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Key factors affecting voltage oscillations of distribution networks with distributed generation and induction motor loads

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ABSTRACT

The existence of critical voltage modes in distribution systems and the key factors responsible for them are presented in this paper. The analysis is carried out over a distribution test system for different types of induction motors. Eigenvalues and participation factors are used to investigate the modal interaction within the system. This study shows that load voltage dynamics significantly influence damping of the voltage modes. These modes have frequencies of oscillations between the electromechanical and subsynchronous oscillations of power systems. Significant parameters of the system which affect the damping and frequencies of the oscillations are identified to provide a clear understanding of the problem. A bifurcation study is performed to determine the dynamic loadability limit of the system. Time-domain simulations are carried out to verify the validity of the modal analysis and provide a physical feel for the types of oscillations that occur in distribution systems. The impact of various distribution network configurations on these modes is also demonstrated through nonlinear simulations.

1. Introduction

Distributed generation (DG) is considered as a solution to meet the increasing demand for electricity with lower transmission losses and higher reliability. In the near future, large-scale penetrations of distributed energy sources such as, combined heat and power (CHP), wind, solar, and fuel cells, are expected in distribution systems. Traditional distribution networks were not designed to include power generation facilities. The integration of DG in these passive networks could affect the dynamic behaviour of systems due to the interactions between closely located loads and generators.

The effect of small disturbances, such as minor changes in loads or generation, on the variables of a system is considered in the small-signal stability analysis [1]. As the loads of power distribution systems (PDSs) are always changing due to residential and commercial activities, they play a very important role in system behaviour [2]. Small-signal instability and poor damping may emerge as a limiting factor for PDSs operation under certain critical loading conditions. Due to the proximity of generation to its load, small variations in the system load can excite the voltage oscillations as a result of the control interaction and reactive power mismatch.

Although doubly fed induction generators, permanent magnet synchronous generators, and solar systems are increasingly popular for DG applications, conventional synchronous generators are still used in CHP and small-hydro plants, as well as some wind energy applications. The behaviour of synchronous generators is different from induction generators or inverter connected renewable energy sources. The electromechanical oscillations are natural responses of synchronous generators due to a mismatch in their net torques. These oscillatory modes may cause instabilities or unacceptable behaviour at some operating conditions [3]. In centralised power generation systems, damping of low-frequency electromechanical oscillations is achieved by using power system stabilisers (PSSs) in the excitation control loop or in voltage control devices such as static var compensators (SVCs) and static synchronous compensators (STATCOMs). The primary objective of a PSS is to introduce a component of electrical torque in the synchronous machine rotor which is proportional to the deviation of the actual speed from the synchronous speed. When the rotor oscillates, this torque acts as a damping torque to counter the oscillation. In [4], there is an extensive description of PSSs which are now widely used in industries. A PSS provides significant enhancement to the small-signal stability of the system [5]. Power oscillation damping can be also supported by wind farm [1]. However, it depends on the wind turbine technology and operating modes used [1]. A voltage source converter-based HVDC link for damping low-frequency oscillations is proposed in [6]. A study on voltage fluctuations

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induced by electromechanical oscillations in a distribution system with a synchronous generation operated at power factor control was presented in [7]. In [7], the objective was to study the impact of electromechanical oscillations in the power quality of the PDS, and the dynamics of loads were not considered. A study on the impact of DGs on the power system transient and voltage stability is given in [8] which concludes that synchronous generator interfaced DGs do not have a significant impact on the maximum rotor speed deviation of the main synchronous generator and they improve the voltage profile of the power system during faults. The analysis in [8] is carried out with static load models for large disturbances in the system. Although static load models are commonly used to model dynamic behaviours of reactive loads, they do not adequately capture the load dynamics [9]. For a system study to be useful, the inclusion of dynamic load models is essential, but that representation exhibits more complex dynamics than the one with constant impedance loads [10]. As induction motor loads account for a large portion of domestic loads for air conditioning, refrigeration, water pumping, ventilation, etc., dynamic load models are needed to analyse system dynamics accurately.

A distribution network is a low- or medium-voltage network with a higher line resistance to reactance (R/X) ratio than a transmission line [11]. Therefore, the connection of a generator to a distribution system significantly affects the system's power flow and voltage profile, and its nodal voltages vary widely as most of the buses are not voltage controlled [12]. To obtain an accurate voltage profile, proper load models are very important in the distribution system analysis. The voltage profile is sensitive to the dynamics of the load and voltage control devices [13]. However, this important issue considering DG has attracted little attention in the existing literature.

A new phenomenon called the "oscillatory voltage mode" in a PDS with generation within it is identified in [14]. Based on the findings in [14], this paper analyses the impact of load dynamics in studies of distribution system damping and provides a clear understanding of the problem. The study is conducted on widely used test systems with different network structures. The key factors that affect the voltage oscillations are identified. The dynamic loadability limits of the system for different induction motors are determined through a bifurcation study and both linear and nonlinear simulations are carried out to investigate the interaction between DG and loads.

The rest of this paper is arranged as follows. Following the Introduction, the paper describes about power system oscillation in Section 2. Detailed mathematical models of the dynamic devices are given in Section 3. In Section 4, modal analyses are carried out for the DG-integrated system with different types of motors. The influence of system parameters on the critical mode is investigated in Section 5. Nonlinear simulations for different motors under various operating conditions are outlined in Section 6. A discussion on the main findings is given in Section 7 and finally, conclusions and recommendations are made in Section 8.

2. Power system oscillation

When a stressed power system is subjected to small or large disturbances, it exhibits complex dynamic behaviours which are not straightforward to analyse [15]. All electrical and electromechanical power systems involve a wide range of resonant oscillatory modes which are described below [16].

- *Local plant mode oscillations*: One type of electromechanical oscillation is associated with coherent units at a generating station swinging with respect to the rest of the power system. Such oscillations are referred to as local plant mode oscillations. The frequencies of these oscillations are typically in the range of 0.8–2.0 Hz [4,17].
- *Inter-area mode oscillations*: The second type of electromechanical oscillation is associated with the swinging of many coherent machines in one part of the system against coherent machines in other parts. These are referred to as inter-area mode oscillations, and have frequencies in the range of 0.1–0.7 Hz [4,17].

Besides these modes, there are other modes called control and torsional modes.

- *Control mode oscillations*: These are associated with generators and poorly tuned exciters, governors, HVDC converters, and SVC controls [18]. Loads and excitation systems can interact through control modes [19]. Transformer tap-changing controls can also interact in a complex manner with nonlinear loads giving rise to voltage oscillations [20]. These modes have oscillation frequencies greater than 2 Hz [1].
- *Torsional mode oscillations*: Subsynchronous oscillations result from the mechanical oscillation of the mass-spring system of the turbine generator and the electrical resonance of the transmission system which are mutually excited causing serious shaft oscillations [21]. Usually these modes are excited when a multi-stage turbine generator is connected to a grid system through a series-compensated line [16]. The frequencies of these oscillations are in the range of 10–50 Hz.

3. Mathematical model

The modelling of dynamic devices used in this analysis is given below.

3.1. CHP-plant model

A CHP-plant consists of a synchronous generator driven by a gas engine. In this analysis, dynamics of the gas engine are neglected and its inertia is incorporated in the inertia of the synchronous generator.

With some typical assumptions, the synchronous generator can be modelled by the following set of nonlinear differential equations [20,22]:

Mechanical equations:

$$\dot{\delta} = \omega\omega_s - \omega_s, \tag{1}$$

$$\dot{\omega} = \frac{1}{2H}\left[P_m - E'_q I_{qg} - (X_q - X'_d) I_{dg} I_{qg} - D\omega\right], \tag{2}$$

Generator electrical dynamics:

$$\dot{E}'_q = \frac{1}{T'_{do}}\left[E_{fd} - E'_q - (X_d - X'_d) I_{dg}\right], \tag{3}$$

An automatic voltage regulator (AVR) is needed to regulate the terminal voltage of a synchronous generator. The input to the AVR is the difference between the set reference voltage and the measured terminal voltage. All modern AVRs or exciters are solid-state devices and, owing to their fast responses, are modelled as static gains. In this paper, the excitation system is a high-gain static system and the terminal voltage is measured using a transducer with first-order dynamics:

$$E_{fd} = K_a u_{fd},$$

$$\dot{V}_{tr} = \frac{1}{T_r}[-V_{tr} + V_t], \tag{4}$$