An Overall Economy Based Optimal Power Flow Control Method of Dual-source Distribution Network with Closed Loop Operation Using UPFC

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Abstract: *Supply reliability can be effectively improved by normally closed-loop operating of distribution network with dual sources, in which there might be large circling power flow. Unified Power Flow Controller (UPFC) has powerful capability to adjust the power flow, however, which would face the techno-economic bottleneck as applied in the distribution system. Based on constant current load model, the power flow distribution of normally closed-loop distribution network with dual sources was analyzed, and the relationship between the network loss, the voltage deviation of load nodes and the compensated voltage was deduced. Then, the optimal power flow control model was presented considering such economical factors as the network loss, the voltage deviation of load nodes and the cost of the apparatus used to produce the compensated voltage. In order to simplify the problem of multi-objective optimization into single-objective optimization model, the fuzzy membership functions and their weight coefficients of the network loss, the voltage deviation and the UPFC's cost were designed respectively, and the weights were determined according to their contribution in economy. The optimal control model was solved with the global optimal algorithm. The simulation results based on PSCAD prove that this method could ensure the overall economy of the system with balancing the power distribution, controlling the node voltage deviation and decreasing the active power loss of the network effectively.*

Key words**:** *Bidirectional power flow, Power distribution, Power system control, PSCAD*

I. Introduction

WITH the rapid development of social economy, improving supply reliability especially to avoid short interruption becomes more and more important[1,2]. And most of interruption comes from the fault occurring in the distribution network. On the other hand, the statistics show that the length of distribution line is about 60% of the whole power system, but the network loss is over 70% and half of loss comes from the medium and low voltage system[3]. Therefore, the technology of fault self-healing to improve the supply reliability and the optimal operation to improve the economy in distribution system has been the hot topic in the research world of smart grid.

The guideline of closed-loop designing and open-loop operating, has been generally followed in distribution network to limit the short current and simplify the protection and control measures. But the radial network can not solve the short interruption effectively, even with Auto Put-into Device, Auto Re-closing Device, Distribution Automation System, etc[1,4,5]. Normally closed- loop operation distribution system with single source has been adopted in some countries and regions with high supply reliability, in which the differential protection is set to cut fault rapidly [4-8]. This mode could avoid the interruption caused by fault in the feeder, but it is helpless to the bus bar or source fault. The normally closed-loop network with dual sources was presented with much higher supply reliability[5], but there might be so large circling power that the system could not keep stably operating. However, conventional power flow control measures, such as On-Load Tap Changer (OLTC) transformers and Phase-Shifting Transformers (PST), could not control the circling power of the loop network with a slow response[9-11].Recently, various types of FACTS (Flexible Alternative Current Transmission Systems) have be presented and used in power system, especially in transmission system [11-13].Among these, Unified Power Flow Controller(UPFC) has powerful capability to adjust power flow. Nevertheless, limited by economy, UPFC is less studied to apply in the distribution system[13-17]. But the cost of UPFC has been falling with the development of power semiconductor technology and modern control theory. And the adjusting capacity is much smaller than that used in the transmission system. More importantly, a short interruption lasting just a few seconds might cause great loss to digital sensitive loads such as semiconductor manufacturers[18-21]. Such customers are concerned about not only electricity cost but also interruption loss[22]. Therefore, UPFC could break the economical bottleneck and improve the supply reliability by its technical advantage in the future distribution system.

Based on the constant current load model, power flow

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distribution characteristics in normally closed loop distribution network with dual sources were analyzed, and the optimal power flow control model based on UPFC considering overall economy(including UPFC's cost) were designed in this paper. The simulating results based on PSCAD show that this method could improve the supply reliability based on the overall economy.

II. Power Flow Distribution Characteristics and Control Law

A. Power flow distribution characteristics

The current distribution characteristics with constant current load model in the closed-loop network with single source was analyzed based on minimum network loss [9], but the network with dual sources was not involved. The latter would be analyzed firstly in this paper. The equivalent circuit with double load branches is shown as Fig 1.

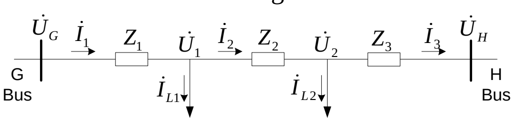

Fig.1 Equivalent circuit of the power flow distribution in normally closed loop distribution network

Where, $\dot{U}_G$ and $\dot{U}_H$ are the voltages of G Bus and H Bus. $\dot{I}_1, \dot{I}_2$ and $\dot{I}_3$ are the currents of line segments ; $\dot{I}_{L1}$ and $\dot{I}_{L2}$ are the load currents and they are both constant; Z_1, Z_2 and Z_3 are the equivalent impedances of line segment, and $\begin{cases} Z_1 = R_1 + jX_1 \\ Z_2 = R_2 + jX_2 \\ Z_3 = R_3 + jX_3 \end{cases}$.

According to KVL and KCL, such equations as followed can be got easily.

$$\begin{cases} \dot{I}_1 Z_1 + \dot{I}_2 Z_2 + \dot{I}_3 Z_3 = \dot{U}_G - \dot{U}_H \\ \dot{I}_2 = \dot{I}_1 - \dot{I}_{L1} \\ \dot{I}_3 = \dot{I}_1 - \dot{I}_{L1} - \dot{I}_{L2} \end{cases} \tag{1}$$

Based on (1), the current distribution of each segment in the loop line is

$$\begin{cases} \dot{I}_1 = \dfrac{\Delta\dot{U} + \dot{I}_{1L}(Z_2 + Z_3) + \dot{I}_{2L} Z_3}{Z_\Sigma} \\ \dot{I}_2 = \dfrac{\Delta\dot{U} - \dot{I}_{1L} Z_1 + \dot{I}_{2L} Z_3}{Z_\Sigma} \\ \dot{I}_3 = \dfrac{\Delta\dot{U} - \dot{I}_{1L} Z_1 - \dot{I}_{2L}(Z_1 + Z_2)}{Z_\Sigma} \end{cases} \tag{2}$$

Where, $\Delta\dot{U} = \dot{U}_G - \dot{U}_H$, $Z_1 + Z_2 + Z_3 = Z_\Sigma$.

B. Power flow control law based on minimal network loss

I_{0i} is defined as the current of each segment line before power flow control and the active power loss is P_{loss} .

$$P_{loss} = \sum_{i=1}^{3} R_i \left| \dot{I}_{0i} \right|^2$$

Equation (2) is taken into above equation,

$$\begin{aligned} P_{loss} &= R_\Sigma \left| \dot{I}_{01} - \frac{R_3(\dot{I}_{L1} + \dot{I}_{L2}) + R_2 \dot{I}_{L1}}{R_\Sigma} \right|^2 \\ &- \left| \frac{R_3(\dot{I}_{L1} + \dot{I}_{L2}) + R_2 \dot{I}_{L1}}{R_\Sigma} \right|^2 + R_2 \left| \dot{I}_{1L} \right|^2 + R_3 \left| \dot{I}_{1L} + \dot{I}_{2L} \right|^2 \end{aligned} \tag{3}$$

Obviously, when the load current and network parameters are fixed, the last three segments of (3) are constant, and P_{loss} is just related to $\dot{I}_{01}$. Therefore, P_{loss} would be minimal when the first segment is controlled to zero. In order to distinguish the parameters before and after control, $P_{loss-\min}$ is assumed as the minimal network loss in theory, and $\dot{I}_{mi}$ (i=1,2,3) is the line current when the loss is minimal.

$$\begin{cases} \dot{I}_{m1} = \dfrac{R_3(\dot{I}_{L1} + \dot{I}_{L2}) + R_2 \dot{I}_{L1}}{R_\Sigma} \\ \dot{I}_{m2} = \dfrac{-R_1 \dot{I}_{L1} + R_3 \dot{I}_{L2}}{R_\Sigma} \\ \dot{I}_{m3} = \dfrac{-R_1 \dot{I}_{L1} - (R_1 + R_2) \dot{I}_{L2}}{R_\Sigma} \end{cases}$$

$$P_{loss-\min} = \sum_{i=1}^{3} R_i \left| \dot{I}_{mi} \right|^2$$

Obviously, when the power loss is minimal, the distribution of line current I_{mi} with the load model of constant current is determined by the resistance, which is similar to the optimal power flow distribution characteristics with the load model of constant power.[23]

$\dot{I}_{loop}$ is defined as the circulating current of the loop circuit as shown in Fig1. Obviously, when the loss is minimal,

$$\dot{I}_{loop} = \dot{I}_{01} - \dot{I}_{m1} = 0$$

The previously defined $\dot{I}_1$ and $\dot{I}_{m1}$ are substituted into above formula, then

$$\begin{aligned} \dot{I}_{loop} &= \frac{\Delta\dot{U} + \dot{I}_{1L}(Z_2 + Z_3) + \dot{I}_{2L} Z_3}{Z_\Sigma} - \frac{R_3(\dot{I}_{L1} + \dot{I}_{L2}) + R_2 \dot{I}_{L1}}{R_\Sigma} \\ &= \frac{\Delta\dot{U} R_\Sigma + j\omega[(L_2 + L_3)R_1 - L_1(R_2 + R_3)]\dot{I}_{L1} + j\omega[L_3(R_1 + R_2) - (L_1 + L_2)R_3]\dot{I}_{L2}}{R_\Sigma Z_\Sigma} \\ &= \frac{\Delta\dot{U} - \sum_{i=1}^{3} j\omega L_i \dot{I}_{0i}}{R_\Sigma} = 0 \end{aligned}$$

Namely,

$$\Delta \dot{U} - \sum_{i=1}^{3} j\omega L_i \dot{I}_{0i} = 0$$

When the distribution network includes n load branches and the network loss is minimal, above expression is

$$\Delta \dot{U} - \sum_{i=1}^{n+1} j\omega L_i \dot{I}_{0i} = 0$$

Where, $\Delta\dot{U}$ is the voltage difference between G Bus and H Bus, L_i is the equivalent impedance of i segment line, R_Σ is the total resistance of loop circuit, $\dot{I}_{0i}$ is the current of i segment line.

Therefore, the network loss could be decreased to minimum by controlling the compensating voltage and the voltage of the loop circle meets such condition as

$$\dot{U}_{SC} + \Delta \dot{U} - \sum_{i=1}^{n+1} j\omega L_i \dot{I}_{0i} = 0$$

Where, $\dot{U}_{SC}$ is the compensating voltage produced by UPFC. $\dot{U}_{SC}$ is to balance the total voltage drop of inductances and the voltage difference between dual sources. It is the basis of the optimal current distribution determined by the resistances. And this rule is similar to the conventional optimal power flow distribution and control principle with the load model of constant power.[23]

UPFC has powerful capacity to adjust the power flow, which could meet the adjusting demand of the closed loop network with double sources. Otherwise, the internal power loss of UPFC is very complicated, which is related to many factors such as the topology structure, control strategy and output power. Up to now, the internal loss model has not been set up and UPFC works with very high efficiency. Thus, the internal loss of UPFC is not concerned in this paper.

C. Voltage control model based on minimal loss

When the compensating voltage based on the minimal loss is to be adjusted further, the circling current will change and the new current is assumed as $\dot{I}'_{loop}$.

$$\dot{I}'_{loop} = \dot{I}_{loop} + \frac{\dot{U}_{SC}}{Z_\Sigma}$$

And the network loss under this condition is P'_{loss}.

$$P'_{loss} = \sum_{i=1}^{3} R_i \left|\dot{I}_{mi}\right|^2 + \sum_{i=1}^{3} R_i \left|\dot{I}'_{loop}\right|^2 = P_{loss-\min} + \sum_{i=1}^{3} R_i \left|\dot{I}'_{loop}\right|^2$$

Then,

$$P'_{loss} = P_{loss-\min} + R_\Sigma \left|\dot{I}_{loop} + \frac{\dot{U}_{SC}}{Z_\Sigma}\right|^2 \qquad (4)$$

Obviously, P'_{loss} is just related to the amplitude of $\dot{I}'_{loop}$, but the voltage of load nodes is determined by both the amplitude and phased of $\dot{I}'_{loop}$. Therefore, the voltage of load nodes could be controlled by adjusting the compensating voltage, with only changing the phase of $\dot{I}'_{loop}$ and keeping the amplitude constant.

As shown in Fig.2, $\dot{U}'_1$ is assumed to describe the voltage of node 1 when the network loss is minimal. When the compensating voltage is adjusted further with the amplitude of $\dot{I}'_{loop}$ kept constant, the compensating voltage variation is assumed as $\dot{U}'_{SC}$ and the voltage of load node 1 is $\dot{U}''_1$. Obviously, the trail of $\dot{U}''_1$ is a circle with $\dot{U}'_1$ as the center and $\Delta U'$ as the radius.

$$\Delta U' = \left|Z_1 I'_{loop}\right| = \left|\frac{Z_1}{Z_\Sigma} U'_{SC}\right|$$

After compensated by UPFC, the voltage of load node i would be described as

$$U_{1i} = \left|\dot{U}_{0i} + \frac{\dot{U}_{SC} Z_{1i}}{Z_\Sigma}\right| \qquad (5)$$

Where, $\dot{U}_{0i}$ is the voltage of load node i when $U_{SC} = 0$, and Z_{1i} is the total line impedance from G Bus to load node i.

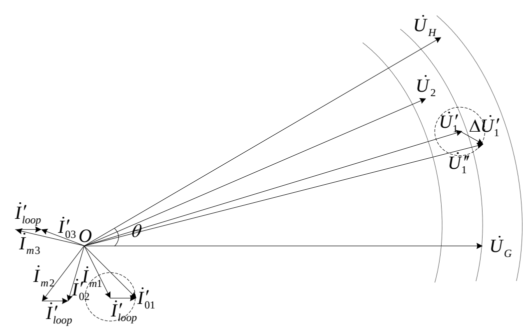

Fig.2 Voltage Control phasor diagram based on the minus loss

III. RELATIONSHIP BETWEEN CAPACITY OF UPFC AND IT'S COST

UPFC has powerful capacity to control power flow, which could meet the circling-power adjusting demand in the closed-loop distribution network. But the economy is the key bottleneck for UPFC to apply in the distribution system. The UPFC's cost $C_{Total}(US\$)$ of unit capacity S_{SC} (MVA) could be described as[24]

$$C_{Total}(S_{SC}) = 0.1S_{SC}^3 - 134.55S_{SC}^2 + 188220S_{SC}(US\$) \qquad (6)$$

Formula (4) and (5) reveal the condition of the minimal power loss and the voltage control law. The power loss or voltage deviation of all nodes will rise when U_{SC} is larger or smaller than the optimal value. And the power loss and voltage deviation follow the same changing trend. Generally, the output voltage could determine the capacity or cost of UPFC. Network power loss and voltage deviation could be regarded as the operation economy of the system. Therefore, the economic operation spot could be controlled by the capacity of UPFC, as the optimal operation curve shown in Fig.3. Meanwhile, the UPFC's cost is determined by its capacity. Because the max load of medium voltage feeders is finite (generally less than 5MW) and the voltage difference between two side buses is not very large ensured by planning, the capacity of UPFC demanded is even smaller (generally less than 1MVA). The relationship between the UPFC's capacity and cost deduced by formula （6）is shown as the cost of UPFC curve in Fig.3. Therefore, the total cost curve could be got by combing the operation economy and the UPFC's cost. Obviously, it has a lowest spot with the varying of UPFC capacity.

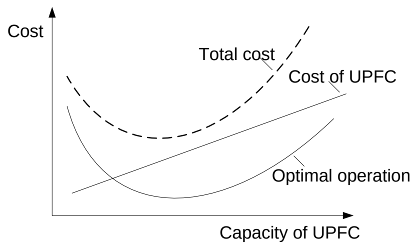

Fig.3 Relation between economy and capacity of UPFC

IV. OPTIMAL POWER FLOW CONTROL MODEL WITH OVERALL ECONOMY

The optimal power flow control model is set up considering the network loss, voltage deviation of load nodes and investment of UPFC, which is a multi-objective optimization problem, hard to solve by regular algorithm. Fuzzy membership function of above three factors is designed to found the single-objective optimization model for simplifying.

A. Fuzzy membership function

The original loss is assumed as $P_{loss-ori}$ and the theoretical minimal loss is $P_{loss-\min}$. Based on equation (4), the fuzzy membership function of active loss, $\mu_{P_{loss}}$ is designed as

$$\mu_{P_{loss}} = \begin{cases} 1 & P_{loss} \le P_{loss-\min} \\ \dfrac{P_{loss} - P_{loss-ori}}{P_{loss-\min} - P_{loss-ori}} & P_{loss-\min} < P_{loss} < P_{loss-ori} \\ 0 & P_{loss-ori} \le P_{loss} \end{cases}$$

Where, $P_{loss-ori}$ is the original loss of the closed loop network without any control measure. P_{loss} is the variable describing the power loss change with the compensated voltage. According to "Power quality-Admissible deviation of supply voltage ", the range of voltage deviation is set within ±7%U_N (rated voltage).

$\mu_{\Delta Ui}$ is assumed as the fuzzy membership function of voltage deviation and U_i is as the current voltage value of load node i. Based on equation (5),

$$\mu_{\Delta Ui} = \begin{cases} 0 & U_i < 0.93U_N \\ \dfrac{U_i - 0.93U_N}{0.07U_N} & 0.93U_N \le U_i \le U_N \\ \dfrac{1.07U_N - U_i}{0.07U_N} & U_N < U_i \le 1.07U_N \\ 0 & U_i > 1.07U_N \end{cases}$$

$S_{SC\max}$ is assumed as the maxim capacity of UPFC needed and $C_{SC\max}$ is the UPFC's cost at $S_{SC\max}$. Based on equation (6), the UPFC's cost membership μ_{C-UPFC} is described as

$$\mu_{C-UPFC} = \begin{cases} \dfrac{C_{SC\max} - C_{Total}(S_{SC})}{C_{SC\max}} & 0 < S_{SC} < S_{SC\max} \\ 0 & S_{SC} \ge S_{SC\max} \end{cases}$$

Where, $C_{SC\max}$ is the cost of UPFC with max capacity and S_{SC} is the UPFC's capacity.

B. Optimal power flow control model

Based on above fuzzy membership functions designed, the optimal power flow control model considering overall economy could be described as

$$f = \max\left(\alpha \sum_{i=1}^{n} \frac{\mu_{\Delta Ui}}{n} + \beta \mu_{P_{loss}} + \gamma \mu_{C-UPFC} \right) \tag{7}$$

$$s.t \quad \begin{cases} S_G \le S_{G\max} \\ S_H \le S_{H\max} \\ U_{\min} \le U_i \le U_{\max} \end{cases}$$

Where, n is the number of load nodes, S_G and S_H are the output power of feeders from G Bus and H Bus, $S_{G\max}$ and $S_{H\max}$ are the upper limits of output power in feeders, U_i is the actual operation voltage of load nodes, $U_{\max}$ and $U_{\min}$ are the upper and lower limits of voltage, and α, β and γ are the weight coefficients of three parts($\alpha + \beta + \gamma = 1$).

V. SIMULATION AND ANALYSIS

The simulation model and parameters of normally closed-loop distribution network with dual sources are shown as Fig.4. In order to compare the adjusting effect under different operation and controlling conditions, simulating states of distribution network are classified as shown in Table 1.

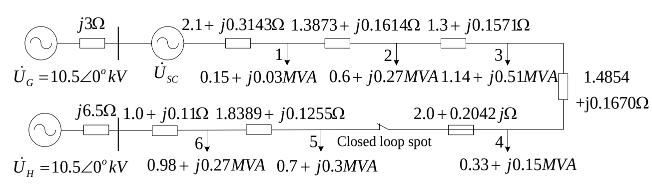

Fig.4 Simulation model

TABLE 1 SIMULATION STATE OF NETWORK

State	State type of network
Case 1	Opened loop operation, namely the switch between node 4 and node 5 is open
Case 2	Closed loop operation directly, namely the switch is close without any power flow control measures
Case 3	Closed loop operation with $\alpha = 0.6, \beta = 0.4, \gamma = 0$
Case 4	Closed loop operation with $\alpha = 0.1, \beta = 0.3, \gamma = 0.6$

Assumption:

$S_{G\max} = S_{H\max} = 3.5MVA,$

$U_{\max} = 1.07U_N, U_{\min} = 0.93U_N$.

Necessary parameters are taken into (7) and the series compensating voltage could be solved by the algorithm of overall optimization.

In Case 3, $\dot{U}_{SC} = 0.7797\angle -127.44^0 kV$.

In Case 4, $\dot{U}_{SC} = 0.6118\angle 238.6^{\circ}$ kV .

A. Comparison of voltage control

The voltage control effect under different conditions is shown in Table 2. Obviously, in Case 1, the voltage deviation of most nodes is too large, and Node 1-Node 4 is low beyond the range given. In Case 2, the voltage quality is generally improved, all voltage within the range given. That proves the effect of normally closed loop operation in the voltage control aspect. In Case 3 and Case 4, the node voltages are further improved, but the result shows that the control effect in Case 4 is little worse than that in Case 3 for the latter weakens the proportion of voltage in the optimal control model.

TABLE 2 EFFECT COMPARISON OF VOLTAGE CONTROLLING

Node number	Vol in Case 1 (kV)	Vol in Case 2 (kV)	Vol in Case 3 (kV)	Vol in Case 4 (kV)
1	8.811	9.848	9.917	9.887
2	8.457	9.536	9.674	9.626
3	8.222	9.332	9.530	9.469
4	8.162	9.289	9.554	9.478
5	9.981	9.304	9.662	9.564
6	10.114	9.460	9.893	9.783

B. Comparison of network loss

The actual power loss in various Cases is shown in Table 3. The actual power loss in Case 2 is less than that in Case 1, which proves that Case 2 is helpful in decreasing the actual power loss. In Case 3, the theoretical power loss is 0.2493MW and the actual loss is 0.2502 MW for the load model adopted in the simulation is the constant power model. In Case 4, the theoretical loss is 0.2550 MW and the actual is 0.2605 MW. Therefore, the theoretical and actual loss in Case 4 is more than that in Case 3, because the latter weakens the weight of loss in the optimal control model.

TABLE 3 COMPARISON OF LOSS CONTROLLING(MW)

State	*Network Loss （MW）*
Case 1	0.3449
Case 2	0.3085
Case 3	0.2550
Case 4	0.2605

C. Balancing output power of feeder

As shown in Fig.5, the curves in 0S-1S are the output power of G side and H side feeders in Case 1 and the output power difference is great. The curves in 1S-2S and 2S-3S are the output power in Case 2 and Case 3. Obviously, the active power difference in Case 2 is 2.03MW and increases much more than that in Case 1. However, the difference could be decreased effectively and the active power difference is just only 0.27MW in Case 3. In Fig.6, the active power difference during 2S-3S is in the state of Case 4, which is 0.284MW and slightly larger than that in Case 3. Thus, the control method presented could lower the output difference and balance the output from both side feeders effectively, and the control effect is determined by the weight coefficients.

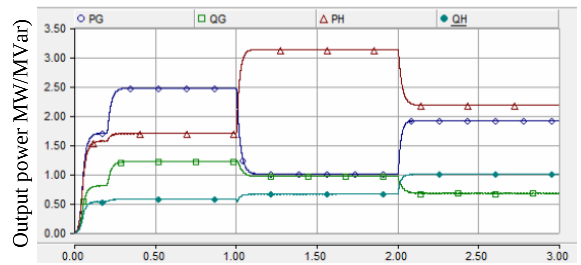

Fig.5 Comparative curve of output power of both side sources

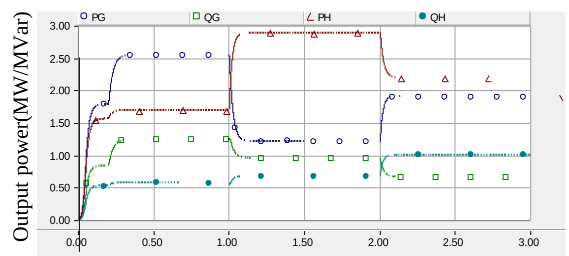

Fig. 6 Contrasting curves of the output power of both side sources

In Fig.5 and Fig.6, PG is the active power from G side feeder, QG is the reactive power from G side feeder, PH is the active power from H side feeder, and QH is the reactive power from H side feeder.

D. Comparison of UPFC's cost

As discussed in 3, UPFC's cost is related to it's capacity. Thus, the application economy of UPFC could be compared by capacity under the same power adjusted condition. When the power adjusted is 1WM in Case 3, the compensating voltage U_{SC} is $0.7797kV$ and the current I_{SC} is $0.11kA$. The capacity of UPFC is

$$S_{SC} = 3U_{SC}I_{SC} = 3\times 0.78\times 0.11 = 0.26MVA$$

When the power adjusted is 1WM in Case 4, the compensating voltage U_{SC} is $0.6118kV$ and the current I_{SC} is also $0.11kA$. The capacity of UPFC is

$$S_{SC} = 3U_{SC}I_{SC} = 3\times 0.61\times 0.11 = 0.20MVA$$

Obviously, under the same power adjusting demand, the capacity in Case 4 decreases 23% than that in Case 3. The result proves that the model parameter in Case 4 is helpful to improve the economy of UPFC applying in distribution system. And the overall economy is determined by the weight coefficients of loss, voltage deviation and UPFC's cost.

VI. CONCLUSIONS

1） Based on constant current load model, the power flow distribution characteristics of normally closed-loop operation distribution system with dual sources are deduced. Power loss is determined only by the amplitude of circling current, but the load node voltage is related to the amplitude and phase of circling current. The conclusion is same to that in closed-loop network with single source. Therefore, the voltage of load nodes could be controlled just by adjusting the phase of the compensating voltage with the constant power loss.

2） Optimal power flow control model of normally closed loop distribution network is presented considering the operating economy and UPFC's cost. The simulation results prove that this method could balance the output power of both side feeders, decrease the network loss, and improve the voltage quality based on the overall economy. The controlling effect such as loss, voltage and UPFC's cost is determined by the weight coefficients. The method presented in this paper lays the foundation for UPFC application in the future distribution system.

3）This paper mainly discusses how to use UPFC to control the steady-state power flow control method of the closed loop distribution network with dual sources. The objective is to ensure the steady-state optimal operation of the whole system without considering the transient behavior of UPFC and the protective measures for the device in case of fault. Certainly, how to select and protect the UPFC devices in case of fault is also very important, which should be studied further in the future. The following three ways present the solutions.

- Bypass UPFC automatically by fast switches in case of a fault.
- UPFC with limiting current function is adopted, and UPFC could automatically switch into the mode of limiting current in case of a fault.[25]
- Select the circuit elements with enough power to sustain the shock of short-circuit current. However, it could not break out the bottleneck of economy, especially used in the distribution system.

With the rapid development of social economy, the unit loss of interruption (especial short interruption) to the important load is increasing gradually. It is highly necessary to study the new supply mode and power flow control method especially based on FACTS in the extremely important load condition. The conclusion of this paper has great guiding effect for the FACTS application in the fault self healing and optimal operation to the future smart distribution grid.

VII. ACKNOWLEDGMENT

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