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Optimal coordinated voltage emergency control against voltage collapse

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ABSTRACT

This paper presents a novel model for optimal coordinated voltage emergency control (OCVEC). It takes account of the dynamics of loads and discrete/continuous nature of controls with coordination of dissimilar controls at different geographical locations in order to keep the desired voltage profiles against voltage collapse during an emergency. An integration index of the bus voltage deviation is adopted as the voltage stability performance index. The sensitivities of this performance index with respect to controls are derived using the optimal control theory. Since the sensitivities can be evaluated using the fast quasi-steady-state time domain simulation results, the intractable OCVEC model can be transformed into a tractable problem of quadratic programming. The effectiveness of the proposed model and its solution strategy is validated by case studies on the New England 39-bus and Nordic 32 power systems.

1. Introduction

Voltage instability has become a major threat for the secure operation of many power systems around the world, especially in the open-access environment where economical and environmental incentives have driven the operation of power systems closer to their limits. Voltage instability can be classified into short-term and long-term [1]. The dynamic of the later usually lasts for over several minutes and it is often triggered by the tripping of transmission or generation equipments. The scenario for long-term voltage instability is that on-load tap changers (OLTCs) try to restore their secondary voltages and hence the corresponding load powers, and dynamic thermostatic loads try to restore their pre-disturbance load powers, while over-excitation limiters (OXLs) restrict the reactive support from generators. The generation and transmission system, as a result, would not be able to meet the load demand. This supply–demand imbalance problem is the fundamental cause of voltage collapse. The time frame of long-term voltage instability is that of aggregate load recovery, secondary voltage control (SVC) and over-excitation protection device acting, lasting typically for several minutes [1]. This paper focuses on the study of emergency control model in long-term voltage instability.

Voltage instability is often triggered by either load increase or serious faults. In the scenario of load increasing slowly, the sensitivities of a load power margin measuring proximity to voltage collapse with respect to controls can provide abundant information in predicting the variation of the load power margin against voltage collapse [2–4]. In the scenario of serious faults, often prompted by emergency or blackout situations, a number of corrective actions could be applied in power systems. However, the majority of the existing control strategies deals with only a single control class, such as generator automatic voltage regulator (AVR) setpoints, transformer tap control, capacitor switching and load shedding separately [5–9], and very few of these methods take account of the discrete nature of controls, the inherent dynamics of the loads and the coordination among dissimilar controls.

A voltage emergency control approach using trajectory sensitivities has been proposed in [10]; however, the initial values of trajectory sensitivities are not easily to determine accurately. The emergency control model in the scenario of long-term voltage instability has been studied in [11–13] taking account of the discrete nature of controls and the inherent dynamics of the loads, and coordinating dissimilar controls. The OCVEC problem is an on-line problem that requires fast solution speed. When the system size becomes larger and with more candidate controls, the computation speed of solving the optimization problem using intelligence methods, such as the tree search and the pseudo-gradient evolutionary programming, to obtain the globally optimal solution would be too time consuming and hence cannot satisfy the requirement of on-line computation. Though knowledge based intelligent techniques could somehow remedy this solution speed problem, there are still difficulties in coordinating the knowledge preparation and learning scheme. In [14,15], an optimization framework with embedded system dynamics has been proposed to derive the preventive and corrective controls for enhancing the angle and voltage transient stability by means of generation rescheduling and load shedding.

This paper proposes a novel OCVEC model in the scenario of long-term voltage instability. The new model excels the existing models in the aspects of computation speed, capability in dealing with load shedding, and adaptability to system modeling and scale.

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2. Qss and generic load recovery modeling

For the study of long-term voltage stability, the quasi-steady-state (QSS) fast time-domain simulation method proposed in [16–19] is commonly adopted. In the QSS model, the faster transient dynamics of generators are neglected and the dynamic equations of the generator are replaced by its equilibrium equations. The general QSS modeling can be expressed as a set of hybrid continuous–discrete time differential–algebraic equations (DAEs) as follows:

$$0 = \boldsymbol{f}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z_c}, \boldsymbol{z_d}, \boldsymbol{u}) \tag{1}$$

$$0 = \boldsymbol{g}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z_c}, \boldsymbol{z_d}, \boldsymbol{u}) \tag{2}$$

$$\boldsymbol{z_d}(\boldsymbol{k}+1) = \boldsymbol{h_d}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z_c}, \boldsymbol{z_d}(\boldsymbol{k}), \boldsymbol{u}) \tag{3}$$

$$\dot{\boldsymbol{z}}_{\boldsymbol{c}} = \boldsymbol{h_c}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z_c}, \boldsymbol{z_d}, \boldsymbol{u}) \tag{4}$$

Eqs. (1) and (2) represent the equilibrium equations of the transient dynamics of generators and the network relationships, respectively. $\boldsymbol{x}$ is a state vector which relates to generators and regulators; $\boldsymbol{y}$ is an algebraic vector which relates to the network complex voltages; $\boldsymbol{z_d}$ is a discrete state vector which typically relates to on-load transformer taps; $\boldsymbol{z_c}$ is a continuous state vector which relates to the load dynamics; and $\boldsymbol{u}$ is the control vector.

It has been demonstrated that load dynamics plays an important role in voltage instability incidents [20]. The total load supplied by a bulk power delivery transformer is a composition of a large number of individual loads. It consists of components without restoration dynamics as well as of components with load restoration at various time scales. Without loss of generality, this paper adopts a multiplicative generic load recovery model [21], which has been verified in several field tests and has been widely used in long-term voltage stability research [11–13,22,23]. This model is described as follows:

$$T_P \dot{z}_P = \left(\frac{V}{V_0}\right)^{\alpha_s} - z_P \left(\frac{V}{V_0}\right)^{\alpha_t} \tag{5}$$

$$P_s = P_0 \left(\frac{V}{V_0}\right)^{\alpha_s}, \quad P_t = z_P P_0 \left(\frac{V}{V_0}\right)^{\alpha_t} \tag{6}$$

$$T_Q \dot{z}_Q = \left(\frac{V}{V_0}\right)^{\beta_s} - z_Q \left(\frac{V}{V_0}\right)^{\beta_t} \tag{7}$$

$$Q_s = Q_0 \left(\frac{V}{V_0}\right)^{\beta_s}, \quad Q_t = z_Q Q_0 \left(\frac{V}{V_0}\right)^{\beta_t} \tag{8}$$

where z_P and z_Q are continuous state variables which relate to load dynamics; P_s, Q_s and P_t, Q_t are the voltage characteristics in steady-state and transient state, respectively; T_P and T_Q are the recovery time constants of active power and reactive power. Usually, the transient load exponents α_t, β_t have larger values than the steady-state counterparts α_s, β_s, so that the transient characteristic is more voltage sensitive. It can be seen from (5–8) that the transient characteristic is always forced to recover to the steady-state one. The generic model is thus restoring load power.

Load shedding is modeled by the application of a scale factor k_l ($0 \leqslant k_l \leqslant 1$) to both the active and reactive power demands; therefore, the active power P_r and reactive power Q_r can be represented as:

$$P_r = k_l P_t \tag{9}$$

$$Q_r = k_l Q_t \tag{10}$$

3. Novel OCVEC modeling

3.1. General OCVEC modeling

The general modeling of OCVEC has the following representation:

$$Min \quad L(\boldsymbol{u}) = \boldsymbol{u}^T \boldsymbol{R} \boldsymbol{u} \tag{11}$$

$$\text{S.T.} \quad \begin{cases} 0 = \boldsymbol{f}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z_c}, \boldsymbol{z_d}, \boldsymbol{u}) \\ 0 = \boldsymbol{g}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z_c}, \boldsymbol{z_d}, \boldsymbol{u}) \\ \boldsymbol{z_d}(\boldsymbol{k}+1) = \boldsymbol{h_d}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z_c}, \boldsymbol{z_d}(\boldsymbol{k}), \boldsymbol{u}) \\ \dot{\boldsymbol{z}}_{\boldsymbol{c}} = \boldsymbol{h_c}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z_c}, \boldsymbol{z_d}, \boldsymbol{u}) \\ \boldsymbol{J}(\boldsymbol{u}) = \int_{\boldsymbol{t_0}}^{\boldsymbol{t_f}} \psi(\boldsymbol{y}, \boldsymbol{u}, \boldsymbol{t}) \boldsymbol{dt} \leqslant \boldsymbol{M} \\ \boldsymbol{u}_{\min} \leqslant \boldsymbol{u} \leqslant \boldsymbol{u}_{\max} \end{cases} \tag{12}$$

where $\psi(y, u, t) = [y(t) - y_r(t)]^T\ \boldsymbol{Q}[y(t) - y_r(t)]$. Eq. (11) represents the cost function. $\boldsymbol{u}$ is the dissimilar control vector including capacitor switching, OLTCs, load shedding and set-points of generator AVR. $\boldsymbol{R}$ is the diagonal cost matrix. $\boldsymbol{Q}$ is the diagonal weighting matrix. y is load bus voltage vector. y_r is load bus voltage reference vector. Since voltage stability relates directly to the load stability, the performance index of voltage stability $J(u)$ usually adopts the integration form of the load bus voltage deviation [11–13]. Rather than incorporating $J(u)$ into the objective function (11), it is considered as one of the constraints and $J(u) \leqslant M$ is used to ensure the controlled system could have the "desirable" dynamical behavior. M is the "target" value of the performance index and is formulated as $(V_D/\eta)^2 \times (t_f - t_0) \times N_y$ where V_D is the targeted average load bus voltage deviation in y during the control interval $t_f - t_0$, η is a weighting coefficient, and N_y is the number of buses in y. $u_{\min}$ and $u_{\max}$ represent the lower and upper bound constraints of the control vector, respectively.

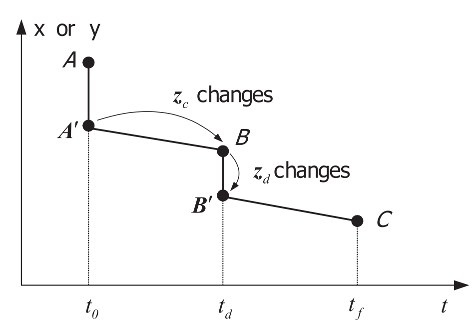

Fig. 1. Long-term simulation procedure.

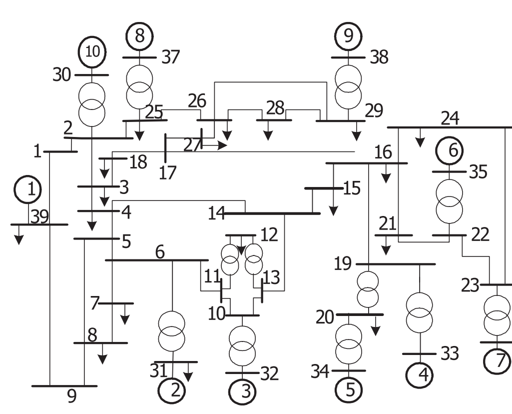

Fig. 2. The New England 39-bus power system.