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Transient stability of a large doubly-fed induction machine in a pumped-storage plant

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ABSTRACT

In recent years, the doubly-fed induction machine (DFIM) has become one of the most commonly used generators, especially for wind-power plants. The second field where DFIMs have a clear advantage over "classic" generators is their application in hydro pumped-storage plants, where larger units are employed. This paper addresses the transient-stability problem associated with DFIMs. In order to be able to understand the machine's behavior at an engineering level, the currents and magnetic fluxes during the transients, as well as the oscillations of the rotor speed and the power after the fault, are analyzed. The results of the analysis show that the resistance of the so-called "crowbar protection" is of vital importance for power- and speed-oscillation damping as well as for maintaining the system's transient stability. Therefore, optimization of the crowbar-protection resistance should be performed prior to the installation of a large DFIM in a relatively weak grid.

1. Introduction

Some of the major problems associated with electric-power systems (EPSs) that involve a considerable proportion of unpredictable renewables could be solved by the introduction of large electricity-storage facilities. At the present time, an economically acceptable option for such purposes is a hydro pumped-storage plant (PSP). As was explained by a group from the USA at a general Cigre meeting, "wind needs a dancing partner", and PSPs could be the ideal "dancing partner" for renewables.

On the other hand, it is not likely that the growing needs for electrical energy in the future can be met only with renewables. One of the lessons from history is that after an economic crisis the consumption of electrical power in Europe will rise more quickly than the long-term trend. This means that after a certain period the level of consumption will probably be following the same trend line as if there had been no crisis. Therefore, large power plants (e.g., coal and nuclear) are still going to be needed for the foreseeable future. However, as these types of power plants are characterized by constant levels of production, and so cannot adapt easily to the changing loads or the fluctuating production from renewables, PSPs could again play an important role.

Existing PSPs are usually based on synchronous machines. Nevertheless, recently, a new technology based on the so-called doubly-fed induction machine (DFIM) has become available. This technology is well known from wind-power plants, although for PSPs the technology is still relatively new. There are some advantages that exist when using a DFIM; firstly the same aggregate can be used for generating and pumping mode (normally such pumping plants use two pipeline branches with two aggregates), further the pumping speed, i.e., power, can be adjusted in accordance to temporary conditions (e.g., available "cheap electricity") and it can achieve a higher efficiency as its speed of rotation can be optimized in accordance to a temporary head in the same time avoiding a turbine cavitation area. It is expected that use of this technology is going to increase in PSP's therefore addressing some basic principles of dynamic behavior of a DFIM in PSPs may be quite timely.

In Slovenia, the 195 MVA PSP Avce has been in commercial operation since 2009, and there are plans to build another. PSP Avce is connected to the weak 110-kV network with only a few small hydro aggregates included, which means there have been serious concerns about the dynamic behavior of the machine during and after faults. For this reason, an extensive study of the dynamic behavior of the EPS with the PSP Avce was performed.

The structure, modeling and control of a DFIM—as a component in wind-energy generation—is well described in Ref. [1]. Since the crowbar protection of a DFIM during a fault turns the DFIM into an induction machine, the relevant literature about induction machines should be considered, e.g., [2], and while for wind-energy

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conversion there are many references regarding the modeling and control of a DFIM [3–10], for the application of a DFIM in a PSP the literature is scarce and incomplete [11–15]. This paper is one of the first attempts to present the dynamic behavior of DFIM in PSP. Basis of a DFIM's operating features can be found in Refs. [16–18].

The mathematical representation of a DFIM is relatively complicated and, in general, it is not easy to understand the behavior of a DFIM, especially during transients. All this makes such an element in a power system rather "suspicious" to operating engineers, who often dislike elements in "their" system that they do not understand. Therefore, one of the aims of this paper is to describe the behavior of a DFIM from the point of view of a power-system engineer in order to be able to properly apply it in computer programs for dynamic simulations and to estimate the plausibility of the results. For this reason a DFIM's behavior in an EPS is analyzed and presented mainly by applying the trajectories of the active power and the speed, while the internal variables like the rotor and stator currents and the magnetic fluxes during the transients are represented descriptively. However, since during and after large faults the converter of a DFIM is disconnected, its control is not considered in the paper.

The paper is organized as follows: Section 2 presents the introduction to the dynamic behavior of a DFIM. Section 3 presents the operating characteristics of a DFIM in the steady state. Section 4 presents the dynamic behavior of a DFIM. Section 5 presents the effect of the resistance of the crowbar protection. The results of the numerical simulations of a DFIM in the model of the Slovenian electric-power system are given in Section 6. Section 7 draws the conclusions.

2. DFIM dynamic behavior

During a fault and shortly after its clearance, the crowbar protection disconnects the converter from the rotor and links the rotor windings, either directly or via ohmic resistances. In this way a DFIM behaves as an asynchronous machine until the crowbar protection is de-activated. It should be noted that a pre-condition for the de-activation of the crowbar protection is a decrease in the rotor current below a certain value, which is acceptable for a converter.

In the literature, the transient stability of asynchronous machines is given far less attention than the transient stability of synchronous machines, which are normally used as generators in electric-power systems (EPSs). In this section the dynamic behavior of a DFIM (as an asynchronous machine) is presented and compared with a synchronous machine.

Steady-state and dynamic behavior will be presented in following sections with the help of magnetic fluxes inside electric machines. Stator windings—that are connected to the network—generate stator magnetic flux Φ_s that is rotating with synchronous (network) speed. Currents in rotor windings generate rotor magnetic flux Φ_r. Its frequency equals to the sum of mechanical speed of rotor and the frequency of rotor current. In steady state this sum equals to the synchronous (network) speed, because rotational speed of Φ_s and Φ_r in steady state equals, only some angle between both fluxes exists. During transients this angle between Φ_s and Φ_r oscillates as it is described in following sections.

3. Steady-state operation

Regardless of the type of machine, the torque that moves the rotor is caused by the angular difference between the rotor's magnetic flux Φ_r and the stator's magnetic flux Φ_s. If Φ_r lags Φ_s, the machine operates as a motor, while in the case that Φ_r leads Φ_s, the machine operates as a generator. A synchronous machine's Φ_r rotational speed is due to the DC excitation being "stiff linked up" with the rotor's rotational speed and the angle between Φ_r and Φ_s is defined as the power angle, which is strongly related to the electrical machine's active power and stability.

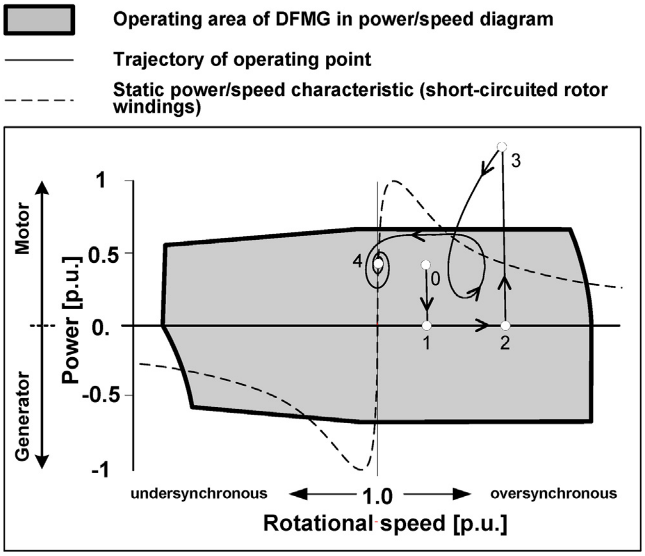

Fig. 1. The trajectory of operating point in P/speed plane during the transient.

In an asynchronous machine the currents in the rotor windings are alternating, their frequency is self-acting set to the difference between the rotational speed of Φ_s and the mechanical rotational speed of the rotor. In this way the frequency of the rotor currents compensates for the leading or lagging of the mechanical rotational speed (i.e., slip) of the rotor according to the network frequency. This means that the angle between Φ_r and Φ_s in asynchronous machines is, during steady-state operation, constant, like in any other type of machine.

In a DFIM the frequency of the rotor currents is not self-acting set according to the rotor speed, as it is in the case of an asynchronous machine, but the other way around, i.e., the rotor's mechanical speed is self acting set according to the frequency of the rotor currents that are forced by the converter. In this way, by using a converter, the rotor speed can be precisely set because the angle between Φ_r and Φ_s is constant during steady-state operation.

4. Dynamic behavior

During transients the angle between Φ_r and Φ_s oscillates. In synchronous machines, where the position of the rotor is stiff linked up with Φ_r, the rotor oscillates in the same manner as Φ_r. This behavior of a synchronous machine is well described in the literature. As already explained, during a transient a DFIM in fact transforms into an asynchronous machine due to the crowbar protection being activated.

During transients the asynchronous machine's angle between Φ_r and Φ_s also oscillates. The trajectory of the operating point in the P/speed plane is presented in Fig. 1. As the operating point before the fault may be anywhere in the operating area (shadowed area for a typical DFIM), let us assume it is at the point 0. At the moment of the fault it jumps to "1" and moves toward "2" during the fault, as the rotor accelerates due to the absence of an electrical torque. The crowbar protection in real machines remains activated for quite some time after the fault's clearance, with the tendency "rather more time, than less", in this way protecting the converter. After the fault clearing, the operating point jumps to "3". If there were no oscillations between Φ_r and Φ_s, and no saturation, the point "3" would be placed on a static power/speed characteristic (dashed line) and the rotor would decelerate along it toward point