Control Engineering Practice 30 (2014) 93–104

Contents lists available at ScienceDirect

Control Engineering Practice

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

A two-level emergency control scheme against power system voltage instability

Bogdan Otomega [a], Mevludin Glavic [b], Thierry Van Cutsem [c,*]

[a] Power System Department, Politehnica University of Bucharest, 313 Spl. Independentei, 060042 Bucharest, Romania
[b] Department of Electrical Engineering and Computer Science, University of Liège, Sart Tilman B37, B-4000 Liège, Belgium
[c] Fund for Scientific Research & Department of Electrical Engineering and Computer Science, University of Liège, Sart Tilman B37, B-4000 Liège, Belgium

ARTICLE INFO

Article history:
Received 21 January 2013
Accepted 7 October 2013
Available online 3 December 2013

Keywords:
Power systems
Voltage instability
Emergency control
Distributed control
Wide-area monitoring
Load control

ABSTRACT

A two-level adaptive control scheme against power system voltage instability is proposed, to deal with emergency conditions by acting on distribution transformers and/or by curtailing some loads. The lower level includes distributed controllers, each acting once the voltage at a monitored transmission bus settles below a threshold value. The upper level benefits from wide-area monitoring and adjusts in real-time the voltage thresholds of the local controllers. Emergency detection is based on the sign of sensitivities. The proposed scheme is robust with respect to communication failures. Its performance is illustrated through detailed simulations of a small but realistic 74-bus test system.

1. Introduction

Voltage instability of power systems is linked to the inability of the combined generation-transmission system to provide the power requested by loads (Van Cutsem & Vournas, 1998). In a typical voltage instability scenario, the maximum power deliverable to loads drops under the effects of a large disturbance and the limitations on reactive power generation; concurrently, the loads connected to the transmission system tend to restore their powers near the value before the disturbance. Those antagonistic effects prevent the system from regaining a state of operating equilibrium with network voltages in acceptable ranges of values (Kundur et al., 2004). Depending on the involved component dynamics and the severity of the disturbance, voltage instability can evolve in time frames of several seconds (short-term instability) or tens of seconds up to several minutes (long-term instability). In this paper, the emphasis is on long-term voltage instability, in which network voltages undergo a generally monotonic decrease after the initiating disturbance.

A typical example from simulation is shown in Fig. 1 (obtained with the system considered in Section 5). The power system is subject to a short-circuit which is cleared by opening a transmission line. The plot shows the evolution of the voltage magnitudes at a transmission and the closest distribution bus.[1] After the fault is cleared, the system is subject to electromechanical oscillations (of the rotors of synchronous generators) before approaching a short-term equilibrium. Next, the system evolves in the long term under the above-mentioned effect of generator reactive power limitation and load power restoration.

When pronounced, and if not controlled, voltage instability may result in voltage collapse. In the case of Fig. 1 this takes on the form of a loss of synchronism of a nearby generator, leading to the sharp final voltage drop. In practice, this will trigger a sequence of events leading most likely to a blackout. The heavy consequences of power system blackouts in terms of economical and societal costs (Union for the Co-ordination of Transmission of Electricity, 2006; US–Canada Power System Outage Task Force, 2003) motivate the improvement of control schemes to deal with voltage instability problems.

Remedies against voltage instability can be categorized into preventive actions and corrective controls.

Preventive actions consist of adjusting the operating point in order the system to be able to face each credible incident (referred to as contingency) of a predefined list. Those actions are taken in a normal operating state, i.e. before the occurrence of any disturbance, and involve costs to protect the system against hypothetical events. However, many voltage incidents resulted

---

* Corresponding author. Tel.: +32 4 366 26 89; fax: +32 4 366 45 82.
E-mail address: t.vancutsem@ulg.ac.be (T. Van Cutsem).

[1] All voltages are shown in *per unit* (*pu*), i.e. divided by the nominal voltage of the corresponding bus.

0967-0661/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.conengprac.2013.10.007

from a severe low-probability disturbance, against which it would be too expensive – if at all feasible – to take preventive actions.

Corrective controls aim at acting after the actual occurrence of a disturbance. They can be broadly classified into open-loop and closed-loop. Open-loop control resorts to actions determined off-line from exhaustive simulations of postulated scenarios while closed-loop control assesses the disturbance severity through measurements, adjusts its actions correspondingly, tracks the system evolution and repeats some actions if the previous ones are not sufficient.

The dominant trend is to integrate emergency controls in System Integrity Protection Schemes (SIPSs) (Madani et al., 2010) while exploiting new technological solutions such as synchronized phasor measurements (Phadke & Thorp, 2008) and fast communications as the main enablers of power system Wide Area Monitoring System (WAMS) (Phadke & de Moraes, 2010). New algorithms are needed to process the data collected in WAMS and effectively control unstable system evolutions.

This paper deals with such an algorithm. It proposes an adaptive two-level emergency control scheme aimed at driving the voltage unstable system towards a new, acceptable equilibrium (Van Cutsem & Vournas, 1998). The lower level consists of distributed controllers acting in the closed-loop on loads once the voltages at monitored transmission buses fall (and stay for some time) below threshold values. The upper level takes advantage of a WAMS to detect instability, and assign their voltage thresholds to the lower-level controllers, in the spirit of an adaptive system. The control scheme is robust with respect to controller or telecommunication failures.

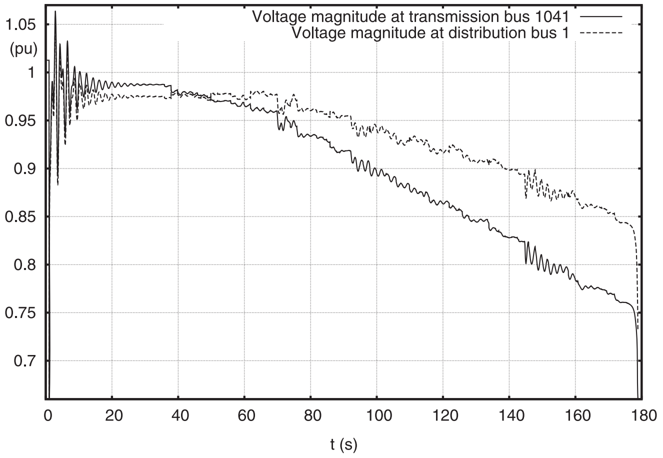

Fig. 1. Example of long-term voltage instability.

The paper is organized as follows. To make the paper self-supporting, some fundamentals of voltage instability and its countermeasures are recalled in Section 2. The lower and upper levels of the proposed scheme are detailed in Sections 3 and 4, respectively. Section 5 is devoted to simulation results, while conclusions are provided in Section 6.

2. Voltage instability mechanism and corrective controls

This section reviews the basic voltage instability mechanism of a power system subject to a large disturbance (Van Cutsem & Vournas, 1998). It uses a two-bus system example made as simple as possible while still capturing the main features of instability. Next, the two corrective controls considered in this work are briefly described.

2.1. Voltage instability mechanism

Consider the system in Fig. 2a in which a generator feeds a load through a transmission line. It is assumed that the generator keeps its terminal voltage V_g constant and provides any active power requested by the load. The line is simply represented by its series reactance X. Finally, the load is assumed to have unity power factor, i.e. it does not consume reactive power. The power flow equations of this system are

$$P=-\frac{V_gV}{X}\sin\theta,\quad 0=-\frac{V^2}{X}+\frac{V_gV}{X}\cos\theta \qquad (1)$$

where all symbols are defined in Fig. 2b. Combining these two equations, the voltage V at the load bus is easily obtained as

$$V=\sqrt{\frac{V_g^2}{2}\pm\sqrt{\frac{V_g^4}{4}-X^2P^2}} \qquad (2)$$

The variation of V with P is shown in Fig. 3 where the upper (resp. lower) part of the curve corresponds to the solution with the $+$ (resp. the $-$) sign in (2). Such a plot is referred to as “PV curve” by power system engineers. The load power is maximum at point C, also called the “critical” point. The maximum deliverable power is $P_C=V_g^2/2X$ under voltage $V_C=V_g/\sqrt{2}$.

Load dynamics play an important role in voltage instability. In the long-term time frame, loads are controlled by Load Tap Changers (LTCs). These devices adjust the turn ratios of the transformers feeding distribution systems in order to keep the voltages at the distribution sides of the transformers close to a set-point. LTCs can act in discrete steps only, corresponding to the available transformer tap positions. They remain the main voltage control means in distribution systems, although this task is expected

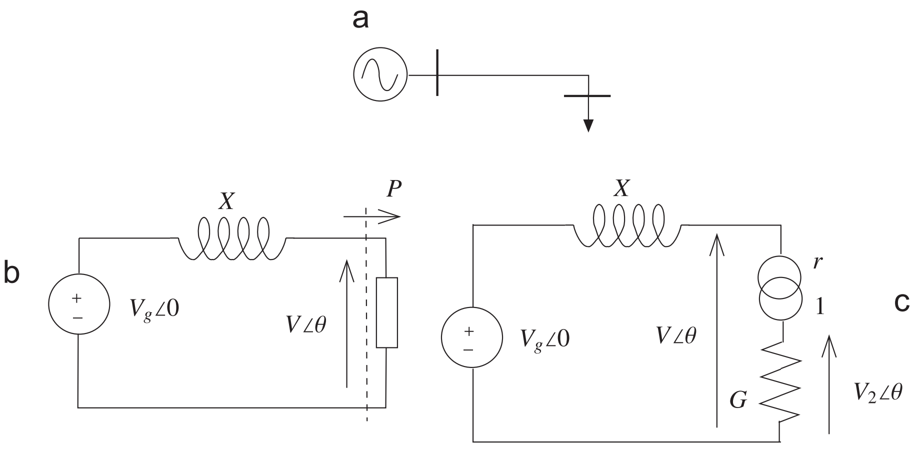

Fig. 2. Two-bus system and corresponding circuits.