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Rapid Real-time Discrimination Method of Transient Voltage Sability Based on Wide-area Response

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Abstract. Quick identify of transient voltage stability of power system, which is based on real-time measurement information from wide-area measurement system (WAMS) is a hotspot issue of today's power engineering. This paper presents a method to early predict the transient voltage stability. The proposed technique uses disturbed voltage-time integral to construct the quantitative indicator which can achieve rapid real-time determination of transient voltage stability. In order to ensure the speed and accuracy of transient voltage stability determination, each of the key parameter variables in the integration method was set reasonably. The proposed method has been tested on a practical example of Guangdong power grid, the results verify that it can guarantee a high recognition accuracy rate while shortening the duration of determination.

1. Introduction

With the increasing of scale and complexity of power grid, especially the extensive use of induction motor load and the application of HVDC technology, the transient voltage stability problem becomes more and more prominent. Time-domain simulation based on accurate modeling is limited by network model, parameters and numerical algorithms, so that it is difficult to meet the requirement of on line transient voltage stability assessment in terms of scale, response speed and analysis means [1]. With the development of phasor measurement unit (PMU), wide area measurement system (WAMS) can synchronously monitor the state quantities such as power angle, phase angle, and generator potential, which makes it possible to realize real-time early warning of transient voltage instability based on disturbance trajectories[2].

The key to rapid identification of transient voltage stability is to find an evaluation index which should be fast, reliable and stable [3]. The voltage stability of the load bus can be judged by comparing the value of the load impedance in transient process with the Thevenin equivalent impedance value of the system at the load bus [4]. The difficulty of this criterion is to obtain the trajectory of the Thevenin equivalent impedance value, the amount of computation is great, especially for complex grids, and this method can easily lead to miscarriage of justice. Some studies have proposed a voltage drop rate - time composite integral method based on the interference voltage trajectory [5], it also has two drawbacks: 1) it will result in missed judgment when it occurs instability after disturbance, but the voltage fluctuation is small and the low voltage duration is long; 2) the proposed criterion often takes longer than 1 s, so it cannot leave more time margin for transient stability control.

In this paper, the interference voltage of each bus in regional power grid is studied, the disturbed voltage-time integral based on disturbance trajectory is combined with engineering experience to identify transient voltage stability, this method can obtain an on-line rapid transient voltage stability identification result within 1 second. Practical example of Guangdong power grid has been tested to demonstrate the effectiveness and fastness of the proposed method.

2. Disturbed voltage-time integration

At present, the frequently-used engineering experience criterion of transient voltage instability is that: if the voltage drop of the bus is lower than the limit value (usually 0.75p.u.), and the duration is longer than 1 s, the system or the load voltage is unstable [6]. From the point of view to avoid loss of load, this criterion uses low voltage level and low voltage duration that the load can bear as the criteria. The criterion takes longer than 1 s. It is not possible to reserve sufficient time for transient stability control, so that the emergency control is often too late after the voltage instability has been determined.

Based on the above analysis, this paper uses the integral area of low voltage amplitude and low voltage duration as the evaluation index of transient voltage stability, which can reduce the impact of single parameter errors on discrimination.

$$\begin{cases} S_i = \int_{t_0}^{t_{\text{end}}} \left(V_{\text{U}} - V_i(t)\right) \mathrm{d}t \\ V_i(t) < V_{\text{U}} \end{cases} \tag{1}$$

Where S_i represents the integrated area of the disturbed voltage trace of node i. V_{U} is the low voltage level, we take V_{U} = 0.8p.u. for Guangdong power grid after a lot of simulation, this empirical value can effectively prevents the fluctuations generated by small disturbances. $V_i(t)$ is the sampling voltage of node i at time t. t_0 and t_{end} represent the integration start time and end time respectively. The disturbed voltage-time integral of the bus i is shown in Figure 1, and the shaded area is the integrated area S_i.

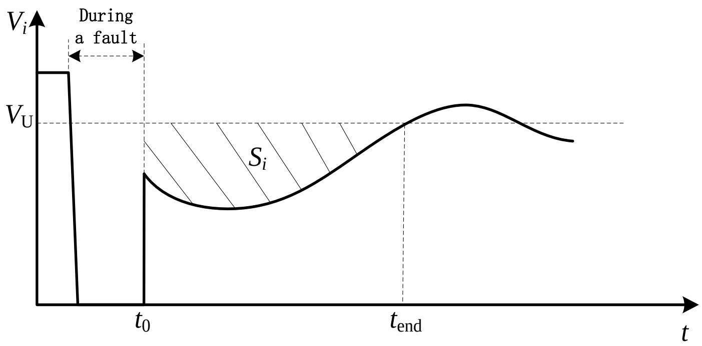

Figure 1. Integral map

The integration method uses low-voltage amplitude and its duration which are the most intuitive information for measuring the bus voltage level as two variables to construct transient voltage stability index. The disturbed voltage-time integral value is used as the evaluation index of transient voltage stability, and the bigger the integral value is, the worse the stability is, which can quantify the transient voltage stability of the system effectively. This integration method is about cumulative evaluation analysis of time domain information, compared with the micro-classification algorithm [7] and the transient energy function method [8], the method has lower requirement for measurement and communication, so it has stronger engineering practicability.

3. Determination of parameters

The common points of the above-mentioned integral algorithm and general-used engineering experience criterion are that they both take the low voltage value and its duration into account, however, the difference is the selection of each parameter. Only when the value of each parameter is reasonably selected can ensure the accuracy and fastness of the transient voltage stability recognition when using the integral method.

3.1. Integral start time

In the short-circuit fault cut-off time, the node voltage trajectory will be mutated. The voltage drop caused by the fault is mainly related to the distance from the fault point to the measuring point. The voltage recovery stage should be calculated from the time when the fault has been removed so that the system has the final network structure, therefore, the integral area during the fault can't be used as a quantitative indicator in this algorithm. Thence, the integral start time of the method is set to be at the time after the fault has cut off, that is, the time when the system network structure is finally formed. As shown in Figure 1, the integration start time t_0 isn't set at the time when the voltage locus falling to V_U, but selects the fault clearing time to start the integral calculation.

In order to identify the fault clearing time based on the disturbed voltage trajectory information provided by the real wide area measurement system, we define the voltage micro-variation as follows:

$$\Delta V_i(t)=V_i(t)-V_i(t-\Delta t) \tag{2}$$

Where, Δt is the sampling time interval. Figure 1 shows that the rapid decline voltage trajectory in the fault is mainly composed of the voltage drop stage and the zero voltage phase, the trajectory characteristics can be described by equation (3), (4). Therefore, if equation (3) or equation (4) is satisfied, the system is considered to be in fault, and the voltage trajectory fall suddenly changes so that we don't enter into the integral phase.

$$\begin{cases} \Delta V_i(t)<0 \\ \left|\dfrac{\Delta V_i(t)}{T}\right|>k \end{cases} \tag{3}$$

$$\begin{cases} \Delta V_i(t)=0 \\ V_i(t)=0 \end{cases} \tag{4}$$

In the formula, the constraint factor k is taken as 30, which is an empirical value.

3.2. Integral end time

Integral termination time t_{end} is a key parameters which determines the disturbed voltage-time integral value directly, the termination time is not only related to the validity of the criterion, but also to the effectiveness of the transient stability control measures. For this reason, t_{end} is determined by following method: based on the disturbed voltage - time integral area S_i obtained by the real-time measurement information, t_{end} is determined at the time when S_i is equal to the pre-set threshold value S_{SET}. If t reaches 1s, but S_i has not yet reached the S_{SET}, then we use engineering experience criteria to determine the voltage stability, that means t_{end} will not exceed 1s. For the determination of transient voltage stability after most disturbances, it can make the transient voltage stability judgment when t_{end} is far less than 1s, so as to reserve more time for transient stability control.

3.3. Transient Voltage Instability Threshold

A lot of simulation results show that: under the condition of critical stability and critical instability in the same type of fault, the integral value of the disturbed voltage trajectory is quite different due to the accumulative function of the integral algorithm. It is reasonable to set an instability threshold, so as to judge the transient voltage stability of the system effectively, meanwhile obtaining a good recognizability. Integral termination judgment is divided into two kinds of cases: deciding instability and determining stability. The instability criterion of this paper is:

$$\max \mathbf{S} > S_{SET} \tag{5}$$

Where $\boldsymbol{S}$ is a column vector composed of all voltage integration values(S_i).

Integral area threshold value S_{SET} is very important to the recognition accuracy of the proposed algorithm. In this paper, the disturbed voltage of each bus in the regional power grid is taken as the research object. The method of determining the instability threshold involves following steps:

a) The off-line simulation of disturbances at different lines is carried out to obtain the disturbed voltage response trajectory of fragile nodes in the critical instability state.

b) The instability degree of each fragile node is quantified by the disturbed voltage-time integration algorithm. According to the characteristics of the disturbed voltage trajectory in a given state which is most close to the critical instability state, an integral threshold value which can identify transient instability is set. In this paper, the minimum integral value of each weak bus' voltage trajectory at the critical instability state is taken as the threshold of transient voltage instability.

$$S_{SET} = \min\{S_1, S_2, S_3 \cdots S_i\} \tag{6}$$

When the structural characteristics or operating mode change greatly, it is necessary to perform the offline threshold setting calculations again.

4. Algorithm implementation flow

The proposed method integrates the advantages of disturbed voltage-time integration method and engineering experience criterion. When the low voltage level and the V_U have no much difference, the integrated area at 1 s after the fault may still less than S_{SET}. In this case, the interference voltage-time integral method cannot determine the instability, thus a missed sentence will happen. At this point, the empirical criteria can be used for judgments. In summary, the implementation process of the proposed method shows in Figure 2.

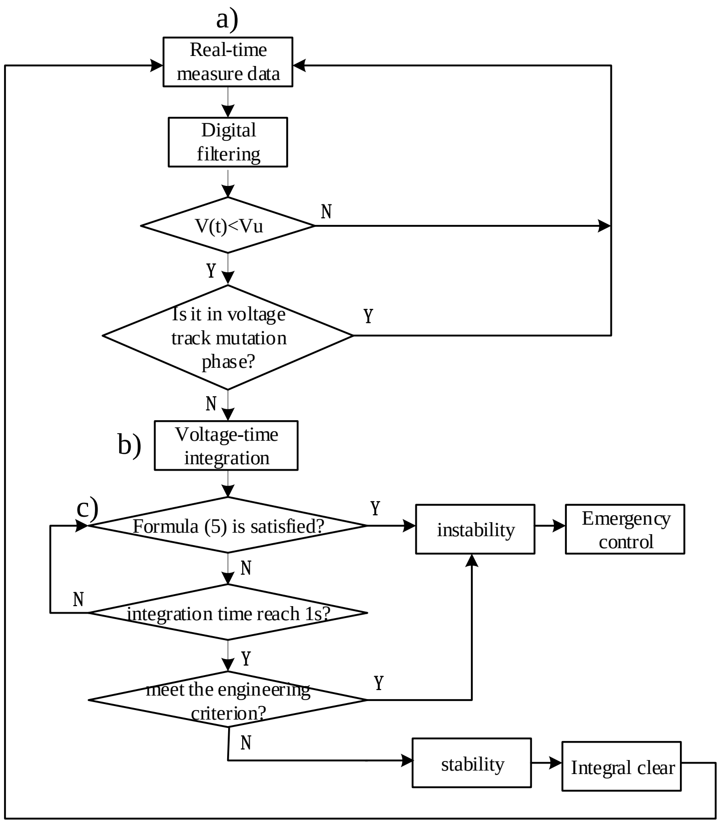

Figure 2. Transient voltage stability identification algorithm flow chart

The method of determining the system transient voltage stability using the above method involves following steps:

a) Obtain the voltage information of each node through the wide-area monitoring system, identify the fault process.

b) Calculate the disturbed voltage-time integral cumulatively.

c) If the integral value exceeds the threshold value, the integral calculation will be terminated and the transient voltage instability of the system will be judged, then enter to emergency control phase; If the integration time is longer than 1s, the transient voltage stability of the system will be judged according to the engineering experience criterion, then emergency control measures will be taken.

5. Case study

The actual system of Guangdong power grid was used to verify the effectiveness of the proposed method. The simulation data from power system analysis software BPA is used to simulate the measured information by WAMS. Taking the three-phase permanent N-1 fault as example, faulty lines include all 220kV transmission lines in Guangdong power grid, with a total number of 590, fault location is set at 2% and 98% of the line respectively, fault duration is 0.12s and the sampling interval is 0.02s. According to the transient voltage instability threshold setting method described above, the threshold for this type of fault is 19.1142pu • s.

All of the above 1180 faults were scanned by BPA simulation, among them, there were 68 transient voltage instability faults according to engineering experience criterion, and the remaining 1112 faults could maintain stable after fault removal. When the disturbed voltage-time integral discrimination was used, 1112 faults that originally maintain stable could be accurately classified as transient voltage stability, the integral areas of the other 68 faults which were voltage instability were plotted in Figure 3.

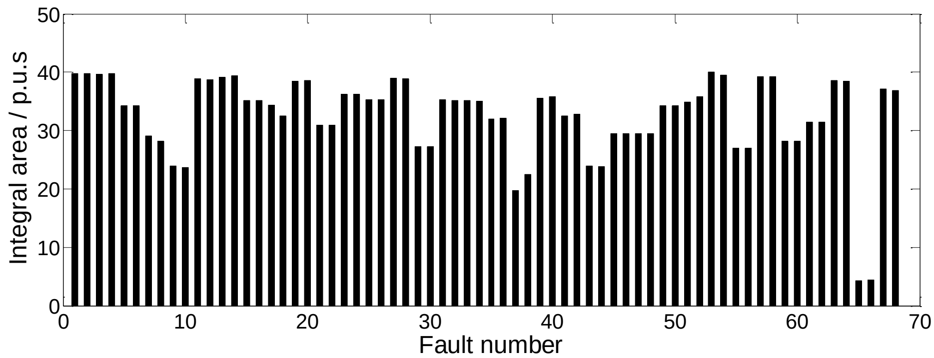

Figure 3. The result of voltage instability fault

As can be seen from Figure 3, the disturbed voltage-time integral areas of the vast majority of the 68 instability cases were greater than the threshold at 1s after the fault had been cleared, therefore, the proposed integral method could clearly determine the system transient voltage instability within 1 s. For the number 65 and number 66 fault, the integrated areas at 1s after fault clearing were 4.3220pu • s and 4.4288pu • s respectively, which means that the threshold value could not be reached and the proposed integral method was invalidated. In other words, for the three-phase permanent N-1 fault in this grid, using the integral method did not occur miscarriage of justice, but omitted some of the instability cases, the accuracy rate of discrimination could be 99.83%.

Number 65 and number 66 fault were further analyzed, the corresponding fault line was TIECHONB -ZHENZHOB line, points of failures was located at 2% and 98% of the line. At this time, the most serious instability bus was the TIECHONB bus, the voltage trace of this bus was shown in Figure 4.

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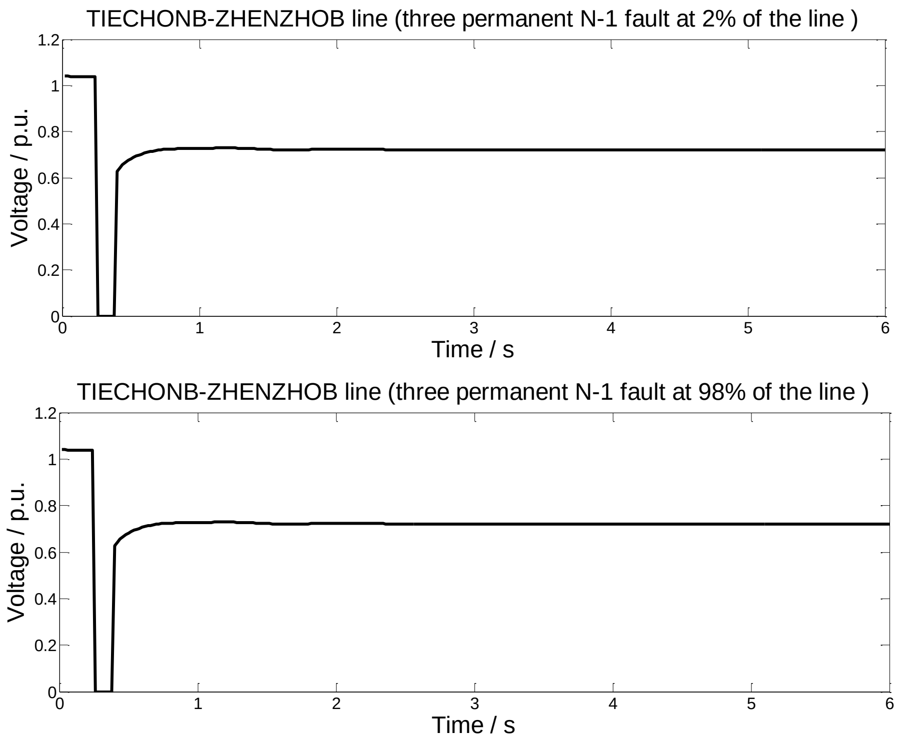

Figure 4. The voltage condition of the TIECHONB bus under No. 65,66 fault

It can be seen from Figure 4 that the reason why the proposed integral algorithm occurred leakage: the voltage dropped slowly but the duration was longer than 1s, the total integral area could not reach the instability threshold. According to the algorithm flow shown in Figure 2, when the integration time reached 1s and the area still did not reach the threshold value, the engineering experience criterion could be used. The voltage sag stage of bus TIECHONB continued 1s, therefore the system was judged voltage instability. In summary, if the bus voltage information of 1s after fault clearing is obtained, the traditional empirical criterion can be added to modify the missing case caused by the integral method, thus a higher judgment accuracy can be obtained.

The goal of transient voltage stability identification is to determine the steady state of the system as soon as possible so as to implement the transient stability emergency control quickly, which is conducive to the safe and stable operation of power grid. Figure 5 depicts the decision time length of the 68 voltage-instability faults using the proposed voltage-time integration method.

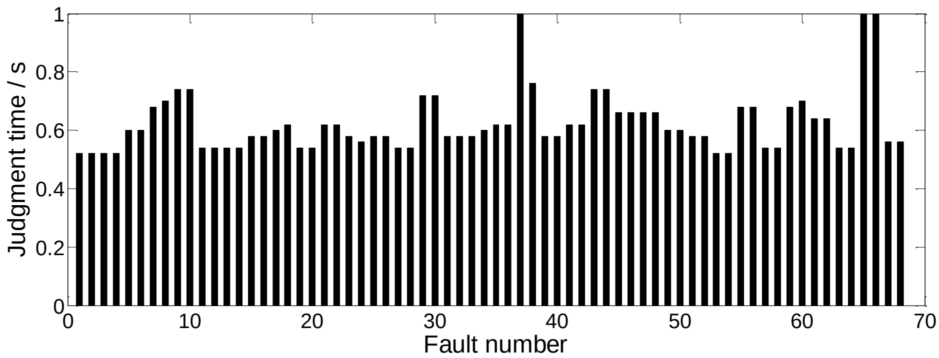

Figure 5. Voltage instability fault identification time

From Figure 5, it can be seen that the disturbed voltage-time integral areas of 65 faults exceeded the threshold value within 1s, then the voltage instability was determined. The time length of discrimination was 0.52s to 0.74s, and the average value was 0.6118s, but the time length of traditional engineering experience always expends 1s, therefore, the proposed method can shorten nearly half of the time compared with the experience criterion. Using the proposed method to identify the transient voltage stability can spare a valuable time for the implementation of transient voltage emergency control, it is better than the traditional empirical criterion from the time point of view. Furthermore, the secondary voltage emergency control and load shedding coordinated control strategy [9] can be used to implement the restoration.

6. Conclusion

In this paper, based on real-time measurement information from wide-area measurement system, the transient voltage stability of the system is evaluated by the combination of disturbed voltage-time integration and engineering experience criterion. The setting method of the three key parameters in this method are elaborated, namely, the starting point of integration, the ending time of integration, the threshold of instability, the realization flow of the algorithm is also listed. A case study of Guangdong power grid shows that: the proposed method can determine the transient voltage stability with high accuracy and short time-consuming, which can meet the requirement of transient stability control. It is suitable for large-scale power grid transient voltage stability discrimination and has good engineering application value.

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