

An Novel Continuation Power Flow Method Based on Line Voltage Stability Index

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Abstract. An novel continuation power flow method based on line voltage stability index is proposed in this paper. Line voltage stability index is used to determine the selection of parameterized lines, and constantly updated with the change of load parameterized lines. The calculation stages of the continuation power flow decided by the angle changes of the prediction of development trend equation direction vector are proposed in this paper. And, an adaptive step length control strategy is used to calculate the next prediction direction and value according to different calculation stages. The proposed method is applied clear physical concept, and the high computing speed, also considering the local characteristics of voltage instability which can reflect the weak nodes and weak area in a power system. Due to more fully to calculate the PV curves, the proposed method has certain advantages on analysing the voltage stability margin to large-scale power grid.

1. Introduction

Continuation Power Flow (CPF) and its improvement tools are widely used in analysing the static stability of power system and calculating the maximum available transmission ability of the system. In the calculation process of CPF, calculation often fails, so in this case, no matter how to narrow the correction step, the solution to wave equation cannot be obtained. This phenomenon can occur near the nasal point of solving trajectory or at a distant place from the nasal point. If the issue of computational divergence occurs at the lower part of calculating the curve, it will not affect the system's stability margin and calculation of other indexes, but only the complete PV curve cannot be described. However, if it occurs at the upper part of the curve, the accurate stability margin and the position of nasal point cannot be obtained, thus the system operation personnel will have pessimistic estimation and fail to take correct coping strategies.

At present, many scholars have proposed strategies to cope with the failure of calculating CPF. Literature [1] proposes a continuation power flow calculation method taking the line reactive power loss as the parametric equation. Literature [2] systematically demonstrates 2 phenomena for the failure of continuation power flow calculation, proposes to use local parameterization method to replace the global parameterization methods like arc length or quasi arc length to avoid the failure of the critical point and adopts parameter forced transformation strategy to avoid the failure of non-critical points. Based on predicting the tangent vector normalization, Literature [3] proposes the parameter selection strategy of improving local parameterization to reduce the possibility of non-convergence in the



process of correcting local parameterization. Literature [4] proposes a node type to expand the continuation power flow mode and gives the two-way transformation logic of new node modes and methods to identify the static voltage's stable critical point types. Literature [5] makes improvement from two aspects: algorithm prediction and algorithm correction so as to get the approximate value of the load margin. Literature [6] uses the maximum and optimal flow calculation result of the load margin to differentiate between limit points of electric voltage stability and load margin's sensitiveness to the controlling variables to quickly determine the limit points of voltage stability.

Voltage instability has strong local characteristics [7-11], which are throughout the course of CPF calculation, so the process of parameterization CPF should take full consideration of voltage stability's local characteristics. Based on this analysis, this paper proposes a continuation power flow improvement method taking line reactive power loss as the parametric equation, which uses the line voltage stability index to select the parameterization lines and constantly updates parameterization lines with the changes of load. Then, it uses the expansion flow equation direction to predict the changes of angles and judge the process of calculating continuation flow by selecting pace control strategies according to different calculation stages. Finally, examples show that method proposed in this paper is effective.

2. Strategies to Solve Calculation Failure

2.1. Improved Parameterization Method

The expanded power flow equation by taking line reactive power loss as the new parametric equation is:

$$\begin{cases} \mathbf{G}(\theta_k, V_k, \lambda_k) = 0 \\ \mathbf{W}(\theta_k, V_k, \lambda_k, u_k) = u_k Q_{k,l} - F(\theta_k, V_k, \lambda_k) = 0 \end{cases} \quad (1)$$

In the formula, θ_k and V_k refer to the voltage amplitude and phase angle of each node in the system in the state k , λ_k refers to the load growth factor, u_k refers to the loss factor in the state k , Q_k refers to the reactive power loss of line l in the state k . Function \mathbf{G} refers to the flow equation composed by active wave equation and reactive wave equation. Function \mathbf{F} refers to the reactive wave equation expression of line l , and function \mathbf{W} refers to the parameterization equation expression with reactive power loss equation as the basis.

Use the Newton-Ralph method to solve the expansion power flow equation and determine the prediction direction \mathbf{t}_k of the next solution as:

$$\mathbf{t}_k = \mathbf{J}_k^{-1} \begin{bmatrix} \theta_k \\ V_k \\ \lambda_k \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ \Delta u_k Q_{k,l} \end{bmatrix} \quad (2)$$

In which, \mathbf{J}_k is the Jacobian matrix of the trend equation in the state k , and \mathbf{J}_k^{-1} is the inverse matrix of \mathbf{J}_k .

2.2. Method Selection of Parametric Route

For the classic 2 nodes' electric system's equivalence grid, the active power P_l and reactive power Q_l transmitted by first end node i of line l to the last node j of line l can be shown as:

$$P_l = g_l V_{l,i}^2 - y_l V_{l,i} V_{l,j} \cos(\theta + \delta) \quad (3)$$

$$Q_l = -(b_l + b_{l,i}^s + b_{l,j}^s) V_{l,i}^2 + y_l V_{l,i} V_{l,j} \sin(\theta + \delta) \quad (4)$$

In which, g_l , b_l and y_l are the conductance, susceptance and admittance of line l . $b_{l,i}^s$, $b_{l,j}^s$ are the corresponding susceptance value of the reactive complementary equipment installed at the i and j side of line l . P_l , Q_l are the active power and reactive power of line l . $V_{l,i}$, $V_{l,j}$ are the voltage value of line l at the first node i and the last node j . θ is the line impedance angle and δ is the voltage phase angle difference of both ends.

Formula (3) and (4) can be written as:

$$\cos(\theta + \delta) = (g_l V_{l,i}^2 - P_l) / (y_l V_{l,i} V_{l,j}) \quad (5)$$

$$\sin(\theta + \delta) = (Q_l + (b_l + b_{l,i}^s + b_{l,j}^s) V_{l,i}^2) / (y_l V_{l,i} V_{l,j}) \quad (6)$$

Remove θ and δ in formula (5) and (6) to get:

$$(g_l^2 + (b_l + b_{l,i}^s + b_{l,j}^s)^2) V_{l,i}^4 + (-2[g_l P_l + (b_l + b_{l,i}^s + b_{l,j}^s) Q_l] - V_{l,i}^2 y_l) V_{l,i}^2 + (P_l^2 + Q_l^2) = 0 \quad (7)$$

In order to ensure stable voltage of the grid, formula (7)'s dimensional equation must have a real solution, i.e., the root of equation discriminant should be greater than or equal to zero. According to this principle and after reduction, the line l 's stable voltage index L_l can be:

$$L_l = \frac{4(g_l^2 + (b_l + b_{l,i}^s + b_{l,j}^s)^2)(P_l^2 + Q_l^2)}{(-2[g_l P_l + (b_l + b_{l,i}^s + b_{l,j}^s) Q_l] - V_{l,i}^2 y_l)^2} \leq 1 \quad (8)$$

It can be seen from formula (8) that, L_l refers to the stability of the line's voltage, the less the L_l value is, the more stable the line is, and the more the L_l value is close to 1, the more unstable the line is. The reactive power loss value of the line and the system load constitute a basic linear relationship. However, the reactive loss values of some lines, especially those that compensate for the more adequate lines, may not increase as the load increases. If the node relates to several branches, calculate the stability index L_{ij} of each branch, select the minimum value of the stability index.

3. Step Adjustment Strategy

In the continuous power flow calculation, the closer the state point is to the nose position, the bigger the angle between the two directions is. Therefore, the calculation phase of the continuous power flow can be judged by using the cosine of the predicted direction angle. As shown in Fig.2, if $k=1$, it shows that the computation is at the beginning state and the current system is far from reaching the turning

point. Update the computation stage sign $S_{k+1}=1$; if $k>1$, and $0 \leq \cos \angle \mathbf{t}_k, \mathbf{t}_{k-1} \leq \alpha$, it shows that the current system has not reached the turning point, and update the computation stage sign $S_{k+1}=1$; if $k>1$ and $\cos \angle \mathbf{t}_k, \mathbf{t}_{k-1} > \alpha$ or $\cos \angle \mathbf{t}_k, \mathbf{t}_{k-1} < 0$, it shows that the current system has reached the turning point, and update the computation stage sign $S_{k+1}=0$, i.e.:

$$S_{k+1} = \begin{cases} 1, & \text{if } k=1 \\ 1, & \text{if } k>1, 0 \leq \cos \angle \mathbf{t}_k, \mathbf{t}_{k-1} \leq \alpha \\ 0, & \text{if } k>1, \cos \angle \mathbf{t}_k, \mathbf{t}_{k-1} < 0 \text{ or } \cos \angle \mathbf{t}_k, \mathbf{t}_{k-1} > \alpha \end{cases} \quad (9)$$

Use the predicted direction \mathbf{t}_k to calculate the pace size σ_{k+1} as:

$$\sigma_{k+1} = \sigma_k / \|\mathbf{t}_k\|_2 \quad (10)$$

In which $\|\mathbf{t}_k\|$ refers to the Euclidean norm of the predicted direction \mathbf{t}_k .

If the computation stage sign $S_{k+1}=1$, then update pace size $\sigma_{k+1} = (\sigma_{k+1} + \sigma_k) / 2$; if the computation stage sign $S_{k+1}=0$, not update the pace size.

$$\sigma_{k+1} = \begin{cases} (\sigma_{k+1} + \sigma_k) / 2 & \text{if } S_{k+1}=1 \\ \sigma_k & \text{if } S_{k+1}=0 \end{cases} \quad (11)$$

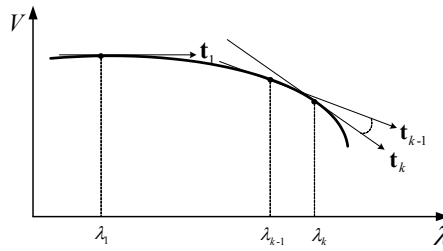


Fig. 1 udge schematic of the stages of CPF

4. Algorithmic Flow

1) Read the basic data flow calculation and the formation of the system network impedance matrix, set the initial stage $k=1$, the initial computation sign $S_1=1$, initial pace size $\sigma_1=1$, the loss factor $u_1=1$;

2) The power flow calculation is carried out to find the voltage, the phase angle and the power phasor of each load node;

3) Calculate the line voltage stability index L_k^{\max} at the current state;

4) Express the reactive loss equation of the line voltage stability characteristic index L_k^{\max} corresponding with line l in the parametric equation, construct expansion continuation flow equation;

- 5) The Newton-Raphson method is used to solve the extended tidal current equation and to determine the direction of the next solution t_k ;
- 6) Using the cosine of the angle between the predicted directions of the two directions to judge the calculation state of continuous power flow;
- 7) Use the predicted direction t_k to calculation the pace size σ_{k+1} ;
- 8) Determine the predicted value of the next solution;
- 9) Use the normal continuation flow correction method to get solution to the above continuation flow equation. If the flow converges, set $k=k+1$, and return to step 3); otherwise, if the computation stage sign is $S_{k+1}=1$, update the pace size as $(\sigma_{k+1}+\sigma_k)/2$, and return back to step 8); if the computation stage sign $S_{k+1}=0$, not update the pace size, directly output the result and end the calculation.

5. Numerical Example

Conduct simulation calculation to IEEE14 node system, take $\alpha = 0.5$. Figure 2 is the PV curve calculated by this method. It can be seen from the figure, this method only through seven state point to reach the inflection point position, the calculation speed. In the state $k=8$, the calculation phase $S_{k+1}=0$, indicating that the system has reached the system inflection point. At the same time, the line voltage stability characteristic index $L_8^{\max} = 0.932$, close to 1, that the system's existing line is in an unstable

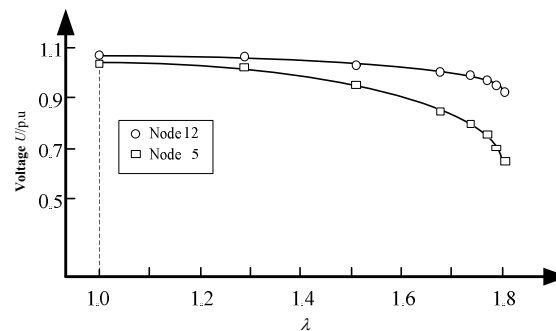


Fig. 2 Part of the PV curves of IEEE14 system

state. Therefore, the calculation phase flag value and the line voltage stability characteristic index value of two important indicators can effectively determine whether the system is in the limit running state.

Figure 3 shows the line labels for the line voltage stability characteristics of each state point. It can be seen from the figure that the line corresponding to the line voltage stability characteristic index proposed by the method of the present invention is not invariant at each state point. Line voltage stability characteristics of the corresponding indicators of the line with the system will change the most unstable area automatically. Therefore, the index can reflect the local characteristics of voltage instability, reflecting the weak nodes and weak regions of the system.

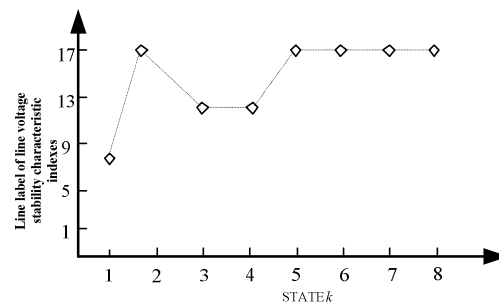


Fig. 3 Line label of line voltage stability characteristic indexes in each state point

Table 1 shows the number of iterations of the extended continuous power flow equation in each state. As can be seen from the figure, the iterative method is less required and the convergence rate is faster.

Table 1. Iterations number in each state point

STAE k	1	2	3	4	5	6	7	8
Iterations number	1	1	1	1	1	2	2	2

Figure 4 shows the calculation stage flag values for each state point. In the figure, the calculation stage flag value is 1 before the state $k=8$ and is updated to 0 only when the state $k=8$, which means that the calculation phase judgment method can accurately judge the calculation phase of the continuous power flow.

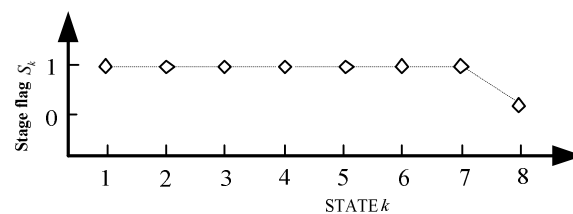


Fig. 4 Stage flag in each state point

The voltage stability margins (PV curve) of the main power grids in Hunan province in the year of 2011 are analysed, and 795 substations are included in the analysis of voltage stability margin, of which 500kV substations are 10, 220kV voltage substations are 139, and 110 kV sub-stations are 646. Table 2 for the method and PSASP program, BPA software and other mainstream power analysis software performance comparison analysis. From the Table, we can see that the success rate of this method is higher than PSASP program, BPA software 2.48 and 2.17 percentage points respectively, the PV curve integrity rate is 3.57 and 3.88 percentage points higher respectively, the average calculation time is only 76.68% of PSASP program, BPA software of the 76.10%, significantly faster computing speed.

Table 2. Performance comparison

Corresponding Index	Proposed method	PSASP	BPA
Computation successful rate (%)	97.68	95.20	95.51
PV curve completion rate (%)	95.98	92.41	92.10
Average calculation time (s)	5.03	6.56	6.61

Note: successful computation in this table refers to able to get the PV curve's state data at the nasal point through computation.

6. Conclusion

Based on the line voltage stability index, the reactive power loss of the line is selected as the new parameterization equation, and the extended continuous power flow equation is constructed. It can reflect the local characteristics of the voltage instability and reflect the weak node and weak region of the system. In this paper, using the method of predicting changes direction vector of power flow equations of the expansion angle calculation stage of continuous flow judgment, based on continuous flow calculation in the process of step control, effectively avoids the calculation of convergence. IEEE14 node computation samples and Hunan Grid's calculation show that method proposed in this paper can effectively, rapidly and relatively completely calculate and get the PV curve, so it has certain advantage in conducting voltage stability margin analysis to a large scale of grid.

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