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The need for voltage stability analysis in voltage-controlled buses

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ABSTRACT

This paper addresses the need to perform voltage stability analysis in voltage-controlled buses. The theory that identifies the existence of a maximum power that can be injected by a generator or compensator into the grid is presented. It is also argued that it is necessary to evaluate the effect of voltage control i.e. whether it produces the expected or inverse effect. The reason for the possibility of having an opposite relationship between the excitation and the terminal voltage is explained. An index relating the two voltages is also presented. A real life illustrative example is provided.

Introduction

Voltage stability problems were originated by the high use of the existing transmission lines, which happened due to the connection of reactive compensation devices. This has become a major threat to the operation of many systems and is a factor leading to limited power transfers [1].

Although the problem has being studied since the late 1960s [2–6], the incidents experienced throughout the world in the 1980s have induced significant research efforts [1]. A series of seminars [7–9] provided a specific forum for research advances in the voltage stability area and the reports of several CIGRE Task Forces [10–13] and IEEE Working Groups [14,15] offered a compilation of techniques for analyzing and counteracting voltage instability. There is still need for further development, as recent papers demonstrate [16–18].

Steady-state voltage stability analysis may be divided into two aspects: the assessment and, if necessary, the reinforcement through voltage level changes and generation rescheduling. The voltage security assessment may find results of two different types: (i) the power flow arriving in a load bus is reaching its maximum, (ii) the effect of voltage control actions in a voltage-controlled bus may be opposite to the expected one [19].

Nowadays, it is well-known that there is a maximum power that the network can transmit to a load bus [20]. However, it is not familiar to many that there is a maximum power that can be injected by a generator into the grid. It is intuitive that there is a maximum amount of power that can injected in any point, since too much concentration of generation of one spot causes increased transfers on lines, which in turn are well known to cause voltage drop problems. However, the voltage stability problem is of concern when the maximum injection is achieved with all voltage inside the usual operating range. It is well-known that low voltage is not a flag for voltage stability. The theory which identifies the existence of maximum power injection is shown here.

It is also of concern in heavily loaded networks, as mentioned, to keep proper voltage control [21,22]. The necessity to deal with voltage control devices was already recognized as early as in 1978 and 1980 [4,6]. To quote Tiranuchit and Thomas [23]: "The actual cases of blackouts characterized by voltage depressions reported in the literature indicate that standard practice procedures such as transformer tap changing, capacitor switching, synchronous condenser adjustment, and load shedding may aggravate an already unstable voltage profile." Generators are to be included in the list of voltage controlling devices.

This paper also shows the need to evaluate the effect of voltage control in voltage-controlled buses by generator and compensator. A control action should be analyzed in terms of whether it produces the expected or inverse effect. Verification of generator behavior as a control device becomes necessary since the system may collapse if the control action produces the unexpected effect.

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The reason for a potential opposite relationship between the excitation and terminal voltage is explained. An index relating the excitation to the terminal voltage is also presented.

All, but one, commercial available tools for voltage stability assessment use the continuation power flow algorithm. Among its limitation, it is not possible to check voltage controlled buses.

Maximum power injection

This section addresses the existence of a maximum active and reactive power flow that can come out of the generator terminal bus, entering the transmission or distribution grid.

Active or reactive injected power and the voltage geometric locus

The equations for the active and reactive power "leaving" the generation bus of the 2-bus π circuit shown in Fig. 1 are presented in (1) and (2) and the corresponding complex/apparent power in (3):

$$P_{GL} = V_G^2 \cdot \left[\frac{\cos\alpha_t}{Z_t} + \frac{\cos\alpha_g}{Z_g}\right] - \left(\frac{V_L \cdot V_G}{Z_t}\right) \cdot \cos(\theta_{GL} + \alpha_t) \tag{1}$$

$$Q_{GL} = V_G^2 \cdot \left[\frac{\sin\alpha_t}{Z_t} + \frac{\sin\alpha_g}{Z_g}\right] - \left(\frac{V_L \cdot V_G}{Z_t}\right) \cdot \sin(\theta_{GL} + \alpha_t) \tag{2}$$

$$S_{GL} = \sqrt{(P_{GL})^2 + (Q_{GL})^2} \tag{3}$$

For each constant P_{GL}, varying θ_{GL} in (1), it is possible to calculate V_G and draw the curve to constant P in the θV plane. For each constant Q_{GL}, varying θ_{GL} in (2), it is possible to calculate V_G and therefore draw the curve to constant Q in the θV plane. For constant ϕ, the angle of the power factor, calculating with (1) and (2), V_G is given in (4). By varying θ_{GL} in (3), one can calculate V_G and hence draw the curve to constant ϕ in the θV plane.

$$V_G = \frac{V_L \cdot [\sin(\theta_{GL} + \alpha_t) - \tan(\phi) \cdot \cos(\theta_{GL} + \alpha_t)]}{\left[\sin(\alpha_t) - \tan(\phi) \cdot \cos(\alpha_t) - \tan(\phi) \cdot \frac{Z_t}{Z_g} \cdot \cos(\alpha_g) + \frac{Z_t}{Z_g} \cdot \sin(\alpha_g)\right]} \tag{4}$$

Therefore, given the transmission line parameters and the voltage on the load bus, one can verify the geometric locus of generation voltage for different levels of active and reactive power and for a constant power factor leaving the generation bus. An example of each of those three curves is shown in Fig. 2.

For each power factor related to the active and reactive power generation there can be two voltages in the generation bus, only one, or even none. In case there are two solutions, one belongs to the normal region of operation, left side of constant ϕ on the θV plane, and the other one to a region considered abnormal, on the right side of the same curve. In case of single voltage, it will be in the frontier between the two regions mentioned, as in the case-example in Fig. 2. That single voltage solution on the generation bus corresponds to the maximum active and reactive power injection for that constant power factor. Therefore, the frontier is made of a set of points, each corresponding to a maximum injection for each power factor.

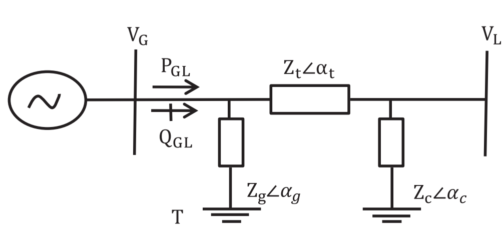

Fig. 1. Active and reactive power leaving the generation bus in a 2-bus circuit.

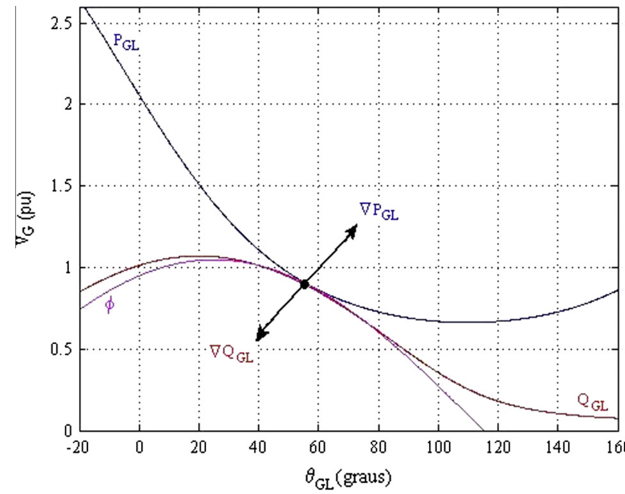

Fig. 2. Voltage geometric locus for constant P_{GL}, Q_{GL} and ϕ.

Critical values at maximum injection

The assessment of the so-called "voltage stability conditions" consists of comparing generation at the operating point under analysis with maximum possible generation that could be entering the grid. It is also important to determine if the operating point is on the left side (normal region of operation) or on the right side of the constant ϕ curve in the θV plane (abnormal region of operation) [19]. As said before, the right and left sides are separated by the point of maximum generation named frontier at the end of section 'Active or reactive injected power and the voltage geometric locus'. The values of the maximum generation and of its corresponding critical voltage need to be known.

For a 2-bus π circuit there is an analytical solution for the voltage on the generation bus, as a result of the solution to the optimization problem: "maximize the active and reactive power flow leaving the generation bus for a given power factor". Optimal conditions of the problem are: (i) gradient vectors ∇P_{GL} and ∇Q_{GL} are aligned under the same direction [19], as shown in Fig. 2, (ii) ϕ is constant. By solving those two conditions one obtains the voltage values, in magnitude and angle, at the point of maximum injection:

$$V_G^C = \frac{V_L}{2 \cdot \left[\cos(\theta_{GL}^C) + \left(\frac{Z_t}{Z_g}\right) \cdot \cos(\theta_{GL}^C + \alpha_t - \alpha_g)\right]} \tag{5}$$

$$tg(2 \cdot \theta_{GL}^C) = \left(\frac{\sin(-\varphi + \alpha_t) + (Z_t/Z_g) \cdot \sin(-\varphi + 2 \cdot \alpha_t - \alpha_g)}{-\cos(-\varphi + \alpha_t) - (Z_t/Z_g) \cdot \cos(-\varphi + 2 \cdot \alpha_t - \alpha_g)}\right) \tag{6}$$

With the critical voltage values given in (5) and (6), maximum active and reactive generation values are determined by replacing them in (1) and (2), thus enabling the following calculations:

$$S_{GL}^C = \sqrt{\left(P_{GL}^C\right)^2 + \left(Q_{GL}^C\right)^2} \tag{7}$$

Therefore, in order to know the conditions of circuit loading, the "distance" between generation at the operating point under analysis and the maximum generation is calculated. The concept of "power margin" in MVA is used to give significance to the comparison [19]: