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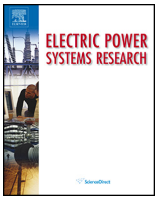

Voltage support in industrial distribution systems in presence of induction generator-based wind turbines and large motors

M.A. Paez[a], M.B.C. Salles[a], C. Rahmann[b], A.P. Grilo[c,*]

[a] University of São Paulo, São Paulo, Brazil
[b] University of Chile, Santiago, Chile
[c] Universidade Federal do ABC, Brazil

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ABSTRACT

Industrial loads are usually composed of large induction motors (IM). These motors present a critical behavior under some circumstances, e.g. during starting and faults in the system. Currently, induction generator-based wind turbines are also connected to distribution systems. Essentially, these generators present the same behavior of large IM and, when directly connected to the system, their interaction can increase voltage sag levels or even lead the system to a voltage collapse. These generators, however, are usually provided with specific controls or power electronic-based equipment to comply with the voltage ride-through capability required by the grid codes. These resources, however, can be used to minimize the impact of large motors in the grid or even minimize their impact on voltage sags caused by faults in the system. In this context, this paper has the objective of analyzing the impact of different technologies used in induction generator-based wind turbines during disturbances in distribution systems in the presence of large IM. The analysis aims to clarify the potential benefit of wind turbine allocation at the demand side of an industrial power distribution system. Based on the results, an adapted control scheme, considering the control strategies currently available, is proposed for the grid side converter of the doubly fed induction generators to improve power quality.

1. Introduction

Among the different sources of power quality issues present in distribution system, the behavior of large Induction Motors (IM) represents an important one [1–3]. Basically, these motors produce or increase voltage sags during transitory operation conditions, which occurs during starting or voltage sags caused by faults in the system. In fact, the starting of large IM at distribution level may produce severe transients and voltage disturbances in the network, depending on their nominal power and operation cycle. The system can be affected not only locally but also in buses electrically remote from the motor connection point [4].

Currently, there are practical recommendations for industry and utilities [5,6] recommending the best practices for minimizing the problems caused by IM. However, these recommendations do not take into consideration that modern distribution networks have distributed generation, specially, wind turbines. Wind power has developed very fast and has achieved considerable penetration level compared to other kind of energy resources.

One of the most employed technologies for wind energy conversion is based on induction machines. Although these generators present the same behavior of large IM, the majority of them is provided with power electronic-based equipment, allowing some specific controls. Fundamentally, these controls have the objective of providing voltage support during disturbances in the grid, given the sensitive behavior of these machines.

The performance of power system considering either IM behavior [1–3,7] or operation control of wind turbines (WT)s [8–12] at distribution or subtransmission level has already been analyzed in several works. However, there are no studies about the dynamic interaction between WTs operation in industrial power distribution system with large IMs. The current literature covers the analysis of the operation of isolated systems equipped with WTs and IMs [2,13,14]. The operation of a distribution system with WTs and large IMs can be challenging during disturbances. During a voltage sag, the rotor speed of WTs based on induction generators will increase considerably, and the generator will need an additional amount of

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Abbreviations: DFIG, Doubly Fed Induction Generator; LVRT, Low Voltage Ride-Through; IM, Induction Motor; GSC, Grid Side Converter; RSC, Rotor Side Converter; SCIG, Squirrel Cage Induction Generator; WT, Wind Turbine.

* Corresponding author.
E-mail address: ahda.pavani@ufabc.edu.br (A.P. Grilo).

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reactive power to sustain operation [9–11] (the characteristic of the rotor circuit become more inductive as the leakage reactance is proportional to the slip). At the same time, IM will also require more reactive power from the system due to the decrease in electromagnetic torque and reduction of the operation speed (increasing slip). Considering the aforementioned situation, the distribution system performance should be evaluated considering critical events in the system, such as motor starting and faults in the system.

This paper analyzes the use of voltage support capabilities available in induction generator-based wind turbines to minimize the impacts of large IM in distribution systems during the motor starting and system faults. As a consequence, the paper aims to clarify the potential benefit of wind turbine allocation at the demand side of an industrial power distribution system.

The analyses are based on simulations considering a typical distribution system with three large IM. Firstly, the interaction between a motor in operation and the starting process of a second and a third motor is investigated. Then, two types of WT generators are considered in the study: squirrel cage induction generator (SCIG) and doubly fed induction generator (DFIG). The DFIG-based WTs are the most installed worldwide, however, SCIG may still be found in some countries where wind power installations were carried out during the early stage or beginning of this technology development. In addition, a few manufactures, like Suzlon, were still commercializing the SCIG technology by 2012 [15].

As a result of these studies, it can be noticed, if the voltage support capability of wind turbines can reduce the impact of large IM on voltage sags. So, the different voltage support devices and control strategies are considered in the simulations. The selected cases are based on the existing technology and on possible advanced configurations that may need small changes in control algorithm only. For the SCIG, the options considered are: capacitor bank, Static Synchronous Compensator (STATCOM), and soft starter and STATCOM. For the DFIG, power factor control (or VAR control) and terminal voltage control will be carried out, considering different buses as reference during the investigation.

This paper is organized as follows. Section 2 provides an overview of the behavior of induction machines during transitory operation conditions. The applied dynamic models and their components are explained in Section 3. Section 4 presents the performed analysis of motor starting. In Section 5, the dynamic analysis during grid fault is discussed. Section 6 presents the main conclusions.

2. Dynamic behavior of induction machines

Voltage sags and interruptions produce each year in the United States a major economic damage estimated to be between U.S. $104 billion and U.S. $164 billion [16]. The voltage sags can be caused by short circuits at transmission and distribution levels, large load variations and IMs starting [1]. Voltage sags last from a few cycles to 1 min [4]. The shape of the voltage depends on network topology, line and cable impedances, load dynamic and the type of disturbance [4]. The induction motor is a source of disturbance (when is starting) and also an affected equipment (while in steady-state operation or also in starting process).

The dynamic behavior of the induction machine can be analyzed by the equivalent circuit of squirrel-cage induction machine presented in Fig. 1a, where R_S and R_R are the stator resistance and rotor resistance referred to the stator; X_S is the stator leakage reactance; X_R is the referred locked-rotor reactance; L_R is the referred rotor inductance; X_M is the magnetizing reactance; V_T is the terminal voltage per phase; s is the slip.

In order to analyze the electromagnetic torque, the circuit of Fig. 1a can be represented by its *Thévenin* equivalent circuit in Fig. 1b, where V_{TH}, R_{TH} and X_{TH} are the stator Thévenin circuit components, they are given by:

$$V_{TH} = V_{\phi}\frac{X_M}{\sqrt{R_S^2+(X_S+X_M)^2}} \tag{1}$$

$$Z_{TH} = R_{TH}+jX_{TH} = \frac{jX_M(R_S+jX_S)}{R_S+j(X_S+X_M)} \tag{2}$$

The influence of voltages sags on the induction machine electromagnetic torque can be seen by analyzing its steady-state equations, see Eq. (3). Such equation shows the relation between the produced electromechanical torque and machine terminal voltage (in this case, the Thévenin voltage), adapted from the generator equations presented in Grilo et al. [17].

$$T_e = \frac{3V_{TH}^2\left(R_R/S\right)}{\omega\left[\left(R_{TH}+R_R/S\right)^2+(X_{TH}+X_R)^2\right]} \tag{3}$$

where T_e is the electromagnetic torque; ω_{sync} is the synchronous angular velocity;

For motor operation, the largest value of X_R and V_{ab} (induced rotor voltage, see Fig. 1) occurs when the induction motor is at rest ($X_R = 2.\pi.f_S.L_R$) and the frequency of the induced voltage at the rotor (f_R) is equal to f_S (60 Hz for this case). The rotor reactance (X_R) and the induced rotor voltage decreases until the rotor achieves its nominal speed. At the nominal speed, the rotor frequency (f_R) depends on the rotor slip (s) and is equal to "$s.f_S$". The nominal slip (around 0.04) is very small compared to the slip at rest (equal to 1). This fact can explain the large amount of reactive power consumption during motor starting.

The quadratic relationship between electromagnetic torque and terminal voltage, shown in Eq. (3), indicates the negative impact of voltage sags. During a voltage sag, the electromagnetic torque will decrease, resulting in decrease (for motors) or increase (for generators) of the rotor speed. As a result, the machine will require more reactive power from the grid. To sum up, the consumption of reactive power by the motor increases when starting or recovering its nominal speed and, by consequence, the depth of the voltage sag and its duration [1].

There are several methods to avoid high voltage sags during IM starting. The most adequate starting method depends on the power system constraints and characteristics, the load to be accelerated and the overall costs of the additional equipment [7]. The main methods are: (a) The full voltage method (or direct connection): It is the cheapest and most commonly employed method. The implementation produces high starting torque, the highest required reactive current and the shortest acceleration time [7]. (b) Reduced Voltage Starting Methods: A reduced voltage is applied and it returns to the nominal value when a predefined speed (or current) set-point is reached [7]. The control of the voltage can be performed by solid-state starters, adjustable frequency drives, autotransformers, soft starter, external rotor resistances, wye-delta connection changes and changes in windings connection types.

Since the voltage sag can be reflected at buses in the vicinity, not only the voltage behavior at the local buses should be verified. The choice of the starting method should also consider other components of the system, for instance, distributed generators connected to the same system. As already pointed out, induction generator-based wind turbines are usually provided with power electronic-based equipment that can be employed for voltage support during disturbances in the grid. These resources can be used to minimize the impact of starting a large motor in the grid or even minimize the duration of voltage sags after faults in the system.