Model-Based Predictive Rotor Current Control Strategy for Indirect Power Control of a DFIM Driven by an Indirect Matrix Converter

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Abstract—This paper presents a new control strategy using model-based predictive current control (MB-PCC) for a doubly fed induction machine (DFIM) driven by an indirect matrix converter (IMC). This strategy proposes the control of rotor currents, whose references are calculated from active and reactive stator power set points and the dynamic model of the DFIM. The control strategy works well in the four P-Q operating regions of the DFIM. The grid synchronization process is carried out by setting the P-Q power set points to zero. The results include the DFIM synchronization procedure as well as the active and reactive power control at variable shaft speed to validate the feasibility of the proposed strategy.

Index Terms—AC/AC power conversion, model-based predictive control (MBPC), doubly fed induction machine (DFIM), indirect matrix converter (IMC), power control, wind energy conversion systems (WECS).

NOMENCLATURE

t_s	Sampling time
Superscripts	
$'$	Variable or quantity referred to stator
$T, k, *$	Transpose, predicted, reference value
Subscripts	
s, r	Stator, rotor
in, f, g	IMC input, filter, grid variable

I. INTRODUCTION

According to the International Energy Agency, by 2018 the share of electricity generation in the world by renewable and waste sources (including hydro), was on track to reach coal as the main source of electricity, and had already surpassed

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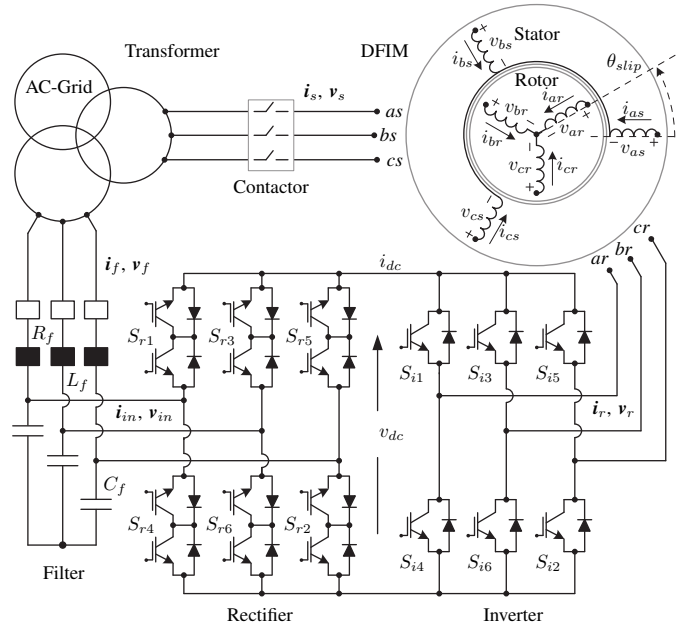
Fig. 1. Wind energy conversion system with DFIM driven by an IMC on the rotor side.

natural gas since 2013 [1]. Together, non-hydro sources such as geothermal, solar, wind, and bio-fuels, grew faster than any other energy source. Moreover, wind energy continues to receive attention within renewable energy sources due to significant government stimulus programs, cost reduction strategies, and technological advancements.

Classified broadly by mechanical, electrical, and control systems, the wind energy conversion systems (WECS) are also known as wind turbine generators (WTG) and are often arranged in groups to form a wind farm on the land (onshore) or on the sea (offshore). Several aerodynamic and electro-mechanic characteristics of the WTGs have changed in the last 40 years. The diameter of the rotor swept area has increased from 15 m to 220 m, the nominal power has increased from 50 kW to 12 MW in 2020 [2], and the driving technology from fixed-speed to full-variable-speed operation over recent years [3], [4].

Two of the main components in the operation of WECS are the electric generator and the power electronic converter. The

doubly fed induction machine (DFIM) is one of the dominating generator topologies for WECS rated at up to 4 MW, with approximately 50 % of the share in today's market [2], [3]. In spite of requiring a gearbox and slip rings that demand regular maintenance, the DFIM presents advantages such as decoupled active and reactive power control, operation on a wide speed range, and principally, a reduced power converter rating when installed at the rotor terminals [5], [6].

The power converter must satisfy the grid requirements, such as the rated voltage and current of the generator, bidirectional power flow, total harmonic distortion among others. The matrix converter (MC) is suitable for the control of variable-speed WECS since it can comply with the mentioned grid requirements. Furthermore, MCs feature sinusoidal input and output currents, high power density, controllable input displacement power factor, lightweight and can operate in environments with harsh temperatures and pressures [7], [8].

The indirect matrix converter (IMC) inherits the suitability and features of MCs to drive a WECS, but with a DC link that makes it easier to control with a more secure current commutation [9]–[11]. The IMC does not have large energy storage elements. The latter enables a compact design but limits the reactive power capability to that of the energy stored in the filter and in the load [12], [13].

Variable-speed WECS require accurate control of the electric torque or machine currents. Many methods have been proposed in the literature to guarantee the stable, secure, and efficient operation of WECS, to maximize energy capture, as well as to comply with fault ride-through capabilities according to continuous grid code updates [14].

Conventional power or torque control techniques for DFIM in WECS can be generally classified as direct or indirect [15]. Indirect control is often related to vector control (VC) and it is characterized by using modulation (e.g. pulse width modulation [16] and space vector modulation [17]) to control the power converter. Direct techniques, such as direct power control (DPC) and direct torque control, establish a direct relation between the controlled variables and the switching states of the converter [18]. VC applied to DFIMs involves relatively complex calculations and requires extra current loops carefully tuned to ensure system performance and stability under the whole operating range [19].

In DPC, the converter's switching states are selected through a table based on the instantaneous errors in the control variables. The key part of DPC implementations is the correct and fast estimation of the WECS power output. The DPC main disadvantage might be the resultant variable switching frequency and excessive power ripple [20]. There are recent works that have proposed predictive DPC with virtual power [21] or virtual torque [22] reference for the synchronization (mode 1) and power regulation (mode 2) of the DFIM in a two-step strategy. Other works have applied predictive control to address unbalanced grid conditions [23]–[25] using conventional converters, and using a MC [26].

A model-based predictive control (MBPC) synchronization strategy for the DFIM was proposed in [11]. There, a simplified DFIM model with an open stator was used, in the $\alpha\beta$ reference frame, achieving the process without the need of any modulation strategy while driven by an IMC.

The selection of an IMC to drive a DFIM in [11] is mainly based on two key characteristics where it has been proven to be better than back-to-back converters: the power density and the power-to-mass ratio [27]. Moreover, the configuration shown in Fig. 1 is intended for both academic research and implementation on remote rural locations for distributed electricity generation where maintenance tasks are difficult to perform.

MBPC has been recognized to be an advanced control method capable of achieving robust results even with the hardest systems' dynamic models. The latter while maintaining a rather simple methodology to always obtain the best switching state of a power converter to deliver optimal results within every sampling time [28]. MBPC has shown significant robustness even with parameters variations or uncertainties along with very fast dynamic responses in AC microgrids [29]. Therefore, MBPC is a very competitive alternative to conventional control schemes for the application described in this work.

This paper proposes an improved model predictive rotor current strategy, when compared to the one in [11], to indirectly control the DFIM active and reactive power, including the synchronization process to the grid, within a single scheme. The latter is easily achieved by initially setting the power references to zero for synchronization and, after closing the stator-grid contactor, applying the required power references to control. The setup is a variable-speed WECS formed by a DFIM driven by an IMC. This strategy controls the DFIM in all four operating regions, MBPC controls the rotor currents with a reference calculated from the dynamic model of the DFIM and the IMC in terms of the rotor speed and position, the grid voltage characteristics, and the power set points. Experimental results are presented from a 5.5 kW test rig to validate the method.

II. BACKGROUND

The primary role of WECS in renewable energy systems is consistent with the continuous development of new topologies. However, research of legacy topologies with modern control strategies also helps to improve the efficient use of electrical energy taking advantage of already installed assets. In this work a well-known configuration for the DFIM, the Scherbius scheme shown in Fig. 1, with a modern power converter topology and control scheme is presented. The IMC is rated to one third of machine power due to the restricted DFIM speed range considered (four-quadrant operation with ± 30 % of synchronous speed) [16].

A. Indirect Matrix Converter Model

The IMC is defined as a two-stage direct AC-AC converter with a virtual DC link. This allows a safe operation using the zero DC link current switching strategy. For the first stage the DC link voltage v_{dc} is calculated using phase voltage vectors $\boldsymbol{v}_{in}$ and the rectifier switching states $[\boldsymbol{S}_r]$ while input currents $\boldsymbol{i}_{in}$ use DC link current i_{dc} and $[\boldsymbol{S}_r]^T$ as follows:

$$v_{dc} = [\boldsymbol{S}_r]\,\boldsymbol{v}_{in} \tag{1}$$

$$\boldsymbol{i}_{in} = [\boldsymbol{S}_r]^T \, i_{dc} \qquad (2)$$

where

$$[\boldsymbol{S}_r] = \begin{bmatrix} S_{r1} - S_{r4} & S_{r3} - S_{r6} & S_{r5} - S_{r2} \end{bmatrix}. \qquad (3)$$

For the second stage the DC link current i_{dc} is calculated using output currents $\boldsymbol{i}_r$ and the inverter switching states while the output voltage $\boldsymbol{v}_r$ is calculated using the DC link voltage v_{dc} and the corresponding inverter switching states as follows:

$$i_{dc} = \begin{bmatrix} S_{i1} & S_{i3} & S_{i5} \end{bmatrix} \boldsymbol{i}_r \qquad (4)$$

$$\boldsymbol{v}_r = \begin{bmatrix} S_{i1} - S_{i4} & S_{i3} - S_{i6} & S_{i5} - S_{i2} \end{bmatrix}^T v_{dc}. \qquad (5)$$

Some constraints validate the model and enable the converter safe operation, such as avoiding a short circuit on the rectifier input phases as well as an open circuit of the inverter output phases. From all the possible states of the IMC only 72 are allowed, nine for the rectifier and eight for the inverter. However, only three of the nine possible rectifier states are used. The latter to impose a positive DC link voltage, giving a finite set of 24 states.

B. DFIM Dynamic Model

The DFIM is usually lighter, smaller and cheaper than other generators [6], such as the squirrel cage induction, the synchronous, and the permanent magnet synchronous generator. In a DFIM-based WECS a partial rated power converter is located at the rotor terminals as shown in Fig. 1.

In this paper the DFIM is modeled as an equivalent electrical circuit using equations referred to the $\alpha\beta$ stationary reference frame fixed to the stator. The time-variant-voltage vectors are defined by equations (6) and (7). This equivalent model is preferred since grid interconnection constraints are imposed directly on the stator variables and it simplifies the control variables.

$$\boldsymbol{v}_{\alpha\beta s} = R_s \boldsymbol{i}_{\alpha\beta s} + L_s \frac{d}{dt}\left(\boldsymbol{i}_{\alpha\beta s}\right) + L_m \frac{d}{dt}\left(\boldsymbol{i}'_{\alpha\beta r} e^{j\theta_r}\right) \qquad (6)$$

$$\boldsymbol{v}'_{\alpha\beta r} = R'_r \boldsymbol{i}'_{\alpha\beta r} + L'_r \frac{d}{dt}\left(\boldsymbol{i}'_{\alpha\beta r}\right) + L_m \frac{d}{dt}\left(\boldsymbol{i}_{\alpha\beta s} e^{-j\theta_r}\right) \qquad (7)$$

with

$$\boldsymbol{i}'_{\alpha\beta r} = I'_r e^{j\theta_{slip}}, \quad I'_r = I_r \frac{N_r}{N_s} \qquad (8)$$

$$\boldsymbol{v}_{\alpha\beta s} = V_s e^{j\theta_g}, \boldsymbol{i}_{\alpha\beta s} = I_s e^{j(\theta_g + \theta_{pf})} \qquad (9)$$

and

$$I_s = \frac{2}{3}\frac{S}{V_s}, S = \sqrt{P^2 + Q^2}, \theta_{pf} = tan^{-1}\left(\frac{Q_s}{P_s}\right). \qquad (10)$$

C. Model-Based Predictive Control

MBPC can be used in the control of power converters, especially those without large energy storage elements. Each sampling instant k, the behavior of the system at $k+1$ is predicted using the mathematical model, minimizing the cost function to select the optimal state of the converter. The cost function can contain the prediction error and any other target subject to control. Such targets can be the switching frequency, the input displacement factor to the converter, etc. [30], [31].
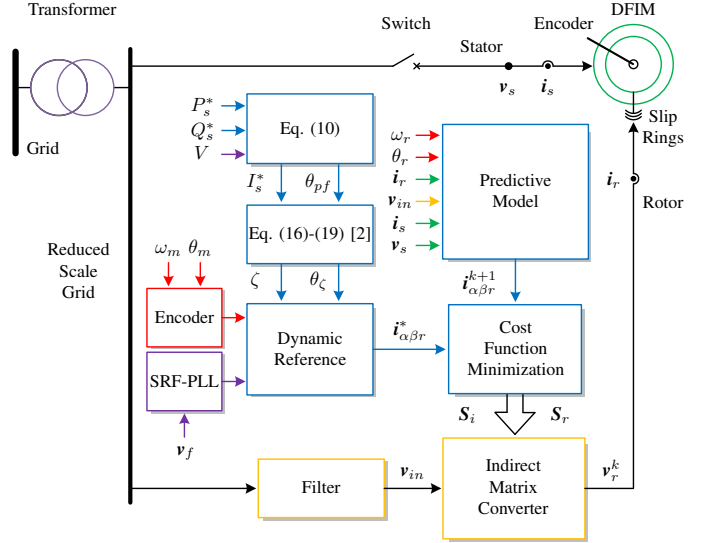

Fig. 2. Block diagram of the indirect power control using predictive rotor current control strategy.

III. PROPOSED SCHEME: INDIRECT POWER CONTROL FOR THE DFIM USING MODEL-BASED PREDICTIVE ROTOR CURRENT CONTROL

The model-based predictive rotor current control, shown in Fig. 2, has been validated in simulation in [32] performing the following tasks.

- Decouple the stator active and reactive power references P_s^*, Q_s^* into a stator current reference.
- Integrate the rotor electrical angular frequency ω_r and angle θ_r, and the grid voltage amplitude, angular frequency ω_g and angle θ_g.
- Develop the dynamic reference of the variable-speed system valid for startup, synchronization and power control as shown in [32].

$$I_r^* = \frac{N_s}{N_r}\frac{\zeta_{mag}}{L_m(\omega_{slip} + \omega_r)} \qquad (11)$$

$$\theta_{aux} = \theta_g + \theta_\zeta - \theta_r - \pi/2 \qquad (12)$$

- Predict the DFIM rotor currents for a stator-fixed time-varying $\alpha\beta$ reference frame as presented in [10], [11].

$$i'^{k+1}_{\alpha r} = \frac{1}{L_s L'_r - L_m^2}\begin{bmatrix} L_s v'^k_{\alpha r}[v^k_{\alpha in}, \boldsymbol{S}^k_{r,i}] - L_m v^k_{\alpha s} - \\ L_s R'_r i'^k_{\alpha r} + L_m R_s i^k_{\alpha s} - \\ L_s L'_r \omega^k_r i'^k_{\beta r} - L_m L_s \omega^k_r i^k_{\beta s} \end{bmatrix} t_s + i'^k_{\alpha r} \qquad (13)$$

$$i'^{k+1}_{\beta r} = \frac{1}{L_s L'_r - L_m^2}\begin{bmatrix} L_s v'^k_{\beta r}[v^k_{\beta in}, \boldsymbol{S}^k_{r,i}] - L_m v^k_{\beta s} - \\ L_s R'_r i'^k_{\beta r} + L_m R_s i^k_{\beta s} + \\ L_s L'_r \omega^k_r i'^k_{\alpha r} + L_m L_s \omega^k_r i^k_{\alpha s} \end{bmatrix} t_s + i'^k_{\beta r} \qquad (14)$$

- Evaluate the rotor current prediction twenty-four times using a cost function.
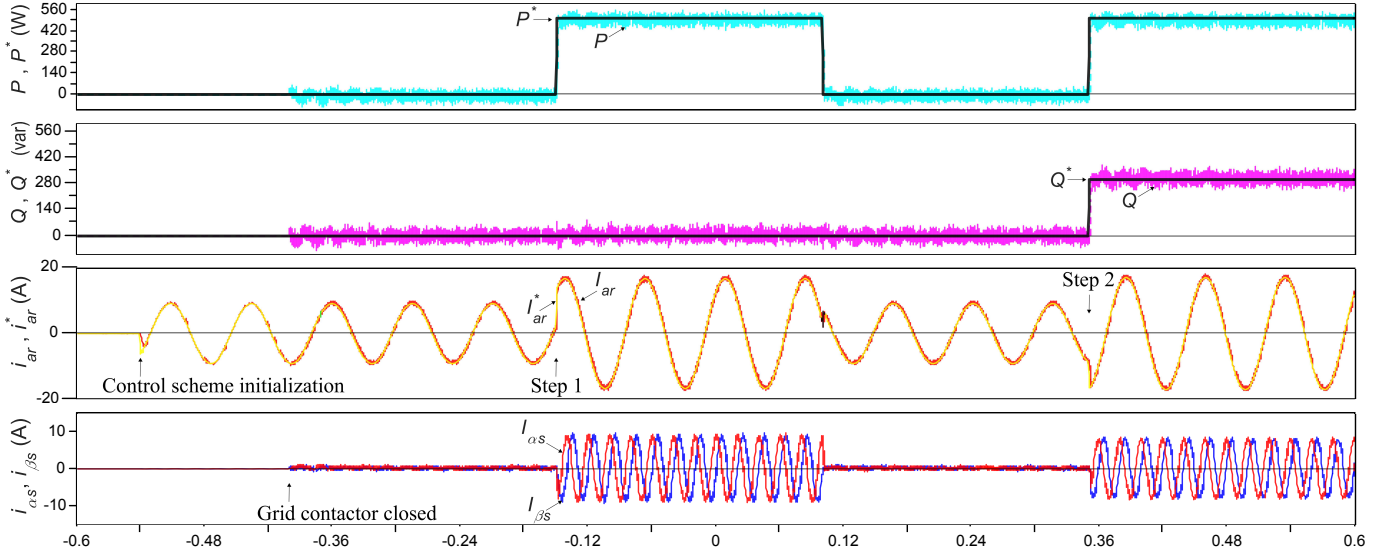
Fig. 3. Rotor and stator currents in three stages: synchronization, active power step, and simultaneous active and reactive power steps at constant shaft speed of 950 rpm.

- Apply the optimum switching state of the IMC, implicitly assuming the use of rotor variables referred to the stator (primed).

$$g^{k+1} = |i_{\alpha r}^* - i_{\alpha r}^{k+1}| + |i_{\beta r}^* - i_{\beta r}^{k+1}| \qquad (15)$$

For a thorough explanation of how the equations (11) to (15) were obtained and how the prediction relation between them works, the reader is encouragingly referred to [10], [11] and [32].

IV. IMPLEMENTATION

The simulations were carried out with the software GeckoCIRCUITS from Gecko-Research (a spin-off company of ETH Zurich, Switzerland). The experiments were undertaken using a dSPACE DS1103 for data acquisition and rotor current control (setting P_s^* and Q_s^* to zero during synchronization), and a Spartan-6 FPGA to provide the converter switching signals using the zero current commutation protocol for the IMC.

A. Simulation Results

The simulation waveforms shown in Fig. 3 present the expected results for the DFIM used to validate the experimental results. Firstly, achieving the stator voltage synchronization with the grid through power control, applying zero active and zero reactive power. Secondly, a step of 500 W with 0 var, and finally applying a step of 500 W with 300 var at the same time. Always imposing constant speed of 950 rpm to the DFIM shaft. As seen in Fig. 3, the rotor current is controlled smoothly, allowing a permissible low ripple in the stator current and consequently in the active and reactive power.

B. Experimental Results

The setup, shown in Fig. 4, includes: 1.- A 5.5 kW DFIM with parameters $R_r' = 0.783\ \Omega$, $L_{lr}' = 10.5$ mH, $L_r' = 75$ mH, $R_s = 0.718\ \Omega$, $L_{ls} = 10.7$ mH, $L_s = 75.2$ mH, $L_m = 64.5$ mH, stator to rotor turns ratio $N_s/N_r = 1.447$ and pole pairs $P_p = 4$. 2.- A 10 kW indirect matrix converter built using bidirectional switches formed by two IGBTs in common collector configuration rated to 600 V and 80 A. 3.- A LC input filter $L_f = 10\ \mu H$, $R_f = 0.5\ \Omega$, $C_f = 40\ \mu F$. The reduced-scale grid is emulated using two three-phase auto-transformers rated to 3 kVA each with a galvanic-isolation transformer at the output. The system output is limited by the rated power of the reduced grid and by the mechanical power input to the DFIM. In this case a 3 kW induction motor works as the prime motor driven by a variable frequency drive rated to 3 kW. The whole system is therefore limited to test this control strategy at one third of nominal voltage.

Active and reactive power references are changed using steps from zero to 500 W and from zero to 300 var. Zero conditions ($P_s^* = 0, Q_s^* = 0$) set the stator current reference to $|I_s^*| = 0$ A and $\theta_{pf} = 0^o$ for equation (10). These parameters establish the synchronization conditions of equal frequency, amplitude, phase and sequence between the stator and the grid as stated in [11].

The rotor current is constantly controlled with the same strategy. The reference is calculated dynamically using the discrete model of the system and the conditions taken from the rotor and the grid. This method selects the optimum switching state $S_{r,i}^{k+1}$ for the IMC to provide the right rotor voltage space vector v_r, and thus to obtain the least possible error. Therefore, with a precise tracking of the rotor current reference, MBPC will ensure fast grid synchronization and fast response to step references with low ripple as it can be seen in Fig. 6 and Fig. 7, respectively.

The synchronization process can be seen in Fig. 5. Before grid interconnection the total harmonic distortion of v_s is 1.52 %. A maximum difference of 30 V between v_s and v_g causes an overshoot of only 1.11 A in the stator currents when the contactor is closed.
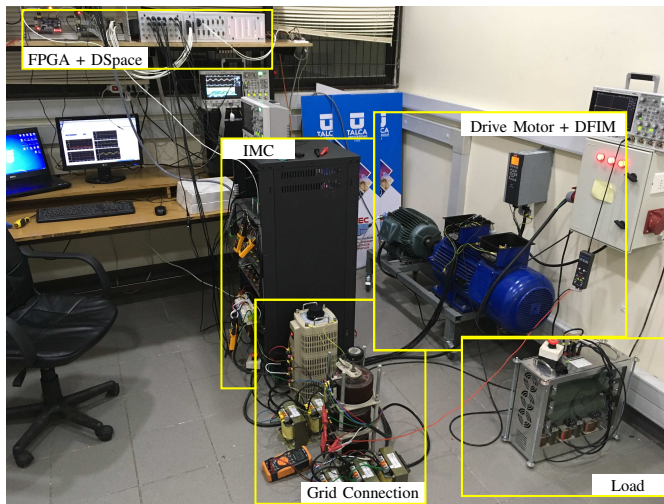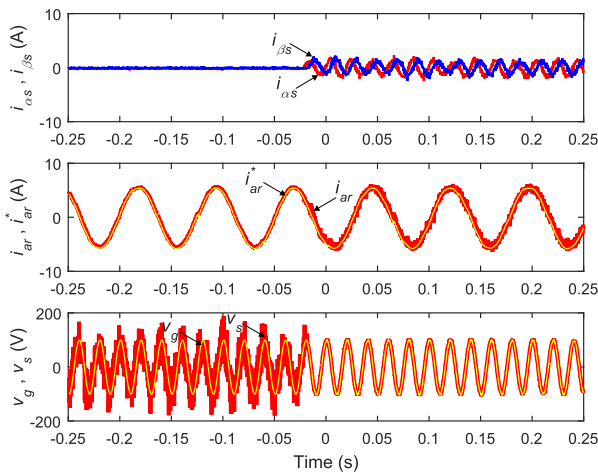
Fig. 4. Experimental test rig.

Fig. 7. Rotor current control with step on the active and reactive power reference at constant speed of 950 rpm.

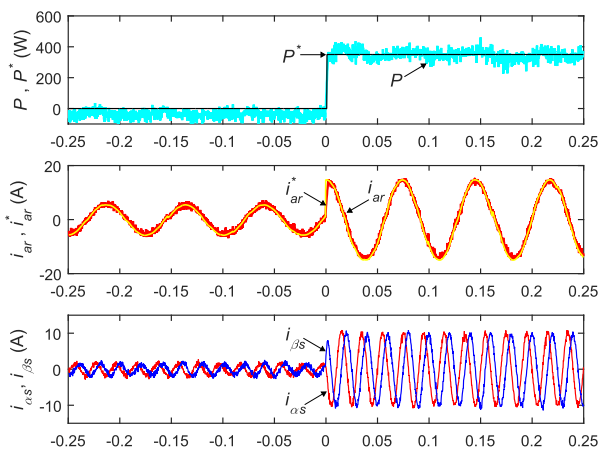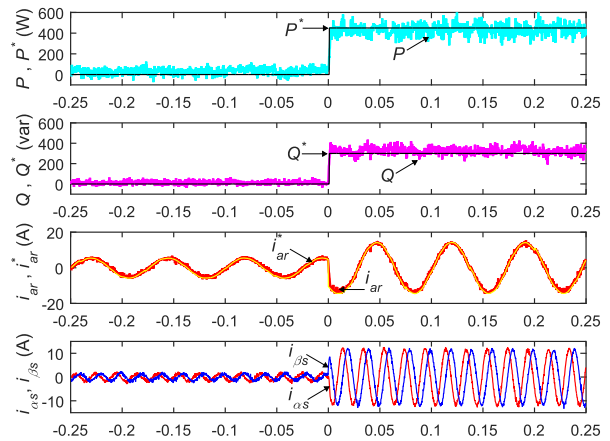Fig. 5. Stator and rotor current, stator and grid voltage during synchronization at constant speed of 950 rpm.
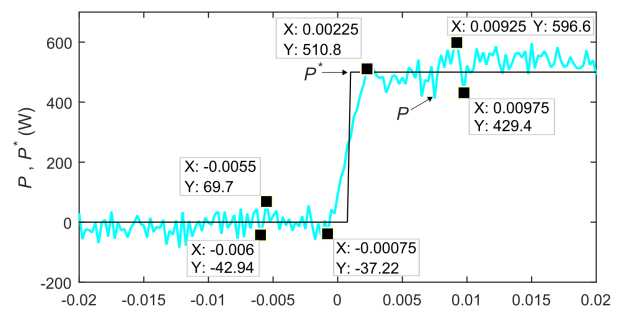

Fig. 8. Close look of the DFIM active power to see the ripple and dynamic response during a step change.

The power references in the experimental results were limited by the element having the smallest power rating. In this case the reference, as shown in Fig. 6, changed from zero to 0.5 kW, and in Fig. 7 from zero to 0.3 kvar plus the same active power as the former. In the middle of Fig. 6, the rotor currents are shown beginning with the synchronization steady state to the corresponding magnitude and phase for the applied power reference. The step changes in the power references were made at the same time as shown in Fig. 7. During the implementation time, the shaft speed of the wind turbine remained steady as 950 rpm. In this constant speed condition, the DFIM is operating above the synchronous speed, which is 750 rpm for the 8-pole 50 Hz machine used in this work.

Figs. 5 to 7 show the synchronization and power flow control for the DFIM using only one control scheme. As can be seen, it is sufficient to know the grid voltage requirements and set $Q_s^* = 0$ and $P_s^* = 0$ to achieve fast synchronization of the DFIM with the proposed predictive scheme. In this implementation, as well as in previous simulations, grid requirements were fulfilled in two cycles of the rotor current as shown in Fig. 5. The grid contactor closure was made 40 ms after the initialization. As it can be seen in Fig. 8, there is a fast response of 1.5 ms to the step change in the power

Fig. 6. Rotor current control with step on the active power reference at constant speed of 950 rpm.

reference. Analyzing the segment around the step, the average power measured goes from –38.52 W to 504.5 W, presenting a maximum ripple of 165.6 W. These results are better to those presented in [22] considering a larger sampling time and the implementation of the method without digital delay compensation.

Moreover, the ripple of active and reactive power is similar for different steps in the reference. The latter leads to better signal-to-noise ratios for higher reference values. The dynamic response is also improved with higher reference values. The rate of change of power over time is 362 kW/s for this low scale implementation, but if the scale of the grid is increased, as well as the power rating, it is expected to have a steeper response. In simulation, 1 kW step in the reference required seven times the sampling time and in this implementation 0.5 kW required fifteen times the sampling time, proving better dynamic response at higher power flow. This reduced-scale implementation can be considered as the worst-case scenario.

V. CONCLUSIONS

A novel rotor current control scheme has been proposed in this paper allowing a smooth grid synchronization and fast response to power step commands at variable speed. It is sufficient to know the grid voltage requirements and set $Q_s^* = 0$ and $P_s^* = 0$ to generate a reference for the rotor current and achieve the DFIM synchronization. This predictive scheme controls the rotor current with a sinusoidal reference and maintains sinusoidal stator waveforms to track the active and reactive power references. The latter with a sampling time of $100~\mu$s and one third of grid voltage for the converter. It is sufficient to change the reference value for P and Q to consequently change the operational point of the machine by adapting the dynamic references of I_r and θ_{aux} to control the rotor current. Future work will present this MBPC-DFIM-IMC configuration as part of a resilient AC microgrid with capability of operating in both islanded and grid-connected modes.

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