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A power control strategy for flywheel doubly-fed induction machine storage system using artificial neural network

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ABSTRACT

A large-capacity low-speed flywheel energy storage system (FESS) based on a doubly-fed induction machine (DFIM) consists of a wound-rotor induction machine and a back-to-back converter rated at 30–35% of the machine power rating used for rotor excitation. This system has been promoted as a viable mean of energy storage for power system applications as grid frequency support/control, uninterruptible power supply (UPS), power conditioning, and voltage sag mitigation. This paper presents a simple power control strategy based on artificial neural networks (ANN) to charge/discharge a flywheel DFIM (FW-DFIM) storage system while maintaining controllable grid side power. The proposed controller is based on conventional vector control system supplemented by an ANN-based current decoupling network used to develop the required rotor current components based on the required grid power level and flywheel instantaneous speed. The controller is designed to avoid overloading both stator and rotor circuits while the flywheel is charged/discharged. Additionally, it avoids using the required outer power loop or a hysteresis power controller, hence, simplifies the overall control algorithm. The validity of the developed concept along with the effectiveness and viability of the control strategy in power system applications is confirmed by computer simulation using Matlab/Simulink for a medium voltage 1000hp FW-DFIM. The simulation study is carried out for uninterruptible power supply (UPS) applications and power leveling to improve the quality of electric power delivered by wind generators.

1. Introduction

The increased penetration of renewable energy sources offers a new set of challenges in balancing consumption and generation in power systems. Therefore, the deployment of energy storage devices in distribution networks becomes a necessity to effectively guarantee this power balance and improve system performance [1]. The intermittent nature of renewable energy sources (e.g. wind energy and solar energy) along with their increasing penetration level in power grids requires economical and efficient storage systems to allow these generators to contribute to ancillary services [2]. Besides, to optimize the economic performance of power systems with high penetration of wind and solar power, it becomes desirable for these sources to participate in unit commitment, economic dispatch, and electricity market operation [2].

Flywheel energy storage systems (FESS) are worthy candidates for such tasks since they are capable of power provision from short bursts to several minutes in an economical fashion compared to other means of energy storage [3]. Flywheels are generally classified into two main groups, namely, high speed flywheels and low speed flywheels. High-speed flywheels have superior energy density but low power rating that is limited by cost and difficulty of cooling [4]. Moreover, supported by magnetic bearings, the rotor should run in a vacuum to reduce friction. Other advantages of high-speed flywheels include their light weight, small form factor, and relatively low power losses [4–6]. On the contrary, low speed flywheels, rated at hundreds of megawatts and normally operated in air, have been used in high-energy physics facilities due to their rugged construction, high reliability, and accordingly lower cost for the same rating [4]. Permanent magnet machines are normally employed with high speed flywheels [7,8] but induction machines are better economical alternatives for low speed flywheels [9–14]. A superconducting FESS is a recent promising electromechanical energy storage system used for high speed applications using non-contact superconductor bearing which offers long life, high energy density, and low rotational loss compared with conventional techniques [15]. Nevertheless, the corresponding high cost represents one of its drawbacks for practical applications [15,16].

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Power electronic converters are required to integrate FESS to the grid. In high power applications, the doubly-fed induction machine (DFIM) possesses an economically advantageous configuration as it utilizes a back-to-back voltage source converter (VSC) rated at 30–35% of the machine size [9,17,18]. This configuration was previously applied in industry for standby supplies [10] and power conditioning [11]. A study of the control of a 20-MW, 200-MJ system to smooth the pulsating demand of a synchrotron is presented in [12]. It was also proposed to improve the quality of the electric power delivered by wind power generators [13,14]. In [19], a novel FESS, flexible power conditioner, which integrates both the characteristics of FESS and DFIM, is proposed to improve power system stability. Power flow control of flywheel DFIM (FW-DFIM) in generator mode, storage mode, and standby mode is also discussed in [20].

Since doubly-fed induction generators (DFIGs) and FW-DFIMs are functionally the same, same controllers can be applied. Generally, FW-DFIM is controlled using conventional field-oriented vector control [21]. A double-closed-loop approach is usually employed. The outer power control loop is employed to attain an independent control over the active and reactive powers of the machine. Synchronous-frame proportional–integral (PI) current controllers are then used in cascade with the outer control loop to regulate the rotor output current [21]. In literature, the quadrature current component of the rotor current is usually driven based on stator reference power [21–23], torque reference [24–28] or grid active power control using additional PI controller loop driven by the total power error [19,29]. Using the stator reference power involves an assumption that the total grid power is approximately equal to the stator power. In reality, both stator and rotor circuits share the power injected into the grid by the FW-DFIM. The rotor power share is speed-dependent and can approximately reach ±30% of the stator power at a rotor speed of ±30% of the machine synchronous speed. Alternatively, the quadrature current component is driven using torque reference which neglects the effect of both stator and rotor losses. Furthermore, the relation between the grid power and the developed torque is speed dependent, which is continuously varying in flywheel applications. Controlling the machine power using additional external PI controller loop may be a simple solution. Yet, the gains of PI controllers are tuned using small signal analysis of the nonlinear equations describing the DFIG behavior. This leads to non-optimal behavior of the overall control scheme over the flywheel wide speed range while being charged/discharged. A tradeoff between maintaining the system stability over the whole speed range and achieving acceptable system dynamic response should be made while designing the PI controllers [21]. The direct torque/power control approach was proposed to solve this problem [30,31]. Nonetheless, there are always significant torque/power ripples. Increasing the switching frequency reduces the ripple magnitude but with a corresponding increase in inverter losses, which is not appropriate for large power applications. In addition, the converter switching frequency depends on the operating conditions and the controller performance may deteriorate during the machine starting and low-speed operation [21].

This paper presents a power control strategy to charge/discharge a FW-DFIM for constant power delivered to the grid. The proposed controller is based on conventional vector control [5,6] supplemented with a current decoupling network based on artificial neural networks (ANN). The ANN is employed to develop the reference rotor current component dependent on the required grid power level and the flywheel instantaneous speed. This technique is proposed for power leveling to improve the quality of the electric power delivered by wind energy generators. The proposed controller can be similarly used in UPS applications where a constant power level needs to be delivered to the load for a predetermined time [9–11]. In comparison with other controllers provided in literature, the proposed ANN-based controller simplifies the overall controller by avoiding the external power loop and the required tuning process. Moreover, due to the nonlinear nature of the DFIM system equations and the flywheel wide speed range, using simple PI controller yields non-optimal behavior and most likely additional stability problems. On the other hand, the proposed ANN-based current decoupling network provides faster execution speed due to its parallel processing, wide speed operation, better performance, and simpler controller. The controller also avoids overloading the stator and rotor circuits while the flywheel is charged/discharged for the whole speed range (0.7–1.3 pu). Since it is preferable to avoid the external power loop, two current decoupling networks are compared. The first decoupling network uses the stator power reference to derive the required quadrature rotor current component, which is commonly used for both squirrel cage IM and DFIM [21–23]. The second is the proposed ANN-based current decoupling network. The validity of the developed concept, along with the effectiveness and viability of the control strategy, is confirmed by computer simulation using Matlab/Simulink on a medium voltage 1000hp FW-DFIM system for different cases.

2. Proposed constant grid power controller

In a DFIM, the power is shared between the stator and rotor circuits. The bulk of the power is processed by the stator. The power shared by the rotor depends mainly on the operational mode (i.e. motoring or generating mode) and machine speed (i.e. sub-synchronous or super-synchronous speed). Hence, the controller should consider the machine speed and operational mode when calculating the required rotor current commands. Previously proposed controllers consider only stator power and neglect the effect of rotor power [5]. If a fixed terminal power is required, then the rotor power should be considered since it can reach magnitudes of ±0.3 pu as the machine speed increases beyond or decreases below synchronous speed. The rotor active power can be approximated by (1);

$$P_r \approx sP_s \tag{1}$$

where s is the machine slip, and P_s and P_r are the stator and rotor active powers respectively.

The grid active power can be then approximately given by (2).

$$P_g \approx (1 - s)P_s \tag{2}$$

This approximation depends on the machine active power rating, its parameters, and whether the machine is running sub or super-synchronously. For a given reference output active power, it is required to determine the required rotor reference current components as a function of the machine speed such that the total grid power is constant. This begins with determining the relation between the stator active power, and machine speed and grid active power. Based on steady state equations, contour charts of varying grid active power are plotted as a function of the stator active power and rotor speed. Then the locus curves for constant output grid active power are used to determine the corresponding rotor current component variation with speed. This calculated relation is the foundation of the proposed ANN-based decoupling network. As mentioned before, the traditional field-oriented vector control used with a DFIG can be applied to the FW-DFIM. However, the reactive power contribution from FW-DFIM systems is of little importance [32]. For maximum flywheel utilization, unity power factor operation of the proposed flywheel system is developed; therefore, the system supplies only active power. Nevertheless, the proposed controller can be simply modified, as will be shown, to effectively contribute with both active and reactive powers [14].