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FAST VOLTAGE STABILITY ASSESSMENT FOR LARGE-SCALE POWER SYSTEMS

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ABSTRACT

Based on power transmission paths, a new method for on-line voltage stability assessment is proposed in this paper. In the large-scale power systems, the local voltage stability index is used to determine weak buses. Based on the electrical distance, participant buses and key power sources of the reactive and active power transmission paths are decided. The weak power transmission paths are searched and the weakest one is computed through the equivalent systems. The voltage stability index incorporating the reactive power reserve of key generators is used as a director for voltage stability assessment. Simulation results of the practical Shandong power system in China demonstrate that the accuracy and the speed can meet the need of on-line application.

KEY WORDS

Voltage stability assessment, power transmission path, reactive power reserve

1. Introduction

Complex dynamic phenomena appear in the huge interconnected power network and damages by voltage instability accidents can be significantly great to the whole society. Voltage stability problem has already become a major concern in planning and operating of electric power systems. Voltage instability presents a common feature of their suddenness and concealment. During the development of accidents, they are very difficult to be detected and controlled timely and effectively. Once voltage instability happens, power systems are difficult to survive. Significant efforts have been directed toward definitions, classifications, new concepts, practices and tools for solving the voltage stability and security analysis problems [1]-[3].

Since the voltage instability phenomenon is of local nature, the primary effort in recent years has been to derive methods that can utilize local data. The main idea behind local methods is that local phasors contain enough information to detect parts of the system that are prone to voltage collapse. These methods are effective for on-line voltage stability assessment (VSA). The local method proposed in [4-6] is based on a comparison of the Thevenin equivalent as seen from the load bus and the apparent impedance of the load. The assessment of the distance to voltage instability is based on the fact that the two impedances are equal at the point of voltage collapse. However, the estimation of the Thevenin equivalent is obtained from two measurements at different times. Much more data are required for a more exact estimation and it cannot indicate effective control directions. Voltage stability indictor of the power transmission path is proposed to assess the voltage stability degree of power systems [7]. Its main disadvantage is in the computation of the weakest power transmission path which is obtained from the equivalent systems of all paths. A local method is proposed based on the fact that the losses consume all of the increased power at the sending in the vicinity of the voltage collapse [8]. The weakness of this method lies in additional checking if the line is loaded below its natural loading.

Based on power transmission paths, a fast assessment method for static voltage stability is proposed. To reduce the calculation, the local voltage stability index is used to determine weak buses in complex power systems. Based on electrical distance, participant buses and key power sources of the reactive and active power transmission paths are decided. The weak power transmission paths are searched and the weakest one is computed through the equivalent system. The weakest path voltage stability index (VSI) incorporating the key generators reactive power reserve is used as a director for voltage stability assessment. Simulation results of the practical Shandong power system in China demonstrate the effectiveness.

2. Voltage Stability Index based on Power Transmission Lines

Although power transmission paths are very complex in practical power systems, the voltage stability degree of a power system can be represented by the voltage stability of the path that is the most prone to voltage instability. By two-bus equivalent systems of power transmission paths, the VSI of the power system can be computed as follows.

A power transmission path fed by a generator ($\dot{V}_1$, $\dot{I}_1$ and $P_1\square jQ_1$) contains a series of buses feeding various load P_i+jQ_i ($2\leq i\leq n$) corresponding voltage phasor $\dot{V}_i$, as shown in Fig. 1.

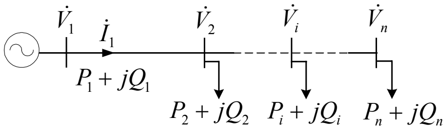

Fig.1 A power transmission path

In order to assess the voltage stability of the power transmission path, the path is transformed into a two-bus equivalent system as shown in Fig. 2.

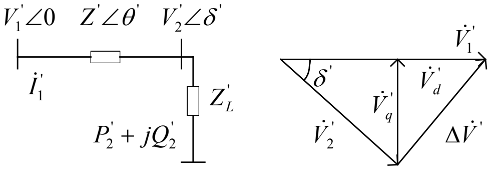

Fig. 2 The two-bus equivalent system and corresponding phasor diagram

In the process of equivalence, three equivalent conditions have to be met [9]. Therefore

$$V_d^{'} = V_d = \frac{P_1 P_{loss} + Q_1 Q_{loss}}{P_1^2 + Q_1^2} V_1 \tag{1}$$

$$V_q^{'} = V_q = \frac{P_1 Q_{loss} - Q_1 P_{loss}}{P_1^2 + Q_1^2} V_1 \tag{2}$$

$$V_1 V_n = V_1^{'} V_2^{'} \tag{3}$$

where P_{loss} and Q_{loss} represent the active and reactive transmission losses along the path.

By the equations of (1), (2) and (3), voltage magnitudes $V_1^{'}$ and $V_2^{'}$ and the angle $\delta^{'}$ can be computed. Similar to the result of the two-bus system, a voltage stability index of power transmission path (*PVSI*) can be defined as

$$PVSI = V_2^{'} \cos\delta^{'} - 0.5V_1^{'} \tag{4}$$

When *PVSI*≥0, the path is stable. Otherwise, the path is unstable.

In the complex power system, several power transmission paths can serve the same load bus. When the *PVSI* of one power transmission path is close to 0, the voltage instability can be expected with in a quite small load increasing due to huge increasing losses in the critical condition of the weakest power transmission path. The minimum value of the path provides the warning voltage stability index of the power system. Therefore, the *VSI* of the power system can be defined as

$$VSI = \min PVSI(L_V, L_\delta) \tag{5}$$

where L_V and L_δ denote the two sets of reactive power transmission paths and active power transmission paths defined in [7], respectively.

The power transmission path with the minimum value of *PVSI* value is the weakest one and the bus at the end of the path is the weakest load bus.

3. The Weakest Power Transmission Path

For a complex power system, it is a heavy burden to compute the *PVSI* of all power transmission paths. In fact, most of paths are usually stable sufficiently. Therefore, if the set of weak power transmission paths that is much smaller than the set of all paths is decided, the search process for the weakest path will be simplified greatly. In order to reach this goal, weak buses are decided by local voltage stability index *L*. Participant buses and key power sources are determined based on the electrical distance information.

3.1 Sets of weak buses

Voltage instability phenomena usually start from some buses which are called weak buses. Weak power transmission paths should be selected from the paths that include the weak buses determined by local voltage stability index *L* [10].

$$\underset{j\in\alpha_L}{L_j} = \left| 1 - \sum_{i\,\in\,\alpha_G} F_{ji}\dot{V}_i / \dot{V}_j \right| \tag{6}$$

where L_j is the local voltage stability index of bus *j*, $\dot{V}_i$ is the voltage of generator *i* $i \in \alpha_G$, $\dot{V}_j$ is the voltage of load bus *j* $j \in \alpha_L$, and F_{ji} is the participant factor.

All load buses can be ranked by index *L*. The bigger the index *L* is, the more weak the buses is. Thus the set of weak buses can be decided.

3.2 Electrical distance

The electrical distance between bus *i* and bus *j* was defined as [11]

$$D_{ij}^V = -\log(\alpha_{ij}\alpha_{ji}) \tag{7}$$

where $\alpha_{ij} = (\partial V_i / \partial Q_j) / (\partial V_j / \partial Q_j)$

Similarly, another electrical distance D^δ that expresses the angle interaction between different buses can be defined as

$$D_{ij}^\delta = -\log(\beta_{ij}\beta_{ji}) \tag{8}$$

where $\beta_{ij} = (\partial\theta_i / \partial P_j) / (\partial\theta_j / \partial P_j)$

3.3 Weak power transmission path

The interaction degree between the weak buses and the other buses can be measured conveniently by D^V or D^δ . According to the physical meaning of electrical distances, the buses close to the weak buses in the electrical distance can also be considered as weak buses. These buses called as participant buses should be included in the weak power transmission paths. Bus *k* is chosen as a participant bus of weak reactive power transmission path if $D_{ik}^{V} < D_{c}^{V}$ where D_{ik}^{V} represents the distance between weak bus i and bus k and D_{c}^{V} is a threshold. As mentioned above, power transmission paths should include power sources. Thus the value of D_{c}^{V} should reflect the impact of the reactive power sources. Let D_{im}^{V} and D_{iM}^{V} be the minimum and maximum of electrical distance D^{V} between bus i and all reactive power sources respectively, then

$$D_{c}^{V} = D_{im}^{V} + \lambda(D_{iM}^{V} - D_{im}^{V}) \tag{9}$$

where λ is a constant between 0 and 1.

Similarly, another threshold D_{c}^{δ} is defined to determine the participant buses in a weak active power transmission path

$$D_{c}^{\delta} = D_{im}^{\delta} + \tau(D_{iM}^{\delta} - D_{im}^{\delta}) \tag{10}$$

where D_{im}^{δ} and D_{iM}^{δ} are the minimum and maximum of electrical distance D^{δ} between bus i and all active power sources respectively and τ is a constant between 0 and 1. Equations (9) and (10) suggest that only a part of buses in the sets G_{V} and G_{δ} can be selected as the power sources of the weak power transmission paths. These buses called as key power sources consist of the sets G_{Vm} and $G_{\delta m}$ respectively. Furthermore, the buses whose electrical distances to the weak buses are less than the corresponding threshold are qualified as the participant buses. As a result, no matter what size of the power system, much less buses are chosen into the weak power transmission paths.

After determining key power sources, weak buses and the corresponding participant buses, the weak reactive and active power transmission paths can be found according to the definition of power transmission paths. After that, the weakest path can further be decided by their equivalent systems..

4. Reactive Power Reserve Indices

The excitation current limit and the armature thermal limit are the two main causes of the generator reaching the limit of the reactive power. In the heavy loading conditions, reactive generation increases with load to maintain the terminal voltage. When it reaches the limit, the ability of voltage support from the generator will lost. The risks of generators encountering reactive power limits are hard to predict, because they introduce the discontinuities in the model. Therefore, the reactive power reserve index (*RPRI*) to be monitored can be defined

$$RPRI = \sum_{i\in G_{Vm}} (Q_{i}^{\max} - Q_{i}) / \sum_{i\in G_{Vm}} Q_{i}^{\max} \tag{11}$$

where Q_{i}^{max} and Q_{i} are the maximal reactive power and the reactive power generation of the i^{th} generator respectively, and G_{Vm} is the set of key generators that transmit the reactive power to the weakest load bus.

5. On-Line Voltage Stability Assessment

Based on the power transmission paths analysis, the on-line VSA can be summarized as the following steps.

i) Getting the system information by power flow computation.
ii) Determining the weak buses by local voltage stability index.
iii) For the weak buses, the key power sources and the participant buses are decided by electrical distance. The weak reactive power and active transmission paths are determined.
iv) Calculating the *PVSI* of every weak power transmission path though its two-bus equivalent system and the weakest one can be decided.
v) Calculating the *RPRI* by the reactive power reserve of key generators.

The voltage instability can be caused either by an inability of power sources to produce enough power to supply a load bus or by inability of power transmission lines to transmit the required power to it. The index *VSI* and *RPRI* measure the voltage stability of the weakest power transmission path and the reactive power reserve of key generators respectively. Therefore, the voltage stability degree of the power system can be assessed correctly by the two indices.

6. Simulation Results

6.1 Shandong power system

The 500 kV backbone of Shandong power system in China is shown in Fig.3. The simulated Shandong power system with about 30 GW installed generating capacity is interconnected with North China power system through a double-circuit 500 kV transmission lines between Xin’an switch station and Liaocheng substation. The major units are coal-fired units of 300 MW and 600 MW. Large power needs to be transferred from the west to the east. The primary transmission interfaces are composed of three corridors. The northern corridor consists of the 500 kV Zibo-Weifang transmission line. The middle corridor consists of the 500 kV Zichuan-Qingzhou-Weifang transmission lines and the southern corridor consists of the 500 kV Tengzhou-Yimeng-Rizhao-Langya-Laoshan transmission lines.

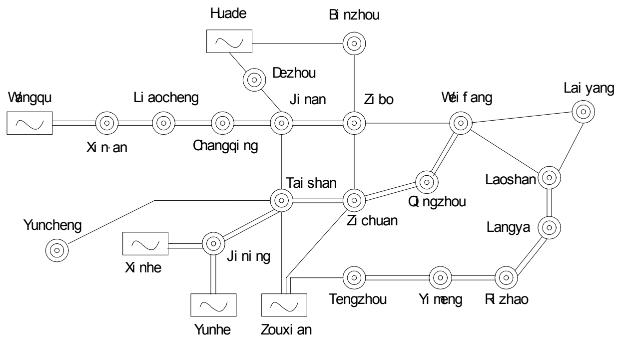

Fig. 3 The 500 kV structure of Shandong power system

6.2 Voltage stability assessment

The proposed method is tested on the Shandong power system. Under the typical operating condition, weak buses of Shandong power system are decided by local voltage stability index *L* as shown in Table I. The third column lists the area where each weak bus lies.

Table 1 Weak buses of Shandong power system

Index *L*	Weak bus	Area
0.299	Pingdu	Qingdao
0.299	Hushan	Qingdao
0.289	Yexian	Yanwei
0.274	Laixu	Yanwei

As seen from Table I, weak buses that are prone to voltage instability are primarily located in the east areas, such as Qingdao and Yanwei. In these areas, load increases rapidly, but the generation is of shortage. Therefore, large power needs to be transferred from the west areas and the ability of voltage support from the local generators is weak. The voltage security criteria of Shandong power system can be specially defined as follows. If the loads in Qingdao and Yanwei can be stressed 8% and reactive power reserves of key power sources are larger than 10% following credible contingencies, the operation point is voltage secure. Otherwise, the operation point is voltage insecure.

Voltage security limit is different with the generation-load transition pattern from the current operation point to the maximum point. The loads in Qingdao and Yanwei are supposed to increase according to a proportional increment, i.e., the active and reactive loads in the two areas are scaled up uniformly by the initial power factors. Considering the distribution of the major plants, the generators in the west areas are selected to scale up active generation uniformly. If the maximum output of one generator is reached, the redundant active load is allocated in other generators. Two patterns are adopted. For Pattern One, the generation in the northwest area is adjusted to match loads increasing and thus power flows of both the northern corridor and the middle corridor are affected mostly. For Pattern Two, the generators in the southwest area are scaled up with loads increasing and thus power flows of both the middle corridor and the southern corridor are affected mostly.

The outages of 220 kV and 500 kV transmission lines are considered as credible contingencies. Software VSAT is used to calculate the Mvar security limit and to rank these contingencies. Some results are shown in Table II. For each contingency, the corresponding MW security limit can also be calculated by combining the Mvar security limit with the power factor.

Table 2 Results of contingency ranking and security limit

Rank	Pattern One Contingency	Limit/Mvar	Pattern Two Contingency	Limit/Mvar
1	Tengzhou-Yimeng (TM)	2183	TM	2180
2	Zichuan-Qingzhou (ZQ)	2230	ZQ	2228
3	Zouxian-Tengzhou (ZT)	2319	ZT	2315
4	Laoshan-Jiaozhou (LJ)	2355	LJ	2353
5	Qingzhou-Weifang (QW)	2373	RL	2369
6	Rizhao-Langya (RL)	2378	QW	2373
7	Laiyang-Guliu(LG)	2391	LG	2383

In order to analyze the influence of line outage on the voltage stability of power transmission paths, the variation of the weakest path voltage stability index caused by each contingency is computed at the voltage security limit level. Some results are shown in Table III. The voltage stability index of the weakest path shows various degrees of decline for different contingencies. The larger the index variation is, the more critical the contingency becomes. Therefore, index variation caused by contingencies can be regarded as a contingency ranking index. The identity of the contingency ranking results between Table II and III demonstrates the validity of the proposed method.

Table 3 Variation of voltage stability index

Rank	Voltage Grade/kV	Pattern One Contingency	Variation	Pattern One Contingency	Variation
1	500	TM	0.075	TM	0.078
2	500	ZQ	0.048	ZQ	0.053
3	500	ZT	0.036	ZT	0.039
4	220	LJ	0.030	LJ	0.036
5	500	QW	0.028	RL	0.030
6	500	RL	0.027	QW	0.029
7	220	LG	0.024	LG	0.027

As seen from Table II and Table III, the seven most critical contingencies can be classified into two groups. One group of outage is located in the 500 kV network, such as TM, ZQ, ZT, QW and RL. The other is located in the east areas, such as LJ in Qingdao and LG in Yanwei. To analyze the factors that have great influence on voltage stability, three representative outage lines (TM, LJ and LG) from two groups are selected and Pattern Two is mainly investigated. For each contingency, supposing the line outage happens at the base load level and loads continue to increase to the maximum load. With load increasing, voltage stability indices of the weakest active and reactive power transmission paths (VSIp and VSIq) are computed, as shown in Fig. 4 and Fig. 5. The symbols N, M and S represent the weakest active power transmission path through the northern, middle and southern corridor, respectively. The RPRI is plotted in Fig. 6.

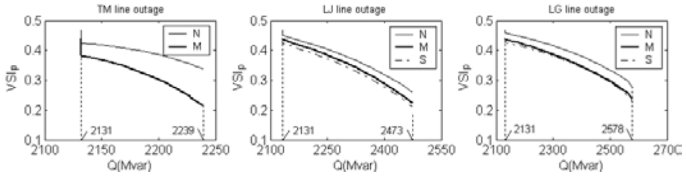

Fig. 4 VSIp curves

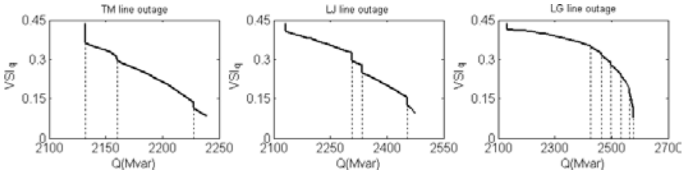

Fig. 5 VSIq curves

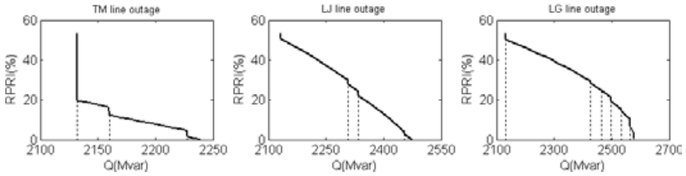

Fig. 6 RPRI curves

As shown in Fig. 4 and Fig. 5, index VSI_q is smaller than index VSI_p with loads increasing and index VSI_q is close to zero at the maximum load level. Therefore, the voltage stability can be assessed more objectively by the voltage stability of the weakest reactive power transmission path. As shown in Fig. 5 and Fig. 6, three sharp jumps of index VSI_q coincide with those of index RPRI during loads increasing. This is because three key generators reach their reactive limits respectively. It suggests that the reactive power reserve of key generators has great influence on voltage stability of the weakest power transmission path. Following the sharp decline of RPRI, its reactive limit is reached and the voltage support from the generator is lost. If the reactive power reserve of load areas is exhausted, remote generators must provide the needed reactive power to sustain the reactive power balance. However, this is inefficient or ineffective according to the transfer characteristic of reactive power. When the generation and transmission system can no longer support the loads and the reactive losses, voltage decay rapidly and voltage instability follows. The fact that index RPRI is close to zero at the maximum load illustrates the conclusion. Consequently, it is necessary for voltage stability assessment to combine path voltage stability index with reactive power reserve index.

7. Conclusion

Based on power transmission paths, a new method for on-line VSA is proposed. Differing from the Thevenin equivalence oriented the whole system, the calculation process of the method only require the information of weak power transmission paths. The local voltage stability index is used to determine weak buses. Based on the electrical distance, participant buses and key power sources of the reactive and active power transmission paths are decided. The weak power transmission paths are searched and the weakest one is computed through the equivalent systems. Reactive power reserve of key generators has an important influence on the voltage stability. So the voltage stability of the weakest power transmission path may decline or/and the weakest one may shift when some generators reach their limits. Combining the voltage stability index and the reactive power reserve of key generators in the process of voltage stability assessment, the simulation results of Shandong power system in China is satisfactory.

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