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Low voltage ride-through strategies for doubly fed induction machine pumped storage system under grid faults

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ABSTRACT

Pumped storage units bring stability to the electrical power system, so they must remain connected to the grid even during grid faults. In this paper, the authors propose efficient and simple solutions for a doubly fed induction machine pumped storage (DFIMPS) system during grid faults. In case of balanced grid faults, a control reconfiguration strategy is introduced and a hardware solution is applied in the case of unbalanced grid faults. The reconfiguration strategy consists of a commutation between different control strategies; when a balanced grid voltage fault occurs during pumping mode, the control algorithm switches to the synchronization one but based on the new grid conditions. So the proposed reconfiguration method reduces the negative impacts of grid fault occurrence on the DFIMPS system by cancelling rotor and stator over-currents and decreasing the electromagnetic torque and stator power oscillations. Simulation results carried out on a 4 kW DFIMPS system illustrate the effectiveness of the proposed approach.

1. Introduction

The amount of electricity produced using renewable energy sources (RES) is constantly increasing and requires more power control in production units and loads [1,2]. The unpredictable behavior and the intermittency of many RES, such as wind turbines and solar panels, can result in fluctuating power generation leading to changes in the availability of electricity [3] which are difficult to control.

Balance has always been the basic requirement. Therefore, additional energy storage systems are needed to ensure grid operation stability [4]. Three main categories of energy storage are currently in use: mechanical processes (pumped storage [5,6] and compressed air [7,8]), electrochemical (batteries [9]) and electromagnetic (super-capacitor [10]). In this field, many published reviews have dealt with storage technologies for fluctuating quantities of renewable energy production [11–13]. In this work, the authors present the different storage technologies of electrical power and their classification according to various criteria such as the storage capacity, lifespan, installation cost and efficiency.

For high power levels, the pumped storage system is the most successfully implemented method when suitable locations are available [14,15]. Such systems exist today, and many potential installations are under development in many countries. In Ref. [16], new structures using variable speed topology are proposed for the Swiss case. Recent projects and future perspectives of pumped storage hydropower in Bulgaria are discussed in Ref. [17], taking into account the historical background and its impact on hydropower. In Ref. [18], the current development of pumped hydro storage projects in Germany is analyzed and potential revenues and possible barriers are evaluated. This storage system uses simple and proven technology: the extra energy provided by RES is used to pump water from a low basin into a higher reservoir when energy consumption is low. This energy is then released when demand is high (turbine mode), as in peak load periods [19].

The feasibility of new pumped storage installations coupled with renewable energy systems have been widely discussed. In Ref. [20], the effect of the integration of wind-pumped-storage on the dynamic behavior and stability of autonomous power systems, such as those existing on small- and medium-sized non-interconnected islands, is analyzed. In Ref. [21], the technical and

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Nomenclature

V_s, V_r, V_g	Stator, rotor and grid voltages
i_s, i_r	Stator and rotor currents
Ψ_s, Ψ_r	Stator and rotor fluxes
$\omega_s, \omega_r, \omega$	Stator, rotor, mechanical velocities
$\theta_s, \theta_r, \theta_g$	Stator, rotor and grid angles
T_{em}, T_L	Electromagnetic and load torques
Ω	Mechanical rotation speed in rad/s
N_P	Pole pair number
J, f	Inertia moment, Friction coefficient
P,Q	Active and reactive Powers
S_{abc}	Switching states
N	Machine rotation speed in rpm
g	Machine slip

Subscript and superscript

s,r,g	stator, rotor and grid indexes
d,q	direct and quadrature component indexes
α,β	α β component indexes
*	Reference values
f, n, syn	Fault, nominal and synchronization indexes

economical appraisal of using seawater pumped storage for regulating the export of renewable energy to the national grid is discussed. In Ref. [22], an optimization of the system design of a hybrid solar–wind-pumped storage system in standalone mode for an isolated micro-grid of a scale of a few hundred kiloWatts is proposed based on a techno-economic evaluation. In Ref. [23], a novel unit commitment considering the association of a wind system and a hydro power station plant is introduced.

These studies mainly concern the economic aspect, the social impact and the legal constraints. Also, literature that addresses the optimal sizing issues and control strategy developments has been reported [24–26].

In order to ensure a fast response to supply peak loads or to store any produced energy in surplus at any operating point, variable speed operation is used. For example, in Ref. [27], a study was conducted for the 26-year-old Kadamparai pumped storage plant (4 * 100 MW) located in India, with the objective of adopting variable speed technology considering the existing hydraulic conditions. In Refs. [28,29], the next generation of variable speed pump-storage power stations in Europe is discussed. In Ref. [30], the characteristics of a 400 MW adjustable speed pumped storage unit for Ohkawachi Power Station is analyzed.

The DFIM (**Doubly Fed Induction Machine**) is preferred in this case to limit the required sizing of the power converter [31,32]. In most common structures, the stator is directly connected to the grid and an AC-DC-AC converter on the rotor side. The power exchanged through them depends on the operating speed range which is generally limited to ±30% of the nominal speed value. Thus, the required rating of converters is about 20–30% of unit rating [33].

Both stator and rotor sides are concerned by the behavior of the grid, so any gird disturbances will directly affect the pumped storage system. In Refs. [34–37], various studies were conducted to analyze the behavior under grid disturbances on wind turbine systems using the DFIM structure, which is the chosen topology of our studied system.

Up until now, various studies have been carried out on the Fault Ride-Through (FRT) capability and many methods have been proposed. All of them are based on hardware redundancies [38,39] or analytical redundancies [40,41] or both [42–44]. Hardware redundancy methods often require additional equipment and increase maintenance costs as well as supplementary supply and space. The analytical redundancy-based approach is achieved through the application of another control strategy after fault detection. Grid fault impact and FRT techniques related to wind turbine systems have been largely reported in the literature since severe grid codes requirements (GCR) have been established for such systems.

As with the wind turbine systems, grid faults could be dangerous for the pumped storage system. Such systems are not concerned by the severe GCR, so limited material has been published on their behavior under grid faults.

Considering the advantages of pumped storage systems, their availability and robustness under grid faults are critical issues. Therefore, service continuity under grid faults is important and new concepts should be found to enhance availability by riding through grid faults and ensuring the stability of the grid even under disturbances.

In order to ensure better stability of an electrical power plant integrating a pumped storage system, this paper deals with the DFIMPS system under grid faults and proposes hardware and software solutions taking into account the working phase, the fault type (balanced or unbalanced grid faults) and the magnitude of the fault (minor or major). Firstly, the different operation phases are detailed. Three main phases are identified: starting, synchronization with the grid and then pumping; for each phase, a control strategy is developed. Secondly, the main contribution of this paper consists in new, simple FRT strategies for balanced and unbalanced grid faults.

When balanced grid faults are detected, a control reconfiguration strategy is adopted. The proposed method is available either for large or small balanced grid voltage drops or overvoltages. It is based on the DFIM speed adjustment when the balanced grid fault magnitude is minor.

When the balanced grid voltage fault magnitude is significant, our investigation is realized through the adjustment of the rotor current control. Compared to the other proposed methods in the literature such as in Ref. [45], where components that oppose the transients appearing in the electromagnetic torque, currents and power are added to the references established for correct functioning. The novelty in our approach is that the rotor current control modification is based on the use of the synchronization control which has already been established. This control is used to adapt the system to the new grid conditions when three-phase voltage dips occur. The adaptation with the new grid conditions is enhanced also when the pumping mode is reestablished by recalculating references taking into account the faulty grid voltage. With regard to the results obtained in this study, the transients are greatly reduced by the use of the grid synchronization algorithm.

The proposed method under unbalanced voltage dips is realized through the use of a three-phase asymmetrical Damping Resistor (DR). Each resistor is only triggered when a voltage dip is sensed in the grid. This method is already used in Ref. [39]. Compared to this cited paper, where the resistors are placed just before the stator windings and the rotor current control is adapted so no unbalanced voltage appears on the stator voltage. The novelty in our proposed approach is that the resistors are placed at the connection point between the DFIMPS and the grid and no rotor current control adjustment is needed in this case. Consequently, the main contribution of the proposed FRT approach is that it can significantly balance the three-phase stator voltage and reduce the negative sequence components of the stator voltage to a negligible value during unbalanced voltage dips using damping resistors without rotor current modification.