2 is $Z_{L2} = (120 + j125)\Omega$. The designing capacity of UPFC is 15kVA, in which both of the series and parallel converter capacity is 7.5kVA. According to the system requirements, the total capacity of series and parallel converters have to be 15kVA and the compensation capacity is 50%, which is 7.5kVA. From the aspect of current switching device ratings and the coordination of voltage relationship between serial and parallel side, the voltage rating of DC capacitor is set as 400V. Considering a certain redundancy, the coupling transformer capacity of series and parallel side are both taken as 10kVA. The transformer on the parallel side adopts Y/Δ-11 connection and the turn ratio is 2.5:1, and the designed leakage reactance of phase A is 4mH, phase B

3.75mH and phase C 3.69mH. To meet the needs for different compensation capacity, the transformer of series side is designed as three voltage taps: when the voltage compensation accounts for 30% to 50% of the system voltage, the turns ratio is 10:8, when accounts for 15% to 30% of the system voltage, the turns ratio is 6:8, when 0% to 15%, the turns ratio is 3:8. If the capacity of compensation reaches the maximum, the leakage reactance of phase A is 0.98mH, phase B 0.95mH and phase C 0.98mH.

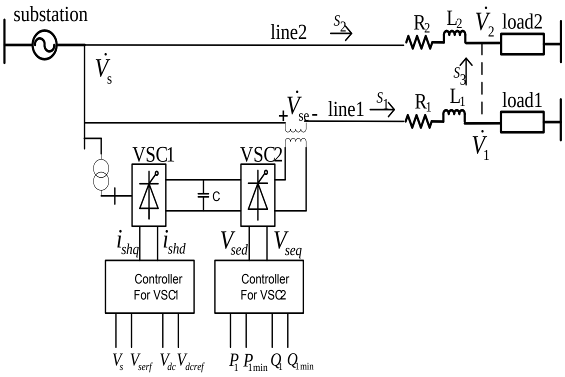


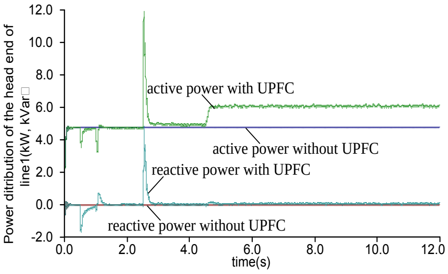
Figure 5. Diagram of simulation system

The PI controller is employed in the system bus V_s, and the parameters are [11]: $k_{p3}=0.89, k_{i3}=0.19$. The PI controller parameters of DC bus voltage V_{dc} of the parallel side are [11]:

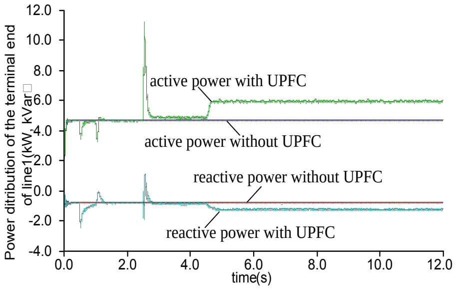
$k_{p4}=0.81, k_{i4}=0.011$. The PI controller parameters of active and reactive power of series side are: $k_{1p}=k_{2p}=0.004882$, $k_{1i}=k_{2i}=0.003556$.

As to the system shown in Figure 5, between 0s and 2.5s the system starts and gradually becomes stable. At 2.5s the parallel side controller based on power control is started up and at 4.5s the voltage-controlled series side controller is started up. The power distribution of the sending and the receiving end of each line are shown in Figure 6, in which, (a) is the power distribution curve of the sending of line 1, (b) is the power distribution curve of the receiving end of line 1, (c) is the power distribution curve of the sending end of line 2 and (d) is the power distribution curve of the receiving end of line 2.

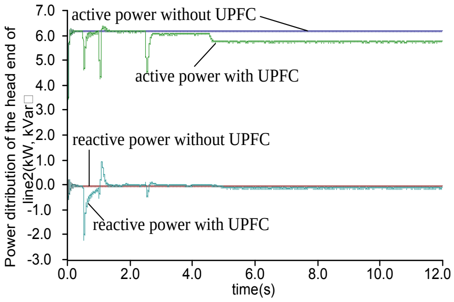
From Figure 6 we can see that because the inductance of the distribution line is relatively small, the reactive power loss caused by it is also small and UPFC almost has no effect on it. But UPFC has great impact on the active power distribution of the line. In the absence of UPFC, the total line loss caused by the loop network is 5.296kW, after the installation of UPFC the total loss is only 1.165kW.



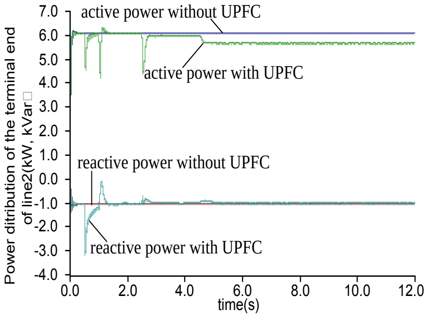
(a) The power distribution curve of the head end of line 1



(b) The power distribution curve of the terminal end of line 1



(c) The power distribution curve of the head end of line 2



(d) The power distribution curve of the terminal end of line 2

Figure 6. Simulation results

6. Conclusion

In this paper, according to the principle of natural power distribution that the power is inversely proportional to the impedance in the loop network, the power distributed in the loop power system which makes the line loss minimum is deduced. Making use of the power control function of the series side of UPFC, the series side controller based on voltage control is designed. The simulation results show that UPFC can reduce the line loss of the loop distribution network by nearly 80%. The load model used in this paper is only the static, there are more works should be made in the future, such as used for the dynamic load.

7. Acknowledgements

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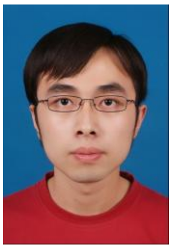

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