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Experimental design for a large power system vulnerability estimation

Fredy A. Sanz [a,*], Juan M. Ramírez [b], Rosa E. Correa [c]

[a] IUSH, Medellín, Colombia
[b] CINVESTAV, Unidad Guadalajara, Mexico
[c] Universidad Nacional de Colombia, Sede Medellín, Colombia

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ABSTRACT

This paper proposes a reliable experiment design for large power system vulnerability estimation. Assuming that in most cases security problems result in voltage instabilities, a strategy that allows a voltage collapse proximity estimation, known as vulnerability, is proposed. The premise is that power flow calculation is not required for vulnerability estimation, requiring only the bus voltage measurements; the approach is a promising tool for on-line implementation. The result is a model based on statistical techniques that analyze databases previously built, that contains voltage profiles for different contingencies and the corresponding calculated value for the Voltage Collapse Proximity Index (*VCPI*).

1. Introduction

The vulnerable system concept means that it operates with a reduced level of security that renders it vulnerable to small changes in electrical variables (load, generation, or moderate disturbances). In this definition, notice that it is weird that a major system failure is the result of one catastrophic disturbance [1,2]. Power system stability implicates the system evolution when a disturbance evolves into a change in the operating point. Although small changes in electrical variables do cause alterations in system performance and can be studied as small signal security, system security is generally concerned with large changes, which are known as contingencies [3]. Although the vulnerability concept may be broad, in this research the vulnerability concept involves the system security level and the tendency of changing its conditions to a critical state that is called the “Verge of Collapse State” [2,4].

The on-line power grid monitoring for maintaining voltage stability is highly important for a reliable power system operation. Inadequate voltage support was a contributing factor in several major blackouts in North America, including the 1996 Western Interconnection, and the 2003 North East US/Canada blackout [5,6]. Due to large power systems complexity, it is difficult assessing the critical point of voltage stability using power flow techniques as on-line voltage stability algorithm, because good decisions in short time are required, which hinders its practical application on power system [7].

Power systems are operated such that power flow through the transmission lines lies within limits. But instigating disturbances, such as generator contingencies, line contingencies, and load increases, can cause that operational limits may be violated, e.g. considering the single line outage case is necessary redistribute the power flow over the network, and the remaining lines in the network would have to carry the power that is originally flowing on the outage line [8]. Therefore, if a particular line is already operating close to its limits, it could be overloaded due to the extra power flow, and thus is tripped. This outage would increase the burden on the remaining lines in the network, and could cause additional outages. This is termed as *cascading* outages. Line outages thus redistribute power flow over the network, and consequently affect the voltage profile and the loading margin of the system. The nominal load margin is the point of voltage instability without any contingency. Whenever a line outage take place, the point of voltage instability could shift, resulting in a decrease in the loading margin [9,10].

In order to quantify the system’s vulnerability changes under load increments on each bus, the *VCPI* behavior is analyzed. Loads are increased until the voltage collapse point, obtaining the bus voltages profiles in each case using the Continuation Power Flow (CPF) method. The *CPF* is used to built the database, but not used

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* Corresponding author. Tel.: +57 3135388407.
E-mail addresses: f.sanz@iush.edu.co (F.A. Sanz), jramirez@gdl.cinvestav.mx (J.M. Ramírez), recorrea@unal.edu.co (R.E. Correa).

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for on-line prediction due to its two main drawbacks, namely: (i) the high computational burden and (ii) the information on the load increment directions. The first issue is due to multiple power flow calculations are required during the continuation process. Secondly, the direction of load and generation increments are not readily available on-line basis [11–13].

Considering that it is important to prevent when a system is moving from a safe area to an unsafe area, a method that estimate the voltage collapse proximity without power flows calculations is proposed. One of the main objectives is that resulting models are consistent with the smart grid approach, specifically in relation to on-line system operation. The purpose is early to attain an estimation of voltage collapse proximity, which allows that operators make decisions before a collapse occurs. Due to the proposed method is intended as a starting point for future works on the smart grid concept, is mandatory to use variables that may be available on-line, e.g. Phasor Measurement Unit (PMU), specifically bus voltages. Taking into account the above arguments, the paper proposes a reliable method in order to establish a model for voltage vulnerability estimation. The paper is organized as follows. Section 2 justifies the proposed approach; Section 3 describes the theoretical principles, and Section 4 presents the proposed method; finally, conclusions are presented.

2. Problem description

Nowadays, it is important developing novel applications and tools that allow monitoring the power system's operation in a safe way, and that help to prevent severe conditions that may lead to voltage collapse, which consequences have led to researchers to develop analytical methods in order to determine possible causes and to propose strategies for attaining safe operation.

The use of a load-flow program allows to analyze a variety of effects, such as generator voltage control, reactive power compensation, the distribution of the real power among the generation units with active governors, and the voltage characteristics of the loads, to be included. Unfortunately the method is computationally time consuming and cannot be used for on-line applications, such as steady-state security assessment, which requires a fast assessment of the voltage stability conditions and an estimation of how far a given operating point is from critical state [6,14,15]. The distance from the critical state is usually quantified by one of the so-called voltage stability indices.

The voltage stability is a dynamic phenomenon by nature, but the use of steady-state analysis methods is permitted in many cases. The voltage stability assessment of static and dynamic methods should be close to each other when appropriate device models are used and voltage instability does not occur during the transit period of disturbance. Steady-state voltage stability studies investigate long-term voltage stability.

The power system stability cannot be fully guaranteed with steady-state studies. On the other hand, devices which may have a key role in the voltage instability include those which may operate in a relatively long time frame (for instance, over-excitation limiters of synchronous generators and the on-load tap changer). Static analysis is ideal for the bulk of power system studies in which the examination of a wide range of power system conditions and a large number of contingencies is required.

Stability indices are useful tools for voltage collapse proximity estimation in electrical power systems. It is intended to analyze indices able to be used under on-line environment. In this context, it is relevant that such indices are reliable, using enough information, available from conventional measurements received at the control centers, and may be calculated in a reasonable time.

For the purpose of this paper, the power flow model is used to obtain a database from modeling system under different operating scenarios, where the variations of constant active and reactive powers are assumed to be the main parameter driving the system to a singularity. Although this simple system model is certainly not adequate to thoroughly study the voltage collapse phenomenon, for certain particular dynamic models, the power flow equations yield adequate results, as singularities in the related power flow Jacobians can be associated with actual singular bifurcations of the corresponding dynamical system [16]. Moreover, regardless of the direct relations between singularities of the power flow Jacobians and the actual bifurcations of the full dynamical system, it is always of interest to determine the system conditions where the power flow problem is not solvable, as most operating decisions nowadays are made on-line based on power flow solutions. Thus, various utilities throughout the world currently use indices as those here discussed, and base some of their operating decisions related to voltage collapse problems mostly on a power flow system model [16].

3. Voltage collapse modeling

The typical quasi-steady state model of a power system considered in voltage stability analysis is generally given by differential and algebraic equations as follows [16,17]:

$$\dot{x} = f(x, y, \lambda) \tag{1}$$

$$0 = g(x, y.\lambda) \tag{2}$$

where x is the vector of state variables; y is the algebraic variables vector. Variable λ is a parameter that slowly changes over time so that the power system moves from an equilibrium point to another until reaching the point of collapse point. The differential equations (1) represent the dynamics of the equipment (including generators and controls) and loads at the buses. The algebraic equations (1) represent the power transfer relationships between the buses as effected by the transmission network. The state variables x of (1) equations (such as generator angles, frequencies, and flux quantities, control state variables and dynamic load variables) are denoted the dynamic state variables. The y variables of the algebraic equations (2) are typically the power flow variables such as the bus voltages and angles[16],

$$P_{D,i} = P_{D0,i}(1 + k_{P,i}\lambda) \tag{3}$$

$$Q_{D,i} = Q_{D0,i}(1 + k_{Q,i}\lambda) = P_{D0,i}\tan(\varphi_i)(1 + k_{Q,i}\lambda) \tag{4}$$

where $P_{D,i}$ and $Q_{D,i}$ represent the active and reactive power demand at ith bus, respectively; $P_{D0,i}$ and $Q_{D0,i}$ are the initial active and reactive power demand before the load changes, respectively; $k_{P,i}$ and $k_{Q,i}$ are constants representing changes (either increments or decrements) in active and reactive power demand at $i$tn bus, respectively; φ_i is the power factor angle at ith bus. The active power output of the ith generator should be modified to accommodate the changed power demand according to [11,16]:

$$P_{G,i} = P_{G0,i}(1 + \lambda k_{G,i}) \tag{5}$$

where $P_{G0,i}$ is the ith initial active power generation; $k_{G,i}$ is the constant specifying the rate of change in generation when λ is varied.

3.1. Steady state stability overview of voltage collapse

Ordinarily, four analysis approaches are used for the steady-state stability assessment: (i) direct method; (ii) modal analysis; (iii) continuation method; and (iv) optimization method [17]. Specifically power flows models are applied in this paper through the continuation method such as strategy for the database required.