Electric Power Systems Research 116 (2014) 187–200

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Finding points of maximal loadability considering post-contingency corrective controls

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ARTICLE INFO

Article history:
Received 10 January 2014
Received in revised form 13 May 2014
Accepted 15 June 2014
Available online 2 July 2014

Keywords:
Corrective control
Hopf bifurcation
Saddle-node bifurcation
Switching loadability limit

ABSTRACT

Lately, much work in the area of voltage stability assessment has been focused on finding post-contingency corrective controls. In this article a contribution to this area will be presented where we search for maximal loadability while considering post-contingency corrective controls. This objective is different from the usual approach to the problem, where the aim is to include the post-contingency controls in a security-constrained optimal power flow.

Our approach gives us an optimal control problem with a variable start point. Optimal control problems are generally very cumbersome to solve in high dimensions. However, under some mild assumptions we find that our infinite dimensional optimization problem can be transformed into a finite dimensional one. More specifically, by assuming that the load recovery is an explicit function of time we can specify a set of constraints that are necessary for optimality.

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1. Introduction

Contingency analysis is one of the most important issues that a power system operator is faced with. When long term voltage stability is of concern, neglecting post-contingency corrective controls will often lead to an overly conservative operation of the power system. However, introducing post-contingency corrective controls turns the contingency analysis problem into an optimal control problem. The objective, which without corrective controls is to find a feasible post-contingency operating point, is now to find a feasible corrective control that saves the system from losing stability.

Several attempts at simplifying this problem appear in the literature. A pioneering paper on corrective control of voltage instability is [1], where a method is suggested that identifies a set of nodes where the load restoration is responsible for collapse. Minimal corrective controls are then determined based a hyperplane approximation of the loadability surface.

A similar approach is taken in [2], but here a measure of the severity of unstable cases is introduced and an energy measure method is utilized to estimate the time available for corrective controls.

In the first instances of corrective security-constrained optimal power flow (CSCOPF) [3] it was proposed that constraints for a feasible post-contingency operating point, allowing for a limited amount of corrective control, should be added to the optimal power flow (OPF) problem. In [4] it was proposed that feasibility immediately following the contingency should be added to the constraints and an example illustrating the importance of this inclusion was given.

In [5] a method where a constant control action is applied throughout the load recovery process is proposed. This constant control action is achieved by solving a single OPF problem. Then feasibility of the corresponding path is investigated through quasi-steady state (QSS) simulation. If feasibility is not obtained, parameters (time available for controls) are changed and the process is repeated until a feasible path is rendered or it is clear that no control action that will save the system can be found in this manner.

In [6] an approach based on model predictive control (MPC) is suggested to find corrective controls in real-time operation. A number of points in time are chosen and a corrective control that solves an OPF with constraints on feasibility at these times, with an assumed load recovery model that depends explicitly on time, is computed. The first step in this control is then applied and the problem is resolved with a new recovery model based on the latest measurements of the systems evolution.

In [7] a technique for maximizing the loadability limit in a specific direction of stress by tuning control parameters was

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http://dx.doi.org/10.1016/j.epsr.2014.06.008
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developed. The method is designed to be able to handle corner points of the loadability surface, since optimal solutions tend to be located at such points.

Although much work has already been done on finding efficient post-contingency corrective controls since the introduction of this problem in [3], no really complete way of tackling the infinite-dimensionality of the problem has been suggested yet. The method proposed in [5] has the appealing feature of guaranteeing feasibility of the control by checking each proposed control with a QSS simulation tool. However, it has the limiting factor of only being able to suggest constant controls. The method proposed in [6] seems efficient, but it does not give us any information of additional system loadability with corrective controls.

In this article a different approach will be proposed where, instead of discretizing the system trajectory, we find the time where the corrected path meets the stability boundary. To be able to do this an explicit dependence of time will be used in the load recovery model (as in [6]). Furthermore, it will be assumed that, except for in very rare cases, there is an optimal path that only meets the stability surface at one time instance.

It will be shown how the loadability in a given direction can be computed when corrective controls are allowed. We use the structure of the feasibility region and approximations of its boundary to estimate a globally optimal corrective control. The method will have its application in the planning stage where the operator of a system seeks to plan operation to be able to withstand contingencies as well as deviations from forecasted levels of uncertain system parameters.

The remainder of the article is organized as follows. In the next section the problem of determining maximal loadability with corrective controls is formulated. In Section 3 the solution procedure is outlined. Then, in Section 4 a set of optimality conditions that applies at points where the system trajectory meets the post-contingency stability boundary is derived. Section 5 describes how approximations of the post-contingency stability boundary can be used to predict the optimal trajectory of the system parameters. In Section 6 it is discussed how these predictions can be corrected using the optimality conditions. A small illustrative example is then given in Section 7, before the article is concluded with a discussion of computational aspects and a summary in Section 8.

2. Problem formulation

To understand how we can solve the problem of maximizing loadability by post-contingency corrective controls we must first define the stability boundary.

2.1. Loadability limits

The following equality–inequality constraint representation of the power system model was introduced in [8]:

$$\psi(x, \lambda) = 0 \tag{1}$$

$$f^{a,i}(x) \cdot f^{b,i}(x) = 0, \quad i = 1, \ldots, n_s \tag{2}$$

$$f^{a,i}(x) \geq 0, \quad i = 1, \ldots, n_s \tag{3}$$

$$f^{b,i}(x) \geq 0, \quad i = 1, \ldots, n_s \tag{4}$$

where ψ is a smooth function representing the power system. $f^{a,i}$ and $f^{b,i}$ are called switching functions and are also smooth. The vector $x \in \mathbb{R}^n$ represent the power system state, in general voltage magnitudes and phase angles at all nodes of the system, and generator state variables for the generators of the system. The vector $\lambda \in \mathbb{R}^m$ contains the system parameters which can represent quantities such as customer demand, or active power production. Here, we split the vector λ into a sub-vector $y \in \mathbb{R}^k$ of controllable system parameters, and a vector $P_L \in \mathbb{R}^l$ of non-controllable system parameters. The switching constraints are introduced in order to take account of controller limits imposing constraints on the power system control parameters. One such limiting constraint is due to the overexcitation limiters in the generators of the system. In unconstrained operation the generator excitation EMF E_f is in equilibrium given by

$$0 = -E_f^i + K_A^i(V_{\text{ref}} - V^i) = f^{a,i}(x). \tag{5}$$

However, limits on the generator excitation EMF dictate that

$$-E_f + E_f^{\lim} = f^{b,i}(x) \geq 0. \tag{6}$$

A point in parameter space where, for some $i \in \{1, \ldots, n_s\}$, $f^{a,i}(x) = f^{b,i}(x) = 0$, is referred to as a *breaking point* [9] due to the shape that the PV-curve takes at such points, or a constraint switching point [10]. At such points the limit of the control variable, in this case E_f, is reached and the set of active constraints change.

From an initial operating point (x_p, λ_p) satisfying the feasibility constraints (1)–(4) the loadability limit in the direction of stress $d_s \in S^{m-1}$ (the unit sphere in $\mathbb{R}^m$) is the solution to the equality–inequality constrained optimization problem

$$\max_{x \in \mathbb{R}^n, r \in \mathbb{R}_+} \{r : (1) - (4) \text{ holds with } \lambda = \lambda_p + r d_s\}. \tag{7}$$

This problem can be solved by various methods such as continuation methods [11,12], optimization methods [9], direct methods [13] and quasi steady state (QSS) simulations [14,15].

2.2. The stability boundary

The stability boundary Σ is the boundary of the domain wherein the system is small-signal stable. The surface Σ is made up of a number of different smooth manifolds [16]. Due to constraint switching there are two types of loadability limits and we get the following different types of points on the stability boundary.

- *SNB:* A Saddle-Node Bifurcation loadability limit is a loadability limit that may occur when the system Jacobian becomes singular. This type of loadability limit is the most commonly addressed loadability limit in voltage stability assessment VSA.
- *SLL:* Switching Loadability Limits [7] correspond to cases when the power system becomes immediately unstable when a control variable limit is reached.
- *HB:* Hopf Bifurcation points are points in parameter space where the real part of one pair of complex eigenvalues of the dynamic Jacobian becomes positive as the system parameters change so that the system is no longer small-signal stable.
- *TL:* A loadability limit corresponding to a TL occurs when the active power transfer over one line reaches the line's thermal limit.

The stability boundary is not smooth but rather made up of a number of smooth manifolds which intersect at non-smooth points that are referred to as Corner Points (CPs).

2.3. Example

Consider the system depicted in Fig. 1. This system was analyzed in [7] and consists of three generators and one load. It is assumed that node 1 is the slack node (where all power deviations are balanced) and that the load is of the constant power type with a fixed power factor. The system has three parameters that are allowed to vary; P_{g2}, P_{g3}, and P_{Load}. It is also assumed that each generator has a limited E_f with $E_f^{\lim} = 2.5968$ p.u. for each generator.

In Fig. 2 the stability boundary Σ, made up of two SLL-surfaces, is plotted when varying P_{g3} and P_{Load}, while keeping P_{g2} fixed at

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