ELEKTROTEHNIŠKI VESTNIK 87(3): 95-101, 2020
ORIGINAL SCIENTIFIC PAPER

Monitoring and Protection of Dynamic Angular Stability Based on Synchronized Measurements

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Abstract. The System Integrity Protection Scheme (SIPS) is a specialized protection scheme which differs to a great extent from the common protection, especially in its main intention. It is designed for integrity protection, failure prevention and mitigation of disturbance consequences in the whole power system (PS) or modern distribution system (MDS) with a significant power of distributed generation (DG). The input parameters for establishing SIPS in PS are synchronized phasor measurements obtained from the Phasor Measurement Units (PMUs), as a globally acknowledged Smart Grid technology. The realization requires that SIPS is added to the existing Wide Area Monitoring, Protection and Control (WAMPAC), based on synchronized measurements. This paper proposes an algorithm that anticipates optimal PMU placement and then uses angular stability protection based on traditional IEDs supported by synchronized measurements. By using such approach, the system avoids possible blackouts due to the combined operation of the traditional protection and WAMPAC. The proposed SIPS system is tested on specific area in the Croatian transmission system integrating hydro power and wind energy converting power plants. Due to the increased power of renewable energy sources (RES), the proposed algorithm is applicable to modern distribution systems.

Keywords: Power System Angular Stability, System Integrity Protection Schemes, Wide Area Monitoring, Protection And Control, Phasor Measurement Unit

Spremljanje in zaščita dinamične kotne stabilnosti na podlagi sinhroniziranih meritev

Povzetek. Shema zaščite integritete sistema (SIPS) je specializirana zaščitna shema, ki se v veliki meri razlikuje od skupne zaščite, zlasti v svojem glavnem namenu. Zasnovan je za zaščito integritete, preprečevanje okvar in zmanjšanje posledic motenj v celotnem elektroenergetskem sistemu (PS) ali sodobnem distribucijskem sistemu (MDS) z veliko močjo porazdeljene proizvodnje (GD). Vhodni parametri za vzpostavitev SIPS v PS so sinhronizirane meritve fazorja, pridobljene iz merilnih enot fazorjev (PMU), kot svetovno priznana tehnologija Smart Grid. Izvedba zahteva, da se SIPS doda obstoječemu nadzoru, zaščiti in nadzoru širokega območja (WAMPAC), ki temelji na sinhroniziranih meritvah. V tem prispevku je poudarek na algoritmu, ki predvideva optimalno namestitev PMU, nato pa uporabi kotno zaščito stabilnosti, ki temelji na tradicionalnih IED-jih, podprtih s sinhroniziranimi meritvami. S takim pristopom se zaradi velikih motenj v (PS) sistem lahko izogne morebitnim izpadom zaradi združevanja tradicionalne zaščite in WAMPAC. Predlagani sistem SIPS je preizkušen na specifičnem območju hrvaškega prenosnega sistema, ki je mešanica hidroelektrarn in vetrnih elektrarn. Predlagani algoritem je zaradi povečane moči obnovljivih virov energije (OVE) uporaben za sodobne distribucijske sisteme.

Ključne besede: Kotna stabilnost elektroenergetskega sistema, zaščitne sheme integritete sistema, spremljanje širokega območja, zaščita in nadzor, merilna enota fazorjev

1 INTRODUCTION

The abnormal PS operating states, such as significant power oscillations or failures which disturb the PS power balance, may cause the rotating masses in generators to oscillate which results in a power swing.

If a part of PS becomes unstable, then all PS generators try to maintain the PS stability. When oscillations are damped, the PS stability is maintained, while in an instability state, the oscillations increase resulting in a loss of synchronism between generators. In these states, the machine excitation stands still, but powerful oscillations of the active and reactive power are still present. The described phenomena result in the change in the voltage angle in certain PS nodes.

Although modern PSs are designed to operate with a great degree of safety in terms of the power swing, these instances are particularly prominent at PS failures and abnormal operating states. The rotating mass oscillations negatively affect generators and other equipment as a result of exceeded mechanical loads.

Received 26 September 2019
Accepted 24 January 2020

The currently available angular stability protection devices use microprocessors, enabling PS power swing protection with a static adjustment of limit values.

Synchronized measurements, which today represent a common tool for monitoring, protection and control of PSs (WAMPAC – Wide Area Monitoring, Protection and Control) enable the monitoring of the PS angular stability in real time, i.e. recognizing the disturbance of the angular stability (calculation of the angular stability limit values in real time). Besides monitoring the angular stability, synchronized measurements enable the installation of an adaptive protection system to operate at a PS synchronism loss (power swing) in real time. It achieves a better selectivity of the power swing protection by splitting PS into power homogenous entities. Such adaptive protection is called System Integrity Protection Scheme – SIPS [1], which is this topic of this paper.

PS monitoring in real time is based on the data obtained by synchronized measuring devices installed at the most important nodes. The data generated by the Phasor Measurement Units (PMUs) are transferred to the Dispatch Centre, to provide an insight into the PS state in real time.

In order to realize SIPS, a series of functionalities should be developed in the area of the PS protective and control functions. This enables a timely retroactive effect on a part of the system or the system as a whole in order to protect its stability and integrity by activating the system protection functions.

The paper presents a conceptual design for a new functionality, i.e. monitoring the PS angular stability [2]. It proposes an algorithm for creating a software support to be used with the existing Wide Area Monitoring Protection and Control system (WAMPAC). The solution is based on synchronized measurements performed by PMU.

2 TRANSIENT STABILITY – DYNAMIC STABILITY

The dynamic stability is critical when the change in the load value is extremely fast:

$$\frac{\Delta P}{\Delta t} \rightarrow \infty \tag{1}$$

The relation (1) can be achieved in two ways:

1. Changing the PS state is considerable, but takes a certain time.

2. The PS state change is considerable and occurs in a very short time, with its duration tending towards zero.

For the dynamic stability, rapid changes in the synchronous machines' load value are critical as they appear in the form of a shock. The most dangerous is the shock caused by a short circuit or unforeseen switching off individual PS elements of. Fast changes in the load value cause machine swinging (shifting the generator rotor together with the mechanically coupled mass oppositely to the reference stator rotating field). The generator rotors in the system shift differently and when at their mutual disruption, the dynamic stability is lost [3-4].

2.1 *Dynamic stability of one generator connected to PS*

When considering the problem of the PS transient stability, the load angle is assumed to be δ. Because of the magnitude of the rotor mass, it cannot be altered immediately. The same applies to the magnetic field determined by rotor electro-motor force E_0. The reactance of the PS elements is assumed to be zero. For a load change, the transient stability equation is obtained by using the effective value of transient rotor E_0' in the phase diagram instead of the effective value of rotor E_0 and if instead of generator synchronous reactance X_d transient synchronous reactance X_d' is used. The initial reactance is not accounted for because its duration is only a few hundredths of a second [5-7]. The equation of the generator transient stability is described by (2):

$$P_{PS} = \frac{E_0{}' \cdot U_k}{X} \cdot \sin \delta_{uk} \tag{2}$$

where:
U_K – power system voltage in point K,
δ_{uk} – total load angle (angle between phasors E_{0f} and U_{Kf})
X – overall reactance of the transfer system,
($X_{dv} = X_d + X_V$),
X_d' – transient synchronous reactance,
X_v – equivalent line reactance.

The angle curve is represented by a sinusoid and the the synchronous machine power takes the horizontal direction. The electrical power provided by the generator to PS is defined by (2) which contains transient rotor E, voltage network U_K, total reactance between the generator clamp and the PS bus, and sinus of the total load angle between the voltage network and transient rotors E. At a given moment, there is a certain power of synchronous machine P_m and at the moment of a shock the synchronous machine controller is assumed not to work. Let the PS operating state before the disturbance be determined by point A_1 and angle δ_1 according to Fig. 1.

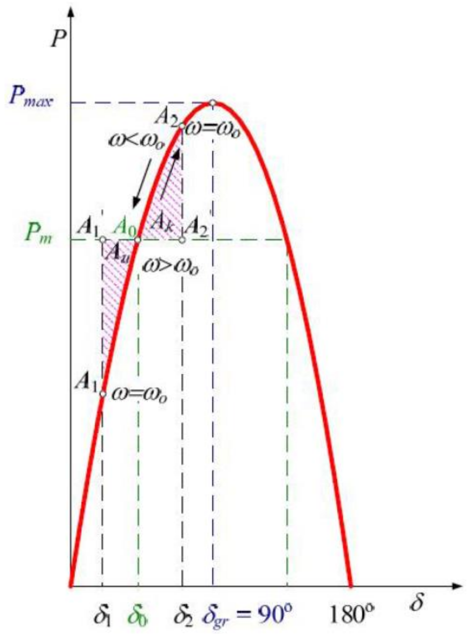

Figure 1. Description of the power system angle stability.

If a disturbance decreases the electric power value, there is a difference in the mechanical and electrical power which has a positive sign and affects the generator rotor acceleration. The angular acceleration in proportional to length A_1A_1'. By accelerating the rotor, the load angle increases (from δ_1 to δ_0) and so does the power generator. The acceleration power decreases, and at point A_0, it is zero. At point A_0, the angular acceleration is zero, but the angular velocity is greater than the synchronous ($\omega>\omega_0$) and the rotor is still accelerated, in that case it is $\delta>\delta_0$. The acceleration power becomes negative and slows down the rotor.

The work performed by the positive acceleration power ($P_a>0$) is an equivalent of the kinetic energy collected by the synchronous machine masses and is proportional to A_u. The collected kinetic energy is consumed by the rotor at the slowdown and in point A_2 all the kinetic energy is consumed and the angular velocity of the rotor equals the synchronous velocity ($\omega=\omega_0$) [7-8]. The rotor swings to angle δ_2. A_k is proportional to the rotor energy consumed at slowing down. Angle δ_2 of the generator rotor swing is determined from the state of equal surfaces: $A_u=A_k$.

At point A_2, the rotor angular velocity equals the synchronous speed, and because of the acceleration force sign at that point, the load angle decreases to δ_0. At point A_0, a balance between the mechanical and electrical power is reached, but the angular velocity is less than the synchronous ($\omega<\omega_0$) and due to its torque, the rotor continues to slowdown to point A_1, provided the system is loss-free. For a loss-free system, the generator rotor swings between points A_1 and A_2. Since no system is loss-free, after a certain time, the rotor calms down at point A_0. The time-dependence of the load angle is called the synchronous machine swing curve [9-10].

The stability is preserved irrespective of the value that reaches angle δ or its variations over the time. It is sufficient to analyse the previous state of equal surfaces. The transient stability limit is achieved when the acceleration surface equals the retardation surface. If the acceleration surface is less proportional than the proportional deceleration surface, the transient stability is maintained, otherwise the synchronism or transient stability will be lost.

The time period of interest for transient stability studies is usually in the range from 3 to 5 seconds after the start of a disturbance. It can be extended up to 10 seconds for very large systems with a dominant internal angular distortion. The transient instability in a system is caused by a major disturbance, the most significant being failures in heavily loaded lines, most often causing their disconnection due to a failure. An outage of heavily loaded generators, a sudden shutdown or a drop in a high load can also cause instability. A disturbance, at least temporary, introduces changes in the system, so the next state differs from the one before the disturbance. It is important, that a new state of a changed system is stable. There is a possibility that a changed system is dynamically unstable meaning the oscillations increase to the point of the system blackout.

2.2 *Monitoring and protection algorithm of the power system dynamic angular stability*

Using synchronized measurements, which today represent a common monitoring tool, enables real-time monitoring the PS angular stability, i.e. instability recognizing the disturbance giving rise to an angular instability [11, 12] (calculation of the angular stability limit values in the real time described above).

For the line angular stability, it is necessary to substitute all generators on both sides of the monitored line by two generators. Two groups of coherent generators may be identified on the basis of synchronized measurements of voltage phasors and by comparing the angles [13, 14].

Fig. 2 shows a scheme for the PS angular stability monitoring. Generators $G_{(n)}$ and $G_{(n+1)}$ are substituted generators on both sides of the line in nodes n and n+1. The central controller is a computer equipment with an installed application for WAMPAC and an additional software module for Power Swing Monitoring and Protection. The central controller collects the data from the synchronized phasor measurements with the time sampling interval of 0.02 s. The processed measurements are transferred to the Power Swing Monitoring and Protection module and after the implementation of the algorithm (Fig. 3), the obtained results are displayed on the operator console. When an abnormal operating situation is detected, a faulty line is disconnected. The time it takes for the angular stability module to act is 1 s.

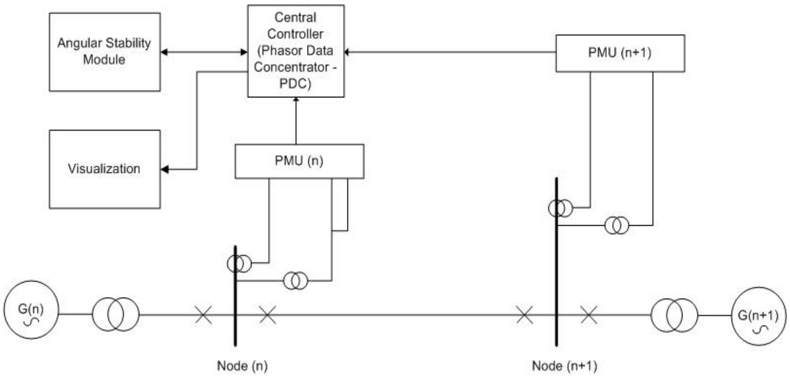

Figure 2. Scheme of the PS angular stability monitoring and protection.

2.3 *Description of the Monitoring and Protection Algorithm of Angular Dynamic Stability*

The important steps of the algorithm shown in Fig.3 for the power swing monitoring and protection module are:

- PS is assumed to be stable in the initial stage, so the value t=0 is given. The power in the observed line is constant, so the difference in angles between the nodes (n) and (n+1) is also constant. The constant values are determined by analyzing the PS stability on a dynamic mathematical model.
- The central controller collects and processes the synchronized phasor measurements and transfers them to the angular stability module.
- The initial values of the angle differences calculated and stored in the previous calculating interval are given.
- The voltage angle difference between the observed line nodes is calculated.
- The load flow on the observed line is calculated.
- The calculated values in the current calculating interval are stored.
- The voltage angle difference between the neighboring nodes is compared with a default (given) value.
- If the angle difference is greater than the default value, it is possible that there is an angular instability on the observed line.
- If the angle difference is less than the default value, there is no angular instability.
- The increase in the angle difference and operating power oscillation is analyzed.
- At an increase in the angle difference, and when the power oscillates, the “Equal Area Calculation” is made to determine whether there is an angular instability on the observed line.
- In case of a PS transient disturbance, the operator gets a warning message.
- The “Equal Area Calculation” is given in Fig. 2.
- If the “Equal Area Calculation” shows an angular instability, the operator is alarmed to disconnect the line.

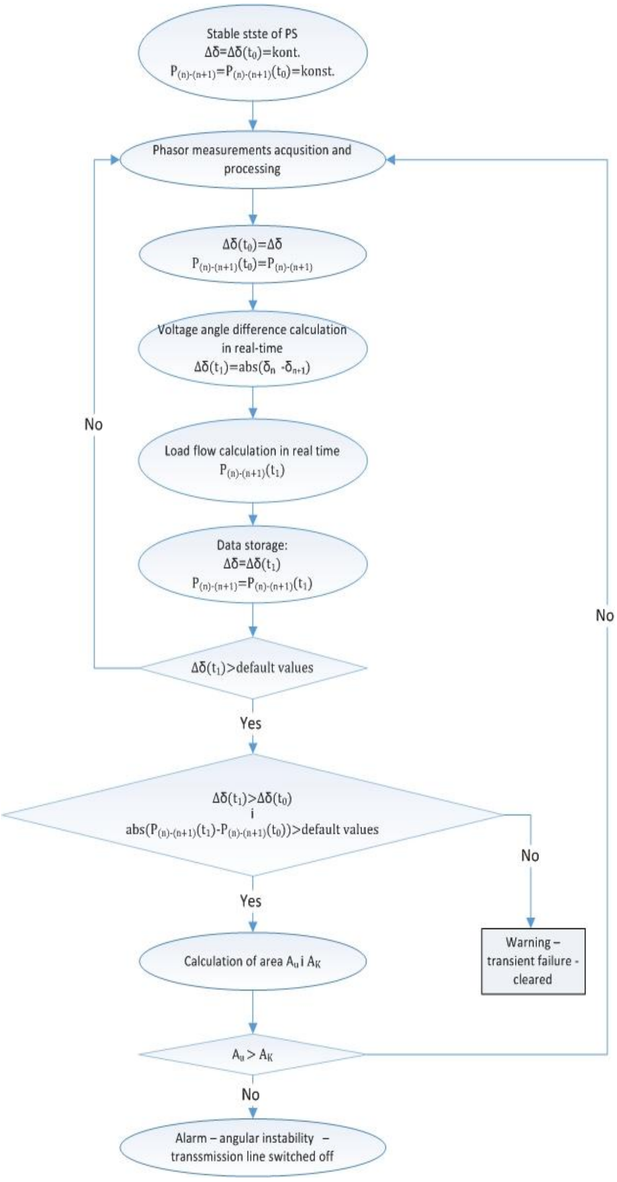

Figure 3. Monitoring and protection of a power swing instability chart-flow.

3 CASE STUDY

The analysis of a of the Croatian costal PS in the vicinity of Krk the transformer station (TS) is made using a dynamic mathematical model of the Croatian power system (transmission voltage levels: 400 kV, 220 kV and 110 kV, see Fig. 4).

The N-1 analysis in the vicinity of Krk TS is conducted by analysing the angular differences between certain nodes. After that, N-1 is analyzed assuming the Krk – Crikvenica 110 kV line is disconnected.

Specific operating states are also analyzed in order to identify scenarios causing significant deviations of the voltage angle and a possible work of the syncro-check function in protective relays. Several dozens of abnormal operating states are analysed and the following characteristic operating states are identified:

- minimal load in the vicinity of Krk TS (islands and coastal area) and at the Krk TS
- maximal generation of the hydro power and wind power plants in a wider coastal area.

Scenario 1:

- disconnected 400 kV Melina-Velebit line
- disconnected 110 kV Krk-Dunat line

Scenario 2:

- disconnected 400 kV Melina-Velebit line
- disconnected 110 kV Krk-Melina line

Scenario 3:

- connected 400 kV Melina-Velebit line
- disconnected 110 kV Krk-Dunat line

Scenario 4:

- connected 400 kV Melina-Velebit line
- disconnected 110 kV Krk-Melina line

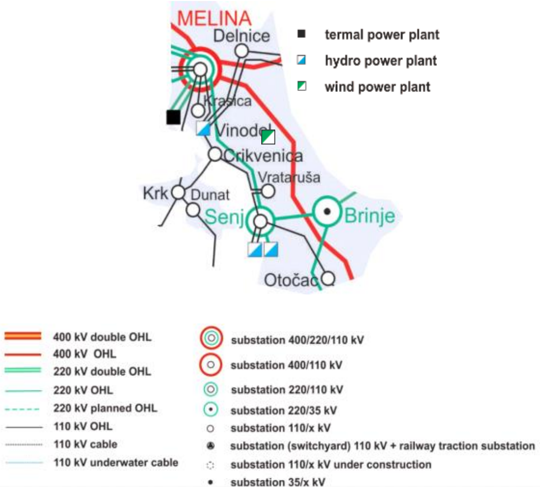

Figure 4. Analysed part of the Croatian power transmission system.

Responses to physical values obtained by using the PSS/E software package in which simulations of the identified operating states are conducted, are given below. The angular differences between the observed nodes are singled out in accordance with the mentioned scenarios. Fig. 5 shows the most significant scenario that emphasizes the angle difference between two neighbouring nodes of a faulted transmission line (Scenario 2).

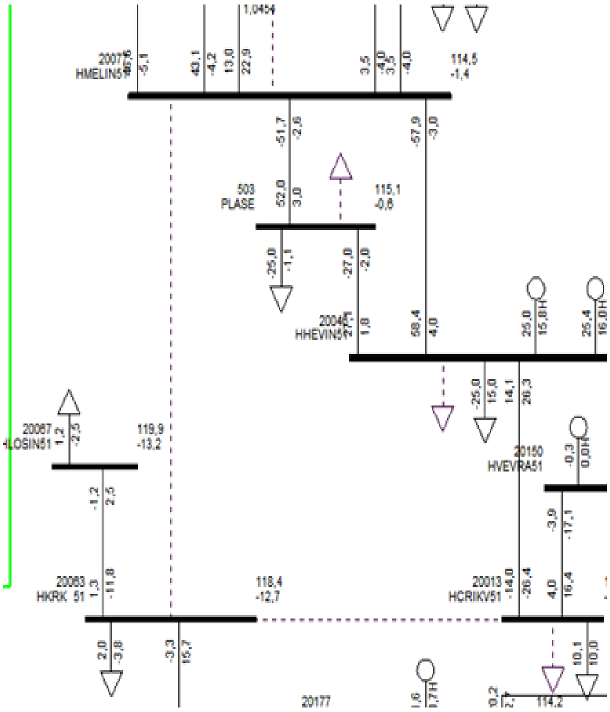

Figure 5. Angle difference between the 110 kV nodes according to Scenario 2.

Table 1 shows the values of the voltage amplitude and voltage angle between the observed nodes obtained by using the scenarios.

Table 1: Characteristic values of the voltage amplitude and angle between the neighbouring nodes

Scenario:	1	2	3	4
Voltage amp. of TS Krk [kV]	115.8	118.4	116.6	125.7
Voltage angle of TS Krk [°]	-1.8	-12.7	-1.7	-7.4
Voltage amp. of TS Melina [kV]	-	114.5	-	114.8
Voltage angle of TS Melina [°]	-	-1.4	-	-1.2
Voltage amp. of TS Dunat [kV]	111.9	-	120.4	-
Voltage angle of TS Dunat [°]	-11.3	-	-5.7	-
Difference of voltage amp. [kV]	3.8	3.9	3.8	10.9
Difference of voltage angle [°]	9.5	11.3	4	6.2

The analyses conducted according to the identified characteristic scenarios are of a theoretical nature. A System Integrity Protection Scheme (SIPS) is proposed for the power swing protection of the costal part of the Croatian PS. During the test period, portable PMU devices are used, until the SIPS scheme is confirmed. Fig. 6 shows the nodes for which the PMUs installation is suggested.

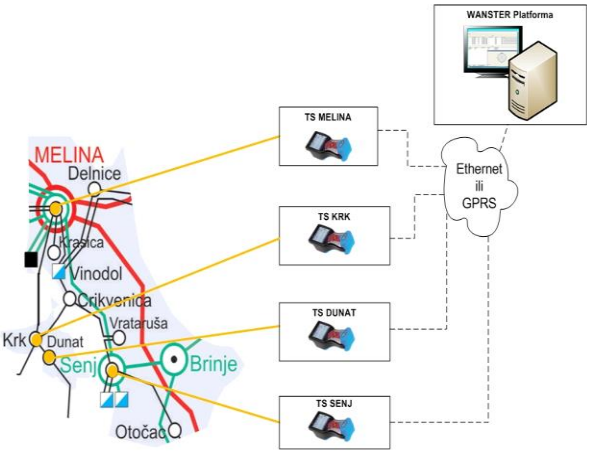

Figure 6. SIPS solution of the angular stability monitoring and protection.

4 DISCUSSION

Using the proposed algorithm reveal the real-time angular state of a wide area of a power system. Following the real time refreshed results, the system stability is maintained by keeping critical power transmission lines in operation, unlike is the case with the traditional local protection where several transmission lines are disconnected due to the voltage angle difference (following a disturbance) and therefore jeopardize the power system stability. A method is presented for a fast and accurate dynamic angular stability monitoring and protection based on synchronized measurement results. In our future work, the proposed method will be implemented on the existing commercial Wide Area Monitoring, Protection and Control (WAMPAC) platform used in the power transmission system as well as on the Supervisory Control and Data Acquisition (SCADA) platform used in the distribution power system.

5 CONCLUSION

The paper proposes a conceptual design of an angular stability monitoring and protection on the basis of synchronized measurement results, as a part of the system integrity protection scheme for large power systems. The suggested solution includes a theoretical background which provides the basis for designing an algorithm for the angular stability monitoring and early detection of the power system angular stability disturbances. The algorithm is a new functionality of the Wide Area Monitoring Protection and Control – WAMPAC system and represents the basis for a software support.

The analysis of the dynamic states is conducted in a part of the Croatian PS, operating on the 110 kV, 220 kV and 400 kV voltage levels, on which there have been incidences of deviations in the voltage angle and amplitude between certain nodes. For that purpose, it is suggested to install PMUs at particular nodes according to the proposed angular stability protection method.

So far the method has been applied on the power transmission system. Due to the increased demand of distributed power generation and double power flow between the transmission and distribution network, the method can be used also for modern power distribution systems. Parts of the power distribution system with a considerable distributed power generation can be anticipated as a virtual power generator in terms of the power transmission for which the proposed PS integrity protection method is an appropriate solution.

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