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Derivation and application of sensitivities to assess transient voltage sags caused by rotor swings ☆

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ABSTRACT

The paper introduces an approach to investigate voltage sags, which are caused by large generator rotor swings following a transient disturbance. Therefore, the method exploits sensitivities derived from the algebraic network equations. These provide information on the impact of a generator on the voltage magnitude at a load bus and the effect of load variation on the generator's power injection. It is shown that these sensitivities give valuable information to identify critical generator–load pairs and locations for applying preventive control measures.

Introduction

In literature on power quality, voltage sags/dips is a topic vastly addressed [2]. While the primary cause is the occurrence of a fault, a less pointed out reason for voltage sags is rotor angle swing, more precisely angular separation of generators, resulting from a fault. From a practical viewpoint, a scenario may be assessed transiently stable considering that generators remain in synchronism, while voltage sags due to the relative rotor angle displacement already result in transiently low voltages for which the system response should be considered unacceptable.

The prediction of this type of voltage sag using the Transient Energy Function was described in the early reference [3]. In [4] sensitivities relative to voltage dip were derived using this method as well. The sensitivities relate the voltage sag depths to certain parameters such as terminal voltages and power generation. The authors of [5] address the transient voltage dip acceptability problem using a two-dimensional table of critical voltage level and critical voltage dip duration. Moreover, the issue of transient voltage stability of dynamic loads such as induction machines is analyzed. In the more recent reference [6] the authors use sensitivities to carry out contingency filtering and ranking with respect to voltage dips. Furthermore, the assessment addresses power quality issues and short-term voltage stability. In [7], the authors present a survey of current practices for transient voltage sag criteria related to power system stability.

The present paper also investigates voltage sags with focus on power system stability rather than power quality. Transient voltage sags are identified using time-domain simulation. Then, sensitivities are derived which provide information on tight couplings between relative change of rotor angles and load voltage magnitudes. These sensitivities are easier to compute than those considered in the above references. The sensitivities can be used, for instance, to identify the contribution of each generator to a drop in voltage magnitude experienced at a particular load bus. A voltage depression at a load bus can trigger consecutive events such as load tripping. Therefore, a second sensitivity is derived, which assesses the impact of a change of load power on generator active powers.

This paper is organized as follows. In Section "Voltage sags caused by rotor angle swings" the power system model used for the discussion of voltage sags and the computation of sensitivities is described. Moreover, a brief discussion of the mechanism causing these transient voltage sags is presented. The voltage sensitivities are derived in Section "Derivation of load voltage sensitivities". This is followed by the presentation of the corresponding results in Section "Results for load voltage sensitivities". The derivation of the second sensitivities, addressing the effect of variation of load on generator power, can be found in Section "Derivation of generator power sensitivities" and the

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corresponding results are shown in Section “Results for generator power sensitivities”. Finally, in Section “Conclusion” concluding remarks are offered.

Voltage sags caused by rotor angle swings

Modelling for discussion of the mechanism causing the voltage sags and for sensitivity analysis

The model used for synchronous generator is the so-called “classical” transient stability model [8]. Each generator is modeled by an e.m.f. $\bar{E}'$ of constant magnitude behind the transient reactance X_d' (see Fig. 1(a)), the mechanical power input is assumed constant, and loads are converted to constant shunt admittances. The simple generator model is valid in the first second after fault clearance and the justification for using it is twofold. First, this model is used for sensitivity analysis and, as indicated in the Introduction, this analysis is aimed at complementing a detailed time-domain simulation in which much more refined models can be used. Second, the “classical” model is not used with constant e.m.f. throughout the whole simulation: instead, the e.m.f. is adjusted so that the “classical” model fits specific operating points where the sensitivity analysis is carried out.

For convenience each generator is represented by its Norton equivalent (see Fig. 1(b)), i.e. a current source $\bar{E}'/(jX_d')$ in parallel with the admittance $1/(jX_d')$. Based on these assumptions, the following well-known linear algebraic equations can be used:

$$\bar{\boldsymbol{I}} = \boldsymbol{Y}\bar{\mathbf{V}} \tag{1}$$

where $\bar{\boldsymbol{I}}$ is the vector of complex currents injected at the generator buses (stemming from the Norton equivalents), $\bar{\mathbf{V}}$ is the vector of complex bus voltages, and $\boldsymbol{Y}$ is the “augmented” bus admittance matrix obtained by adding the contribution of generators and loads to the matrix relative to the network.

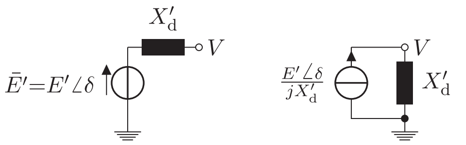
A system with n buses and m machines is considered ($n > m$). It is assumed, without loss of generality, that the buses where machines are connected are numbered from $n - m + 1$ to n. Hence, Eq. (1) can be detailed as:

$$\begin{bmatrix} 0 \\ \vdots \\ 0 \\ \bar{E}_1'/(jX_{d,1}') \\ \vdots \\ \bar{E}_m'/(jX_{d,m}') \end{bmatrix} = \boldsymbol{Y} \begin{bmatrix} \bar{V}_1 \\ \vdots \\ \bar{V}_{n-m} \\ \bar{V}_{n-m+1} \\ \vdots \\ \bar{V}_n \end{bmatrix} \tag{2}$$

where the zero sub-vector has dimension $n - m$ and $\bar{V}_i$ is the complex voltage at the i-th bus.

Voltage sag mechanism

The mechanism behind voltage sags caused by rotor swings can be discussed and illustrated graphically under consideration of a simple example system such as the one shown in Fig. 2.



(a) Thevenin Equivalent (b) Norton Equivalent

Fig. 1. Thévenin and Norton equivalents of generator.

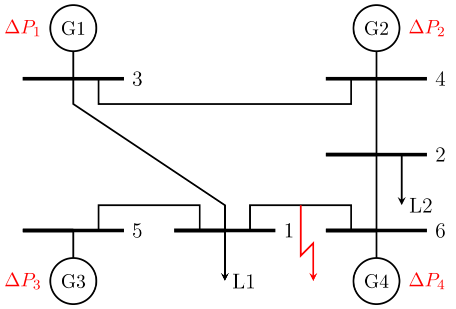


Fig. 2. One-line diagram of a simple example test system with 6 buses. A three-phase short-circuit on the transmission line connecting Buses 1 and 6, which is indicated by the red zigzag arrow, causes a change ΔP_i in the power injection of each generator Gi.

As mentioned in the previous section the generators are represented by the “classical” transient stability model. The angle of the e.m.f. can then be used to represent the rotor angle of the generator [8]. Moreover, in this example the generators’ mechanical powers are assumed constant and the loads are modeled as constant impedances for sake of simplicity.

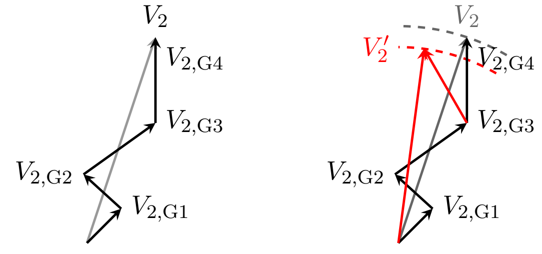
With these and the aforementioned assumptions, Eq. (2) reveals that the complex voltage at a bus is the sum of contributions of the generators. The contribution of a generator is determined by its e.m.f., which is scaled and rotated corresponding to the entry in the inverse of the admittance matrix divided by the respective transient reactance.

Fig. 3(a) shows the complex voltage at Bus 2 (from the simple example system) and the contributions of the individual generators, which add up to the voltage measured at the respective bus.

The effect of an increase in rotor angle, e.g. due to a transient disturbance, on a particular bus voltage can be assessed under consideration of the linear algebraic equation Eq. (2).

In the example shown in Fig. 2, a short-circuit occurs on the transmission line connecting Buses 4 and 5. The fault alters the admittance matrix and leads to a change of the electric power injection of the generators, which causes a relative acceleration or deceleration of the generator rotors. In the example, it is assumed for clarity that the fault only affects generator G4 resulting in its acceleration and an advancing of its rotor angle relative to the remaining generators.

The effect on the voltage at Bus 6 is shown in Fig. 3(b) from which it can be observed that the relative increase in rotor angle depresses the voltage magnitude at the bus. This observation gave the impulse for the investigation of transient voltage sags using sensitivities.



(a) Bus voltage at initial state (b) Effect of rotor angle increase of generator G4

Fig. 3. Example of complex voltage at Bus 2 as sum of generator contributions.