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Quantitative transient voltage dip assessment of contingencies using trajectory sensitivities ☆

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ABSTRACT

A new index, voltage critical clearing time (V-CCT), is presented for quantitative assessment of transient voltage dips subject to various contingencies. Calculation of V-CCT needs estimation using trajectory sensitivities of voltages with respect to fault clearing time. The V-CCT indices indicate the severity of fault-initiated contingencies by comprehensively evaluating transient voltage dips according to dynamic performance criteria. Using trajectory sensitivities to obtain V-CCT minimizes the computational effort by avoiding repetitive trial-and-error time-domain simulations. Performance of the proposed transient voltage dips assessment method has been tested on a 9-bus system, the New England 39-bus system and a 13,000-bus system. For the small test systems, some selected contingencies are compared to verify the consistency of ranking using V-CCT with time-domain simulation analysis. The computational efficiency of the proposed assessment method is analyzed. Then the case studies on the large system build up the relation between analysis results and system operating condition. The results show that the assessment using V-CCT reflects the contingency severity in scope of transient voltage dips.

Introduction

Transient voltage dip (TVD) refers to the short-term voltage magnitude reduction after faults or other disturbances, such as transformer energizing, large motor starting and heavy load switching [1], that result in extreme increase of currents. TVD is an important aspect of power quality. Severe TVD brings high consequences in various industry areas [2–5]. To avoid TVD, time-domain simulations must be done and preventive actions taken when unacceptable TVD is detected [6]. In this paper, we present a new index to facilitate fast TVD assessment after fault-initiated contingencies.

There is a significant body of literature on assessing TVD. In [7], the IEC and IEEE TVD standards and application areas were reviewed. Ref. [8] presented various TVD indices relating voltage dip duration and energy variation. Ref. [9] developed a TVD index considering compatibility between equipment and supply. The TVD duration assessment criteria were summarized in [10] from various industry resources. Some other TVD assessment standards include voltage dip window criterion [11] and economic cost [12]. In [13,14], stochastic methods were presented for TVD assessment.

Inspired by critical clearing time (CCT), a familiar metric to indicate power system rotor angle stability [15,16], this paper proposes an index called voltage critical clearing time (V-CCT). The system dynamic security subject to fault-initiated contingencies is quantified by fast estimation of V-CCT. To obtain V-CCT, voltage trajectory sensitivities with respect to fault clearing time are first calculated. The calculated trajectory sensitivity information is used to estimate V-CCT, which is defined as the maximum fault clearing time for which the limit of TVD dynamic security region is reached. V-CCT is a comprehensive index, because it considers multiple TVD dynamic performance criteria that define the TVD dynamic security region. Using trajectory sensitivities to calculate V-CCT avoids time-consuming repetitive trial-and-error time-domain simulations to obtain those critical values. The calculated V-CCT are used to rank the TVD severity of assessed contingencies.

The rest of the paper is organized as follows. Section 'Trajectory sensitivities with respect to fault clearing time' introduces the trajectory sensitivities with respect to fault clearing time, including the calculation, initial condition determination and computational efficiency analysis. Section 'TVD assessment' introduces the TVD dynamic performance criteria used by NERC/WECC to define the TVD dynamic security region and presents the concept of V-CCT. Then the procedure of using V-CCT for TVD assessment is

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described. Section ‘Estimation error index’ introduces an index to quantify the estimation error. Section ‘Case studies’ provides the case study results from the tests on three benchmark systems. Section ‘Conclusions’ summarizes the contributions of this paper.

Trajectory sensitivities with respect to fault clearing time

The dynamics of a power system considering switching actions can be described by a differential algebraic discrete model as in [17]. A special but common case is the model described by differential algebraic equations (DAEs)

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

$$0 = \begin{cases} g^-(x, y, t, \lambda) & s(x, y, t, \lambda) < 0 \\ g^+(x, y, t, \lambda) & s(x, y, t, \lambda) > 0 \end{cases} \tag{2}$$

where x are dynamic state variables, y are algebraic variables and λ are system parameters and initial conditions. Examples of system parameters are transmission line impedances, generation levels and load parameters. To calculate V-CCT, the system parameter λ considered in this paper is fault clearing time t_{cl}. The discontinuity of the system is represented by switching between algebraic equations, denoted by superscripts “–” and “+”. A switching event occurs when the trigger function equals zero, i.e., $s(x,y,t_{cl}) = 0$. In this paper, g^- represents the period of time during the fault (the fault-on period), and g^+ the period of time after the fault (the post-fault period).

To better understand the post-fault trajectory sensitivities with respect to t_{cl}, the differential equations are also represented with a fault-on set f^- and a post-fault set f^+. Since f are continuous, $f^- = f^+$ is satisfied at t_{cl}.

Refs. [18–24] studied trajectory sensitivities with respect to both system parameters and initial conditions. Change of fault clearing time t_{cl} is a special case, because it results in the initial condition deviations of all variables for the post-fault period. Differentiating the post-fault part of (1), (2) yields

$$\frac{\partial^2 x}{\partial t \partial t_{cl}} = \frac{\partial f^+}{\partial x}\frac{\partial x}{\partial t_{cl}} + \frac{\partial f^+}{\partial y}\frac{\partial y}{\partial t_{cl}} + \frac{\partial f^+}{\partial t_{cl}} \tag{3}$$

$$0 = \frac{\partial g^+}{\partial x}\frac{\partial x}{\partial t_{cl}} + \frac{\partial g^+}{\partial y}\frac{\partial y}{\partial t_{cl}} + \frac{\partial g^+}{\partial t_{cl}}. \tag{4}$$

DAEs (1), (2) describe a time-variant system, in which time t is an independent variable but not explicitly expressed, thus $\partial f^+/\partial t_{cl} = 0$ and $\partial g^+/\partial t_{cl} = 0$ are satisfied. Define

$$\frac{\partial^2 x}{\partial t \partial t_{cl}} \equiv \dot{x}_{tcl}, \quad \frac{\partial x}{\partial t_{cl}} \equiv x_{tcl}, \quad \frac{\partial f^+}{\partial x} \equiv f_x^+ \text{ and } \frac{\partial g^+}{\partial x} \equiv g_x^+.$$

The trajectory sensitivity Eqs. (3), (4) become

$$\dot{x}_{t_{cl}} = f_x^+ x_{t_{cl}} + f_y^+ y_{t_{cl}} \tag{5}$$

$$0 = g_x^+ x_{t_{cl}} + g_y^+ y_{t_{cl}}. \tag{6}$$

Both $x(t,t_{cl})$ and $y(t,t_{cl})$ vary with t_{cl}. Given a small change in fault clearing time Δt_{cl}, the resulting deviation of a variable trajectory is estimated through Taylor series expansion as

$$\begin{aligned} \Delta\varphi(t, t_{cl} + \Delta t_{cl}) &= \frac{\partial \varphi}{\partial t_{cl}}(t, t_{cl})\Delta t_{cl} + \text{higher order terms} \\ &\approx \frac{\partial \varphi}{\partial t_{cl}}(t, t_{cl})\Delta t_{cl} \equiv \varphi_{t_{cl}}(t, t_{cl})\Delta t_{cl} \quad (t \geqslant t_{cl}) \end{aligned} \tag{7}$$

where $\varphi = [x,y]$.

For a specific pre-fault operation condition, changing fault clearing time affects only fault-on trajectories and post-fault trajectories. The initial conditions of post-fault trajectory sensitivities for dynamic state variables are obtained using the fact that they are variable sensitivities to time t at t_{cl}. i.e.,

$$x_{t_{cl}}(t_{cl}, t_{cl}) = f^-(x, y, t, t_{cl})|_{t=t_{cl}} = f^+(x, y, t, t_{cl})|_{t=t_{cl}}. \tag{8}$$

The initial conditions of post-fault trajectory sensitivities for algebraic variables are obtained from (6) as

$$y_{t_{cl}}(t_{cl}, t_{cl}) = \left\{-\left[g_y^+\right]^{-1} g_x^+ x_{t_{cl}}\right\}\Big|_{t=t_{cl}}. \tag{9}$$

Eq. (9) requires that g_y^+ be nonsingular along the post-fault trajectories. Otherwise, the inverse of g_y^+ results in infinite sensitivity, a special case when sensitivity based estimation is not applicable [19].

Eqs. (1), (2), along with their augmentation (5), (6), give the solutions of post-fault trajectories and their trajectory sensitivities with respect to fault clearing time. An efficient calculation of trajectory sensitivities shown in [19,25] is used in this paper: if an implicit method such as trapezoidal rule is used for integration of DAEs (1), (2), and a Newton method is used to solve the nonlinear equations in each integration step [26], the Jacobian matrix factorization calculated in the solving process can be directly reused for solving the trajectory sensitivity Eqs. (5), (6). Since Jacobian matrix factorization is the most time-consuming part in the DAE solution [27], the additional computational effort of solving for the sensitivity equations is minimized.

TVD assessment

TVD dynamic performance criteria and dynamic security region

Calculation of V-CCT requires dynamic performance criteria to determine the TVD dynamic security region. Commonly used criteria consider both low voltage and high voltage limits during the oscillations and the time duration when a limit is violated, i.e., violation duration, as shown in Fig. 1. The criteria are used to evaluate the post-fault transient voltage trajectories and define the boundary of TVD dynamic security region. System performance subject to various disturbances can then be classified as acceptable or unacceptable in terms of TVD [28,29]. Unacceptable cases need special attention to enhance the system dynamic security.

We use the criteria defined by NERC/WECC, stated as follows [10]:

- *N-1 contingencies*: Not to exceed 25% at load buses or 30% at non-load buses; not to exceed 20% for more than 20 cycles at load buses.
- *N-k* ($k \geqslant 2$) *contingencies*: Not to exceed 30% at any bus; not to exceed 20% for more than 40 cycles at load buses.

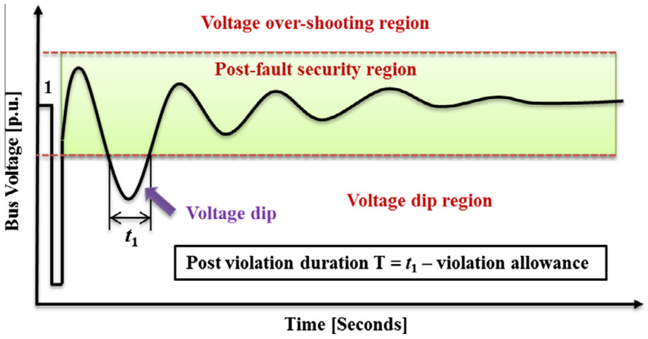

Fig. 1. Illustration of TVD dynamic performance criteria.