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Editorial

Doubly-Fed Induction Generator (DFIG) in Connected or Weak Grids for Turbine-Based Wind Energy Conversion System

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In the last thirty years the quantity of wind electricity generation has grown significantly due to its high-power density. Advances in wind energy technology have significantly decreased the cost of producing electricity from this renewable source. Nowadays, the generation of energy from wind sources plays a crucial role to increasing the green energy. In this context, wind energy conversion systems (WEC) must guarantee, in connected or weak grid operation, good stability in balanced or unbalanced conditions, high efficiency, high reliability and maximum power tracking in order to achieve the best performance when operating conditions vary.

Several solutions have been proposed in literature, some of which have also spread commercially. In particular, one of the most interesting approaches proposes the coupling of a wind turbine with a doubly-fed induction generator (DFIGs).

The adoption of a DFIGs generator in a WECs is characterized by several advantages: robust and flexible system, energy generation in a wide operating range of wind turbines, simplicity of the control system and cost-efficient operation. Indeed, DFIG is directly connected to the AC grid on the stator side and driven through a power converter only on the rotor side. The rating of the converter varies typically between the 25% and 35% of the rated power, allowing an operation speed range of wind turbine from 50% to 120% of the rated speed.

However, this system also has an important disadvantage: the presence of slip rings leads to an increase in maintenance and in its costs. This has been a stimulus for scientific and industrial research in order to propose new or more performing solutions in order to be able to overcome or at least mitigate the negative effects of this aspect. In addition, the monitoring is also a fundamental issue: wind energy farms spread both in onshore or offshore arrangement making maintenance operations difficult and very expensive. From this point of view, the monitoring and/or predictive-maintenance approach represents an aspect that shouldn't be underestimated for the reliable and good operational availability during useful life of the whole system. All of the issues mentioned have been addressed in several scientific articles, the most significant of which have been selected and summarized below.

Starting from the management strategy of the several DFIGs belong to large wind farms (WF), an optimized solutions are proposed in literature in order to obtain the best value total WF active power. In [1] the authors propose an optimized reactive power distribution aimed to reduce the total losses and maximize the total active power production. The particle swarm optimization (PSO) algorithm is used to distribute the reactive power among the different groups, whereas a proportional approach assigns the single DFIG reactive power contribution in each group. An extensive numerical analysis includes losses shares of DFIG, power converters, inductive filter and transmission network, and accounts for power balance constraints, power grid reactive power dispatching constraints, voltage constraints, and DFIG rated power constraints. Simulations show a reduction of the total losses around 1% occurring for a peak active power of 5 MW generated by the single DFIG of 6 groups.

A particular issue of wind power plant is related to the forecasting of the power production through traditional power curves. These models are typically based on a uniform inflow wind, whereas the specific complex and heterogeneous terrains of installation make the DFIG subjected to a different turbulent wind condition. In [2], the authors propose a new model for effective axial induction factor of wind turbines that can be used for power prediction. The proposal is applied to a 2.5 MW stand-alone wind turbine, built in 2012 on the northeastern part of Kirkwood Community College in Cedar Rapids, Iowa. Data from SCADA System and a nearby meteorological tower confirmed that the proposed model performs better than the standard power curve, reducing power prediction error as much as 75%.

The most popular control for a DFIG is the Fiel Oriented Control (FOC), which offers numerous advantages that are widely known in the literature.

However, one of the main drawbacks of standard FOC schemes is represented by high ripples in active and reactive power. To minimize the fluctuations in active and reactive power, in [3] a synergetic sliding mode controller (SSMC) is proposed for a DFIG coupled to a dual-rotor wind turbine system. By replacing the exact linearization term of a conventional sliding mode controller with a synergistic control law, the SSMC is obtained. Such controllers are then employed in place of traditional PI controllers in the d-q current control loops of a direct FOC scheme. Numerical simulations show that current THD as well as active and reactive power ripples can be effectively reduced by SSMC scheme, which also features higher robustness against parametric variations.

As an alternative to the FOC control, in [4] the authors propose a modified Direct Power Control (DPC) capable of operating in presence of unbalanced power grid. Although the control is experimentally implemented in an orthogonal stationary reference frame related to the stator side, it is worth mentioning that all equations, equivalent circuits, and control diagrams are also presented in the d-q rotating frame. As main advantage, even in presence of unbalanced grid voltages, the proposed approach can be implemented without the need of positive- and negative-sequence voltage decomposition, reducing the computational burden. This can be achieved by adding a resonant contribution to the standard regulators operating on the stator power components. As testified by both numerical analysis and experiments, the introduced modification, which consists of a rotor current feedback in the stator-controlled reference frame, helps reducing the transient oscillation and introduces minor steady state improvements. In [5], instead, the authors present the stator flux control with the aim to operate the DFIG in a grid-forming mode, where the same control structure can be employed for grid-tied, stand-alone or islanded operation. The proposed approach ensures good grid forming and grid supporting behavior using stator flux tracking by an inner rotor current loop driven by droop control of both frequency and magnitude of the stator voltage. The control scheme is applicable both for grid-tied operation and for islanded operation. The proposed control scheme has been experimentally validated with reference to a 10 kVA test bench system.

The transient conditions of wind power plants can negatively impact on the grid stability. In particular, the power irregularities can induce grid frequency deviations and speed oscillations of the nearby synchronous generators (SG). The authors in [6] develop a novel control technique aiming at reducing these oscillations. In simulation environment, a DFIG is interconnected with the main SG through an infinite bus-bar system transmission line. The main goal is to develop a controller that guarantees system stability by damping the frequency due to the deviations of the SG rotor speed. The state of the system is observed by a Kalman filter and linear quadratic Gaussian (LQG) control approach is used for the oscillation damping. The results confirm the capability of the control to quickly damp oscillations with small settling times. As an additional advantage, thanks to the Kalman filter, the proposed approach avoids complicated signal measurements and relies on a reduced number of sensors.

The stability in WEC is an important aspect especially when wind systems are located in remote areas, where the connections to the grid are usually through long feeders of high impedance, leading to a weak interconnection. In this context, the authors in [7] present a new voltage regulator design for the static var compensator (SVC) with the aim to actively damp subsynchronous resonance (SSR) events by the implementation of a tweaked damping controller. The proposed approach has been validated through time domain simulations when the system is subjected to frequency disturbances on the grid side, mimicking the action of speed governors.

Most DFIG control schemes rely on the integration of the stator voltage equation to estimate the stator flux vector for the needed d-q frame orientation. In [8] the authors propose a full-order adaptive state observer to estimate the stator flux and rotor speed for a sensorless field-oriented torque control of a grid-connected DFIG. In the proposed scheme, the error in the observed rotor position is also estimated through an adaptive law based on Lyapunov theory by regarding the estimation error as an additional parameter of the DFIG dynamic model. To obtain a robust estimation around zero rotor voltages without affecting the FOC performance, a current injection strategy is also envisioned. The experimental tests on a 11 kW rotor-wound induction machine confirm that the adaptive full-order observer estimates the rotor position with a maximum error of 8 degrees, whereas the error of the non-adaptive observer can be as high as 20 degrees. As a result, the overall performance of the sensorless FOC control is improved.

The issue of a robust estimation of flux and rotor position is also addressed in [9] with application to a self-excited induction generator (SEIG) operating together with a battery storage system to supply an AC load in a standalone DC microgrid. In this work, discrete-time Kalman filters are used to estimate the SEIG rotor flux and the frequency at the AC load side, while a multilayer recurrent artificial neural network (ANN) is employed to track the SEIG rotor position. To train the ANN, an online procedure is conceived which uses the error between the rotor fluxes estimated by the standard SEIG voltage model and the Kalman filter to update the network weights. The envisioned sensorless schemes for the control and power management of the microgrid are assessed experimentally and prove robust to parametric variations and sensor inaccuracies, also allowing the avoidance of the PLL at the load side.

Increasing the efficiency of an electric machine is a mandatory completion in all fields of the industry. This improvement takes on even more importance for the production of electricity, especially from renewable sources. A significant increase in the overall system efficiency over direct online induction motors (DOL-IM) can be achieved by properly driving the electrical machine through suitable power converters. However, induction motor-based drives are much expensive solutions than the DOL-IM ones. In this perspective, the authors in [10] have proposed a new design solution within the context of direct online double-winding IMs (DOL DWIM) to obtain a significant increase in efficiency in a grid-connected WEC system while keeping reasonable the increased cost of the system with respect to DOL-IM solution. In particular, an auxiliary winding with the same distribution of the main winding, although with a reduced number of turns, is placed on the stator of an induction machine with the aim to set the machine power factor, increase the efficiency of the power conversion and mitigate speed oscillations due to torque disturbances. The auxiliary winding is supplied by a voltage inverter featuring a floating DC-bus capacitor. The inverter power and voltage ratings are much lower than those of the motor.

Some control strategies for the DFIG aim to improve the harmonic content of the three-phase network voltages when it works in islanding mode. In the [11] the authors present a control for the rotor-side converter (RSC) developed to provide symmetrical and three-phase voltage with minimized harmonic content at the terminals of the islanded load. Islanding operation is indeed characterized by uneven load on each phase and random behavior. In this context an optimum control has been developed with the aim to provide the reference voltages through the minimization of a square cost function. The voltages references are then imposed by properly controlling the rotor currents. Therefore, the control system also provides protection against exceeding the generator nominal ratings.

The simulation results achieved by randomly varying the three-phase load of the islanded grid are presented.

Other authors investigate, instead, about how a fault occurring in a wind power plant can affect the system performance and security. In [12], simulations and experiments are carried out to analyze the behavior of DFIG during grid voltage sag and swell. The analysis shows that fault-ride-through capability with Supervisory Control and Data Acquisition (SCADA) viewer software, Active Servo software and wind sim packages are more adaptable to the variations of voltage, avoid loss of synchronism, and improve power quality. Additionally, a braking chopper should be also used together with a resistive crowbar for protection purposes. Indeed, during the fault, the dc-bus voltage connecting the machine side converter and the grid line converter could rise to high values, with potential damage to the dc link capacitor.

Despite most DFIG control strategies discussed in literature refer to a nominal operating condition, a smooth startup procedure must be also envisioned to avoid high transient currents in the stator windings resulting from excessive mismatch between grid and open-stator voltages. Moreover, as wind power plants can be in remote areas with a high unbalance in grid voltages, the startup procedure should be able to manage a smooth connection of the generator to such unbalanced grid. A complete synchronization procedure for a low-impact connection of a DFIG to an unbalanced grid is presented in [13]. The procedure is achieved by including a negative-sequence controller for the rotor current. During open-stator operation, the controller enables to obtain unbalanced stator voltages that exactly match the grid voltages. As confirmed by experiments, the proposed control minimizes the stator current transients and achieves low-impact DFIG insertion into the grid.

With the growing interest in the use of induction generators for wind power systems, the need of reliable procedures for incipient detection and diagnosis of machine faults arises. As the condition monitoring of electrical machines evolves into the digital era, unsupervised data-driven methods that do not require expert knowledge and extensive labeled data for training are gaining attention. In [14], the authors assess the performance of unsupervised k-means clustering to recognize stator and rotor inter-turn faults and brush faults. To this end, harmonic signatures in stator currents and voltages and rotor voltages are employed as both stand-alone and combined features for the high-dimension cluster modeling. Extensive measurements on a 1 kW wound-rotor induction machine are carried out, and the performance of different clustering models is assessed by means of silhouette tests and elbow plots. The results show that k-means clustering yields accurate clustering structures and low values of mean squared error with respect to the ground truth, especially when employing the combined current and voltage harmonic signatures as features.

The condition monitoring is becoming more and more a crucial aspect for the WEC systems in order to ensure good availability and reduced cost of the produced power. Being able to identify a breakdown promptly allows you to better manage maintenance interventions. In [15] the authors discuss non-invasive monitoring techniques of the generator shaft alignment, which if compromised and untreated can lead to catastrophic system failures. The proposed approach is based on supervised machine learning analysis on the readily available generator controller loop signals to achieve detection of shaft misalignment conditions. This method provides an effective low-cost solution for misalignment monitoring in comparison with the traditional field practice that relies on invasive and costly drivetrain vibration analysis. The achieved results show an average recognition accuracy rate of up to 98.8%.

Finally, in the paper [16], the authors propose a viable control approach directed to brushless doubly fed induction machines (BDFIMs). BDFIM-based systems address the main inconvenience of DFIG-based ones: the presence of slip rings which leads to increased maintenance costs and outage times. However, the solution presents the penalty of complicated controller requirement connected to the variables decoupling capability strongly affected by the machine's non-linearity. In this context, the authors develop where an enhanced performance indirect vector controller able to decouple effectively the control of active and reactive powers. The proposed controller performance is investigated under various loading conditions showing enhanced transient and minimal steady-state oscillations.

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