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The composite fuzzy reliability index of power systems

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ABSTRACT

This paper describes a method for fuzzy calculation of power system reliability. It introduces a composite fuzzy security and fuzzy adequacy indices encompassing the power system segments of generation, transmission, and the segment of load nodes. The fuzzy security index is determined by the security membership grades of the power system components which are found to be the worst in their segments. The fuzzy adequacy index is based on the adequacy indices of generation, transmission, and transmission integration segments. The composite fuzzy reliability index enables the system operator to have a continuous insight into the distance between the power system's actual state and the closest unreliable state by tracking the system's components with the lowest security and adequacy membership grades of the respective segments. The algorithm has been tested on the models of the IEEE Three Area RTS-96 and Bosnia–Herzegovina power systems.

1. Introduction

During the power system operation, it is difficult to determine its reliability level due to its dynamic nature. The reliability level could be expressed as the distance between the system's actual state and the closest unreliable state. When the power system is at the lowest reliability level, an outage or a component failure may lead to either a complete system outage or a partial outage reducing its security and adequacy. For the entire system, one must consider two reliability factors: security, which depends on the system's transient performance and adequacy, which depends on the available generation and transmission capacity covering operating reserve needs (Porretta et al., 1991).

Numerous reports investigate the system security, adequacy, and reliability aspects of the power system operation. The security-oriented reports are mainly focusing on voltage security aspects, using the neural networks (Liu et al., 1998; Jensen et al., 2001) and simulation procedures such as particle swarm method, multi-agent concept, and Monte Carlo sequential simulation (Yoshida et al., 2000; Jung et al., 2002; Rios et al., 1999). Some of them investigate high flows and low voltages security aspects using the probabilistic approach (Wam et al., 2000).

The reports investigating the adequacy issues are focusing on the power system robustness to withstand planned and unplanned outages, considering the generation and transmission capacities and their respective reserves. In the reports, generation adequacy and transmission network adequacy are assessed independently one of another (Billinton and Gan, 1991; ISO New England Inc., 2008) or jointly as composite power system adequacy (Goel and Low, 2002), using the deterministic and probabilistic techniques. After the dramatic transmission network cascading events in the year of 2003, the UCTE has done several investigations on the UCTE system adequacy (UCTE Annual Reports) considering the generation and transmission network adequacy in the context of the European power market and electric power interchange between UCTE zones. The *UCTE System Adequacy Subgroup* published the UCTE System Adequacy Forecast 2009–2020 (UCTE, 2009). For the period from 2015 to 2020, this document identified the tightening situation with respect to the generating capacity with the remaining capacity decreasing drastically and the adequacy reference margin that cannot be respected. After 2015, additional investments in generating capacity are required to maintain the level of adequacy at an appropriate level in the UCTE grid.

To determine the reliability level of the power system, different approaches have been applied. Some of them aim to detect the critical states by screening a set of contingencies and mark those which behave subversively. These approaches are able to estimate the state in which a system could face a failure rather precisely. The North American Reliability Association (NERC) has developed the acceptable reliability standards of the bulk power system in North America (NERC Board of Trustees, 2008), similar to the role of the European Network of Transmission System Operators for Electricity (ENTSO-E). A series of the operation handbooks has been published by ENTSO-E taking into account some reliability aspects based on the risk assessment philosophy

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(UCTE OH—Policy 3, 2009). However, there is still no efficient method of recognizing the imminent onset of the unreliable operating state.

The fuzzy approach to the power system reliability level estimation proposed in this paper considers a power system current state with respect to the power system's predefined fuzzy component limits. The result of this research can be viewed as twofold, comprising a static and a quasi dynamic state estimator with respect to the power system reliability. The static estimator is used for scheduling a normal operating regime, while the dynamic one could be applied in a contingency case. The proposed approach allows for combined insight about security and adequacy aspect of a power system state.

The paper is organized as follows. Fuzzy rendering of power system operation and the proposed algorithms are presented in Section 2, in which a composite fuzzy security, adequacy, and reliability indices are described along with the appropriate algorithms for their calculation. In Section 3, the power system variables are represented via fuzzy numbers in the proposed security framework composed of three segments: generation segment, transmission segment, and segment of nodes. Section 4 discusses the power system operation variables in the proposed adequacy framework, represented via fuzzy numbers. Two test systems, IEEE Three Area RTS-96 and Bosnian power system are used in Section 5 to verify the feasibility of the proposed approach. Conclusions are drawn in Section 6. Finally, Appendix presents data on Bosnian power system used in purpose of calculation.

2. Fuzzy rendering of power system operation and proposed algorithms

For the complex power system operation, a soft approach is used to present the interaction of the system components and segments. The fuzzy power system reliability level is calculated on the bases of the fuzzy security and adequacy levels. First the fuzzy security level is calculated (Halilčević et al., 2010). Each power system segment is characterized by the smallest security membership grade (SMG) of its components. Each power system segment dictates its own security level and correspondingly affects the power system global security level. The fuzzy power system adequacy level is presented through the fuzzy adequacy indices, such as the adequacy of the generation capacity, transmission capacity, and transmission integration. This approach allows one to calculate a joint fuzzy level of the power system security, adequacy, and reliability using the composite fuzzy security index (CFSI), composite fuzzy adequacy index (CFAI), and composite fuzzy reliability index (CFRI).

The binary mapping is used in aggregation of the relevant security membership grades (SMGs) of the segment components to find the smallest SMG of each of the system segments. The binary mapping is based on the binary operator T (Nguyen and Kreinovich, 1998; Baldwin, 1996). By means of the Larsen implication rule (Larsen, 1980) the smallest SMGs are multiplied with each other to find CFSI. The same implication rule is used in aggregating the adequacy membership grades (AMGs) of the system adequacy segments in the phase of CFAI calculation. CFRI is found out by multiplying the given CFSI and CFAI with each other.

The approach makes use of an adapted Bellman–Zadeh model. If $S=\{s_i\}$ is a set of possible power system operating states, then a fuzzy reliable operating state is defined as a fuzzy set in S, characterized by its reliability membership grade $\mu_{(ri)}: S\rightarrow[0,1]$. Here $\mu_{(ri)}(s_i)$ specifies the grade of membership in a continuous domain of a particular level $s_i\in S$ regarding limits of the system components and the installed generation and transmission capacities.

2.1. A composite fuzzy security index

For a power system segment in the current power system operation state $s_i\in S$, the fuzzy security level of an operating state s_i can be expressed as (1) where the fuzzy operator $\wedge$ of the right-hand side of (1) represents the minimum of the relevant component SMGs

$$\mu_{pss}(s_i)=\mu_1\wedge\ldots\wedge\mu_i\wedge\ldots\wedge\mu_n \qquad (1)$$

where S is the set of the power system operating states, μ_i the SMG of ith component consists of the considered power system segment, and $\mu_{pss}(s_i)$ is the SMG of power system segment (pss).

The transmission segment SMG may refer to the allowable load limit parameter describing loading on an ith physical power system component taking into account power system operating state s_i.

The CFSI is a function of the states that the power system segments pass through, exerting an influence upon the security state of a whole power system. The security level is expressed as a distance between a current and the most imminent of the warning operating states, which is characterized by CFSI=0. It may warn the system operator to undertake adequate corrective actions, i.e. increase the power reserve given the SMG of generation segment $\mu_{gs}=0$; to prevent a transmission line outage due to possible loading increase given the SMG of transmission segment $\mu_{tr}=0$; or voltage collapse of a node given the SMG of segment of nodes $\mu_{ns}=0$. Namely, the consequences of a power system operation in the operating state marked by CFSI=0 can be severe.

CFSI is set up as an aggregation of the power system segments SMGs in the operating state s_i through the fuzzy intersection operator

$$CFSI=\mu_{agg}(s_i)=\prod_{pss}\mu_{pss}=\mu_{gs}\cdot\mu_{ts}\cdot\mu_{ns} \qquad (2)$$

where pss is a power system segment, as presented in Fig. 1, and μ_{pss} the minimum value of SMG of the generation segment, transmission segment, and segment of nodes with respect to the security.

The product of the three segment membership functions is formed by Larsen implication rule (3), which produces a new fuzzy set with a membership function $\mu_{agg}(s_i)$. It implies the following product operation:

$$R=A\times B\times C=\int_{X\times Y\times Z}\mu_A(x)\cdot\mu_B(y)\cdot\mu_C(z)/(x,y,z) \qquad (3)$$

where "$\cdot$" is the algebraic product operator, and $\mu_A(x)$, $\mu_B(y)$, and

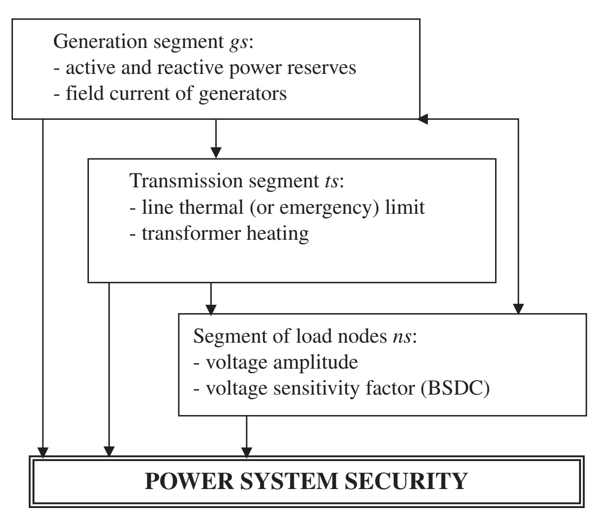

Fig. 1. Interaction of the power system's security segments.