Variable Speed Synchronous Condenser Using Doubly-Fed Induction Machine

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***Abstract* – The wound rotor induction machine (WRIM) presents characteristics that make it attractive as an energy storage system where the energy is stored as kinetic energy in the rotor moving parts. When operating in the doubly fed mode (DFIM), with the rotor fed by a variable frequency power converter, the WRIM behaves as a synchronous machine, with the advantage of variable speed operation and larger dumping effect when subject to disturbances. As the converter needs only be designed to handle a fraction of the total power, the system can be used at high power levels. This paper presents the analysis of a Doubly Fed Induction Machine (DFIM) used as a controlled active and reactive power compensator. The simulation and experimental results obtained show that this system can be used for voltage control in a power system as well as load-leveling device.**

I. INTRODUCTION

Voltage sags and voltage swell are responsible for almost 80% of the problems related to power quality complains. Generally, the systems presently suggested to mitigate the effect of voltage sags rely on energy storage systems and one of them is that using the kinetic energy stored in the rotating parts of electrical machines, which has been generally referred to as "flywheel generator" [1][2]. These systems have been receiving attention and are being proposed for voltage and frequency control [3][4].

When using a wound rotor induction machine (WRIM), with the stator connected to the grid and the rotor fed by a power converter, this converter needs only to be rated for a fraction of the total system power. Therefore, this system may be interesting for application at high power levels (above hundreds of MVA). Also, the possibility of operating at variable speed in conjunction with the power converter control make the machine to present high dumping factor of the oscillations due to faults in the grid. This dumping factor is larger than in the case of synchronous machine [5].

Recently, the use of a Doubly Fed Induction Machine (DFIM) as a variable speed synchronous condenser (VSSC) has been presented [6]. It has been shown that the VSSC can be used to control its terminal voltage by controlling the capacitive or inductive reactive power. This control is achieved by the adjustment of the converter output voltage. It has also been shown how the system can work as a low speed flywheel generator being able to supply or absorb active power and the de-coupling of these two controls has been suggested.

The aim of this paper is twofold. Firstly an analytical model of the DFIM will be developed. This model will be used to demonstrate how the power factor of the stator winding can be controlled with the converter. This analysis will be confirmed with simulations and laboratory measurements on a 3 HP machine. Secondly, a vector control scheme will be presented which de-couples the reactive and active power control. This control will be validated with simulations based on SABER® [9] simulator.

II. POWER FACTOR CONTROL

Fig. 1 shows a steady-state equivalent circuit for the DFIM. This equivalent circuit can be used to analyze the effect of the converter output voltage on stator winding power. The following assumptions are made: fixed stator winding voltage and constant rotor voltage frequency, as imposed by the converter.

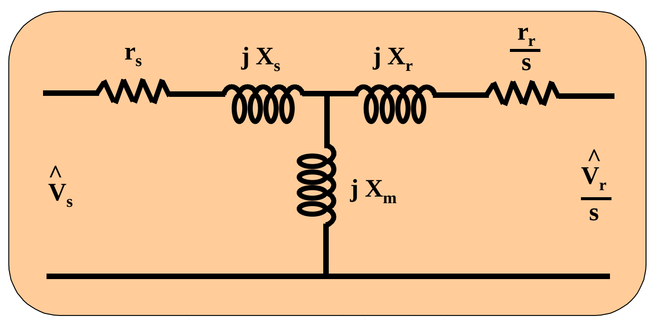

Fig. 1 – DFIM equivalent circuit

where:

$\hat{V}_s$ - Stator voltage;

$\hat{V}_r$ - Rotor voltage;

r_s - Stator resistance;

$\frac{r_r}{s}$ - Rotor resistance referred to the stator;

X_s - Stator leakage reactance;

X_r - Rotor leakage reactance referred to the stator;

X_m - Magnetizing inductance.

With the previous assumptions, the equivalent circuit can be further simplified if we using Thevenin´s Theorem. Therefore defining

$$\hat{V}_R = \frac{\hat{V}_r}{s} \frac{j X_m}{\frac{r_r}{s} + j(X_m + X_r)} \tag{1}$$

$$r_R + j X_R = \left(\frac{r_r}{s} + j X_r \right) // \, j X_m \tag{2}$$

where $\hat{V}_R$ is the equivalent Thevenin voltage and $r_R + j X_R$ is the equivalent Thevenin impedance. We can also write

$$\hat{V}_s = \hat{V}_R + (R + j X)\hat{I}_s \,, \tag{3}$$

where:

$$R + j X = (r_s + r_R) + (x_s + x_R) = Z \angle \theta. \tag{4}$$

Defining:

$\hat{V} = V_s \angle 0$ as reference voltage;

$\hat{V}_R = V_R \angle -\delta$ as internal voltage;

$\hat{I}_s = I_s \angle -\phi$ as stator current, where ϕ is the power factor angle, the power in the stator winding can be calculated as

$$S = P + Q = 3\hat{V}_s\, \hat{I}_s^{\,*} = 3V_s\, I_s \cos\phi + j\,3V_s\, I_s \sin\phi. \tag{5}$$

Writing the current I_s as a function of V_s, V_R and Z, and substituting in (5) results in the expression for the power absorbed from the system

$$P = 3\frac{V_s^{\,2}}{Z^2} R + 3\frac{V_s V_R}{Z} \sin(\delta - \alpha) \tag{6}$$

$$Q = 3\,\frac{V_s^{\,2}}{Z^2} X - 3\frac{V_s V_R}{Z} \cos(\delta - \alpha) \tag{7}$$

where:

$\alpha = 90 - \theta.$

Equations (6) and (7) can now be used to investigate the effect of the rotor voltage on the stator winding power factor. For example, suppose that the active power is constant. If the rotor voltage is increased, from (6), the term sin (δ-α) has to decrease. Therefore cos (δ-α) will increase and so will the second term on the right hand side of (7). In (7) we see that the reactive power is composed of two components. One depends only on the stator voltage and the machine parameters and is constant for a fixed voltage. The other depends on stator and rotor voltages and the cosine of the Thevenin voltage phase minus the impedance angle. Keeping the active power constant, we can generally find a value for the rotor voltage, which will cancel the reactive power in (7). From this value, an increase in the rotor voltage will result in a negative value for Q, which means that the machine is generating capacitive reactive power to the grid (the sink convention was assumed in the development of the model). A decrease in the rotor voltage will result in a positive value for Q, therefore the motor will be generating an inductive reactive power.

This analysis can be better illustrated in Fig. 2 which shows simulated results relating the reactive power in the stator of a DFIM to the voltage applied to the rotor. The machine is connected to an infinite bus and for a fixed value of rotor voltage frequency (namely 1.0 Hz) the converter voltage was varied.

The same behavior can be seen in Fig. 3, Fig. 4 and Fig. 5 which show measurements of stator voltage and current of a 3 HP DFIM at the Power Electronics Laboratory at COPPE/UFRJ. Those figures show that by varying the rotor voltage we can obtain lagging (Fig. 4), unity (Fig. 3) or leading (Fig. 5) power factors in the stator. In those figures, the fundamental rms components of the rotor voltages are 6 V, 6.9 V and 8.6 V, respectively.

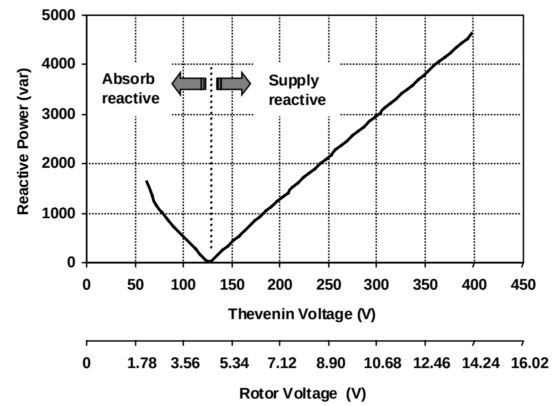

Fig. 2 - Variation of stator reactive power with rotor voltage

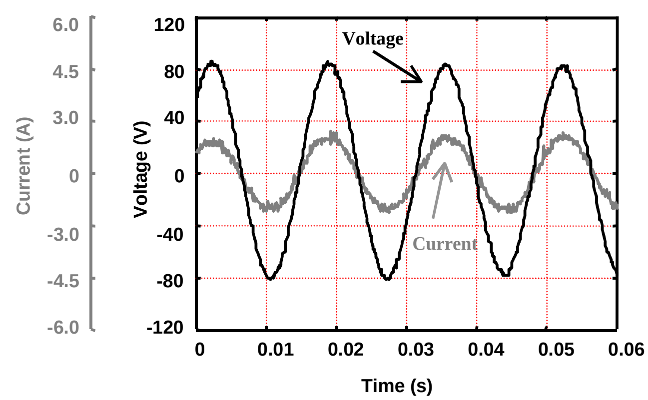

Fig. 3 - Stator voltage and current (unity power factor)

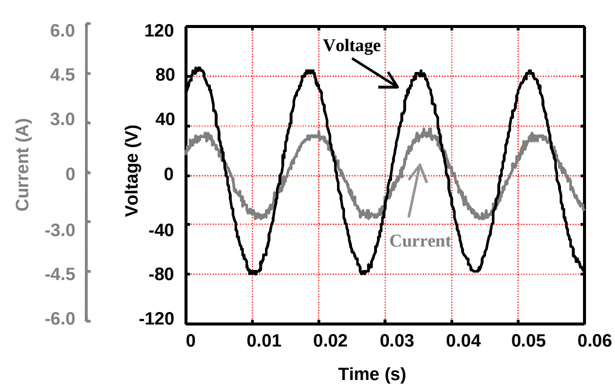

Fig. 4 - Stator voltage and current (lagging power factor)

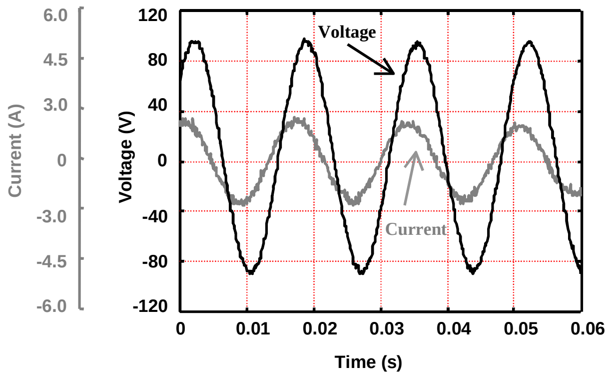

Fig. 5 - Stator voltage and current (leading power factor)

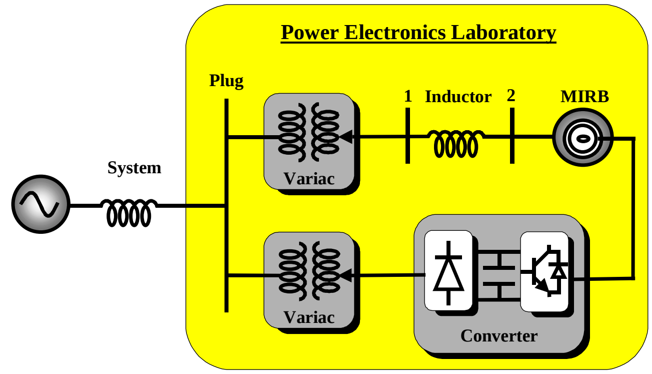

Fig. 6 – Laboratory test rig.

III. VOLTAGE CONTROL

In [6], the authors presented some simulation results where the DFIM was used as a synchronous condenser, in order to control the voltage in a power system. In that work the rotor voltage was directly controlled and the rotor frequency was kept constant. Fig. 6 shows the laboratory test rig, which was used to validate those simulations. The system consists of a DFIM, which is fed from the mains via a three-phase autotransformer. The inductors between the machine and the transformer are used to ensure that there will be a voltage difference between these two terminals. The rotor is fed from a commercial inverter, which works with constant V/f ratio. As the control scheme relies on a fixed frequency / variable voltage characteristics, the second autotransformer is used to control the converter input voltage, therefore the DC link voltage. It should be pointed out that this was a simple laboratory set-up used just to validate the study.

The test consists of reducing the first transformer voltage in order to reduce the voltage at the machine terminals, simulating a fault on the supply system. After that the converter output voltage is varied in order to bring the stator voltage back to its initial level. This can be seen in Fig. 7, which shows the voltage at the compensator terminals measured with an oscilloscope. This figure shows that until t=1.2 seconds the DFIM stator voltage is around 98.3 Vrms when it's decreased approximately 10 %. At t=2.7 seconds the rotor voltage is increased from 5.5 Vrms to 9.0 Vrms which brings the stator voltage to its pre-fault level. The effect of the reactive power in the stator winding of the DFIM on its terminal voltage can be seen in Fig. 8, which shows the instantaneous three phase reactive power calculated from the measured values of voltage and current. Due to converter limitations, which limited the voltage range applied to the rotor, it was not possible to adjust the system to operate with a unity power factor before the voltage was reduced, as would normally be the case. Therefore, in this test the voltage was restored with a reduction in the reactive power absorbed by the DFIM

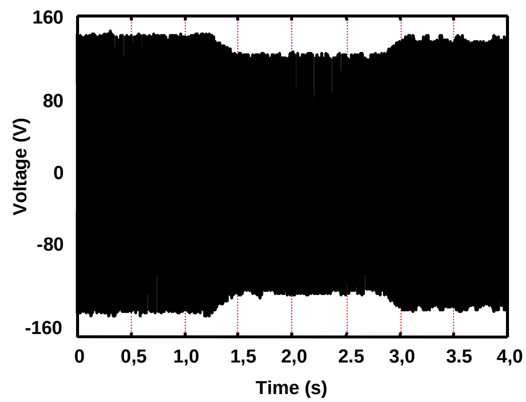

Fig. 7– Phase voltage at DFIM terminal.

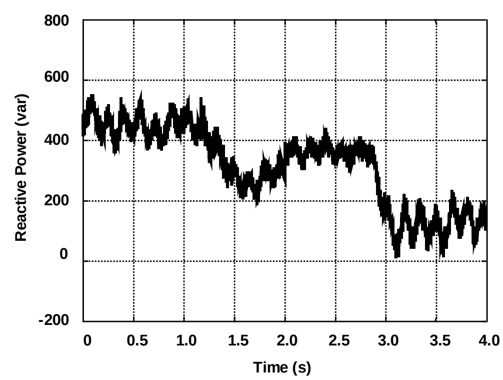

Fig. 8– Reactive power in the stator.

IV. VECTOR CONTROL

Both simulated and experimental results presented in the previous sections used a scalar control strategy where only the magnitude and/or frequency of the rotor voltage were varied. Those results were useful to validate the application of the DFIM in mitigating voltage fluctuations at sensitive load terminals in power systems. As presented in [6] the same system can be used as a flywheel generator and operate as a load leveling system. However its is believed that the equipment response can be greatly improved if a field orientated control is implemented.

In this analysis, a mathematical model of the symmetrical DFIM is used, where instantaneous values of voltage and current at the stator and rotor windings phases, v_a, v_b, v_c, v_A, v_B, v_C and i_a, i_b, i_c, i_A, i_B i_C, are transformed to an arbitrary reference frame using Park's transformation as in Fig. 10,

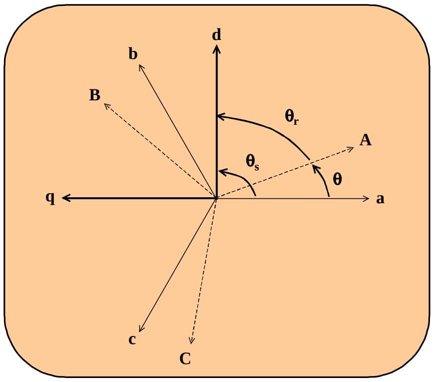

Fig. 9 – Park's transformation.

where

- a,b,c , refer to the magnetic axis of the stator phases;
- A,B,C, refer to the magnetic axis of the rotor phases;
- d,q, arbitrary rotating reference frame.

It can be shown that the machine can be modeled by a set of equations, which relates applied voltages to voltage drops and flux linkages as

$$v_{ds} = r_s i_{ds} + \frac{d}{dt}\lambda_{ds} - \frac{d\theta_s}{dt}\lambda_{qs} \tag{8}$$

$$v_{qs} = r_s i_{qs} + \frac{d}{dt}\lambda_{qs} + \frac{d\theta_s}{dt}\lambda_{ds} \tag{9}$$

where, v_{ds} and v_{qs} are the stator voltage components. λ_{ds} and λ_{qs} are stator flux linkages components and are given by

$$\lambda_{ds} = L_s i_{ds} + M_{sr} i_{dr} \tag{10}$$

$$\lambda_{qs} = L_s i_{qs} + M_{sr} i_{qr} \tag{11}$$

where i_{ds} and i_{qs} are the stator current components. A similar set of equations may be written for the rotor where the suffix "r" refers to rotor quantities. Therefore

$$v_{dr} = r_r i_{dr} + \frac{d}{dt}\lambda_{dr} - \frac{d\theta_r}{dt}\lambda_{qr} \tag{12}$$

$$v_{qr} = r_r i_{qr} + \frac{d}{dt}\lambda_{qr} + \frac{d\theta_r}{dt}\lambda_{dr} \tag{13}$$

$$\lambda_{dr} = L_r i_{dr} + M_{sr} i_{ds} \tag{14}$$

$$\lambda_{qr} = L_r i_{qr} + M_{sr} i_{qs} \tag{15}$$

The above system of equations is general and can be used for any reference frame. For example, taking the magnetic axis of stator phase "a" as reference, and substituting for the flux linkages, it can be written

$$\vec{v}_s = r_s \vec{i}_s + L_s \frac{d}{dt}\vec{i}_s + M_{sr}\frac{d}{dt}\left(\vec{i}_r e^{j\theta}\right) \tag{16}$$

where

$$\vec{v}_s = v_{ds} + jv_{qs}$$

$$\vec{i}_s = i_{ds} + ji_{qs} \tag{17}$$

$$\vec{i}_r = i_{dr} + ji_{qr}$$

Defining the leakage factor σ_S, where $L_s = (1+\sigma_s)M_{sr}$. we may write.

$$\vec{v}_s = r_s \vec{i}_s + M_{sr}\frac{d}{dt}\left[(1+\sigma_s)\vec{i}_s + \vec{i}_r e^{j\theta}\right] \tag{18}$$

As presented in [7], with a proper choice of a reference frame the control of active and reactive power in the stator can be decoupled and be implemented by controlling the two components of the rotor current. In this work the reference frame proposed in [7] was used, where the "d" axis is aligned with an extended magnetizing current vector responsible for the stator flux including stator leakage, defined in (17). With this choice of reference frame, the stator reactive power is related to the "d" component of the rotor current and the active power is related to the "q" component as indicated in Fig. 11.

$$\vec{i}_{ms} = i_{ms}(t)e^{j\mu(t)} = (1+\sigma_s)\vec{i}_s + \vec{i}_r e^{j\theta} \tag{19}$$

Substituting from (19) into (18) gives

$$T_s \frac{d}{dt}\vec{i}_{ms} + \vec{i}_{ms} = \vec{v}_s \frac{(1+\sigma_s)}{r_s} + \vec{i}_r e^{j\theta} \tag{20}$$

Working with the "d" and "q" components, we may write

$$T_s \frac{d}{dt} i_{ms} + i_{ms} = v_{ds}\frac{(1+\sigma_s)}{r_s} + i_{dr} \tag{21}$$

$$\frac{d\mu}{dt} = \omega_{ms} = \frac{1}{T_s i_{ms}}\left[v_{qs}\frac{1+\sigma_s}{r_s} + i_{qr}\right], \tag{22}$$

where T_S is the time constant of the stator circuit, which are used in the calculation of μ as in Fig. 10.

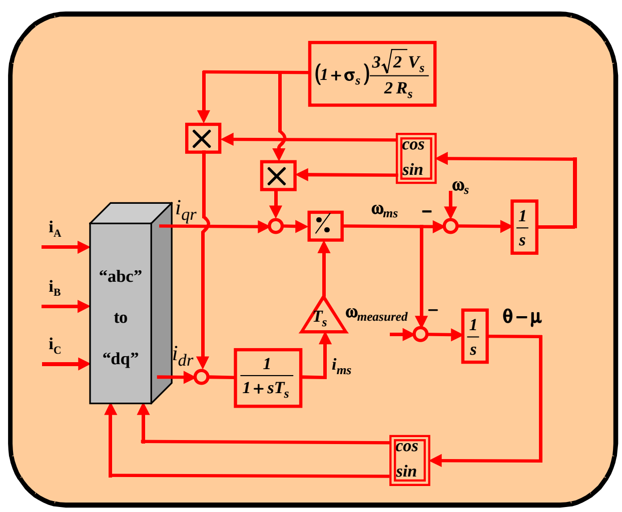

Fig. 10 – Field orientated control.

It can be shown [7] that with a proper choice of a reference frame the control of active and reactive power in the stator can be decoupled and be implemented by controlling the two components of the rotor current. Hence stator reactive power is related to the "d" component of the rotor current and the active power is related to the "q" component as indicated in Fig. 11.

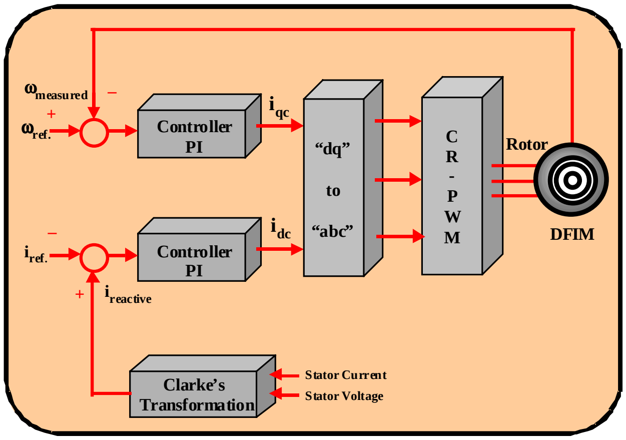

Fig. 11 – Decoupled control.

A. *Reactive Power Control*

The control implemented relies on the knowledge of the reactive component of the stator current. In this work this component is calculated using the instantaneous power theory [8]. This can be easily accomplished if we transform the instantaneous values of voltage and current at the stator windings phases, v_a, v_b, v_c and i_a, i_b, i_c, to a stationary reference frame using Clarke's transformation.

$$\begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \times \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{23}$$

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \times \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{24}$$

The reactive power can be calculated from

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{25}$$

Defining $\Delta = \boldsymbol{v_\alpha}^2 + \boldsymbol{v_\beta}^2$ it can be written

$$\begin{bmatrix} i_{\alpha\, reactive} \\ i_{\beta\, reactive} \end{bmatrix} = \frac{1}{\Delta} \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} 0 \\ q \end{bmatrix} \tag{26}$$

from where the reactive power component of the stator current can be calculated as

$$i_{reactive} = \sqrt{i_\alpha^{\,2} + i_\beta^{\,2}} \tag{27}$$

Fig. 12 and Fig. 13 show simulated results where a variation of the "d" component o the rotor voltage is applied. The rotor is supplied with a Current Regulated Pulse Width Modulation Converter (CR-PWM). Fig. 12 shows that at t=2.0 seconds there is a step change in the reactive current reference from -1 pu to +1 pu and Fig. 13 shows that this is followed by a similar change in the stator reactive power. Fig. 14 shows a negligible variation on the rotor speed as expected from the decoupled control.

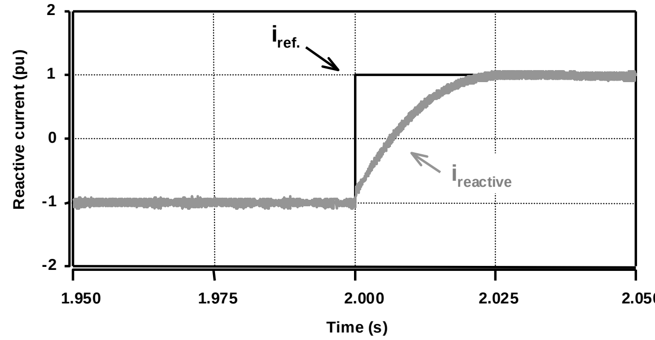

Fig. 12 – Simulated reactive component of stator current.

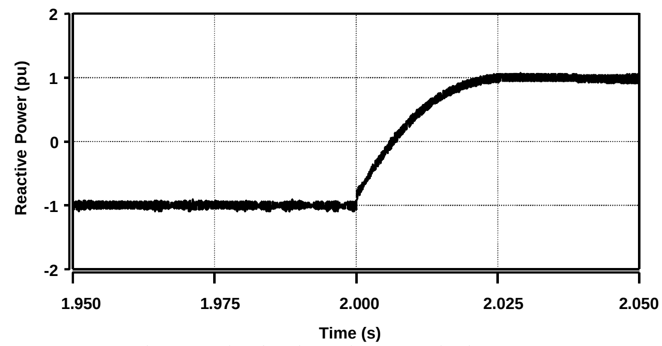

Fig. 13 – Simulated reactive power in the stator.

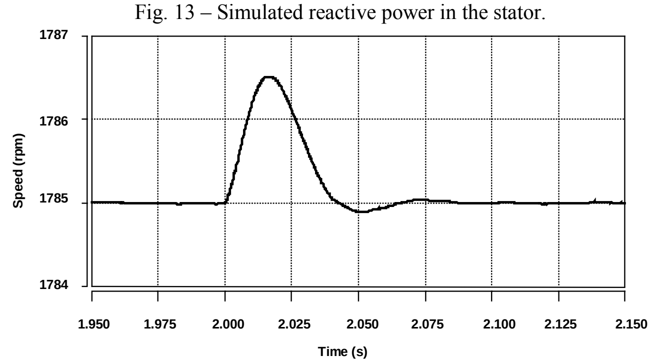

Fig. 14 – Simulated DFIM speed variation.

B. *Operation as a load leveling device*

One of the great advantages of the system using a DFIM is that the kinetic energy stored in the rotating parts can be used to supply or absorb active power from the grid. This, however, can be done for a limited period of time, despite the absence of any mechanical device connected to its shaft and using a power converter rated for a fraction of the total power. Considering the kinetic energy stored at two different speeds

$$W_1 = \frac{1}{2} J\, \omega_1^2 \;\; Joules \tag{28}$$

$$W_2 = \frac{1}{2} J\, \omega_2^2 \;\; Joules \tag{29}$$

where W is the kinetic energy stored in the rotor, ω is its angular speed in rad/s and J its total inertia in kg.m^2. If the rotor speed can be varied over a time interval, the stored energy will vary as

$$\Delta W = W_2 - W_1 \;\; Joules \tag{30}$$

and will cause an active power flow given by

$$P = \frac{\Delta W}{\Delta t} = \frac{1}{2} J \frac{(\omega_2^2 - \omega_1^2)}{\Delta t} \; Watts \qquad (31)$$

Equation (31) indicates that if the rotor speed is reduced the energy difference will be transformed in active power and will be supplied to the grid. On the other hand, in order to increase the rotor speed, energy will have to be extracted from the grid in the form of active power. Equation (31) also suggests a relationship between the active power in the stator and the speed variation, which can be used in the decoupled control presented in Fig. 11. This can be seen in Fig. 15, Fig. 16 and Fig. 17, which show the effect of a step change in the rotor speed reference. Fig. 15 shows that step changes were imposed at t = 1.4 seconds and 1.46 seconds. Fig. 16 and Fig. 17 show the effect of those changes on the rotor current “q” component and therefore on the active power flow in the stator windings. Fig. 18 shows the variation of the current in the stator windings.

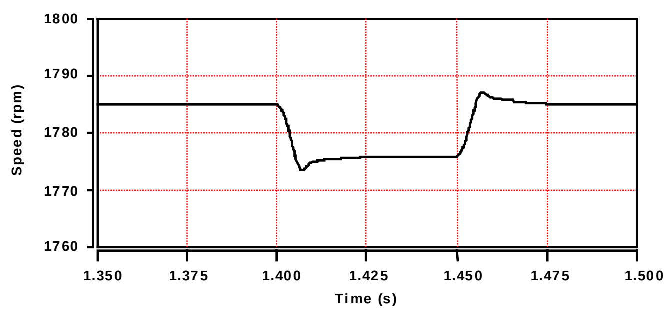

Fig. 15 – Simulated DFIM speed variation.

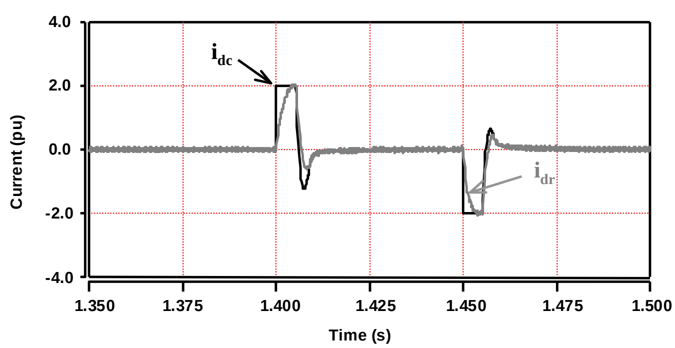

Fig. 16 – Simulated active power component of rotor current.

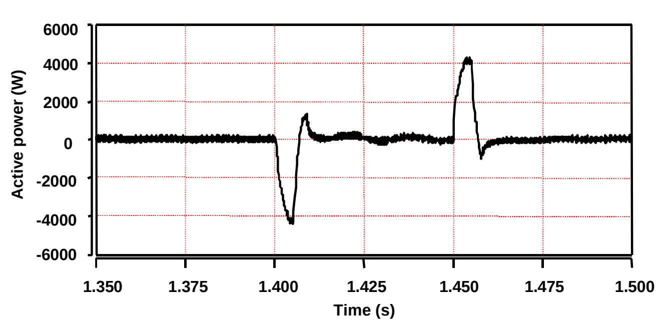

Fig. 17 – Simulated active power in the stator.

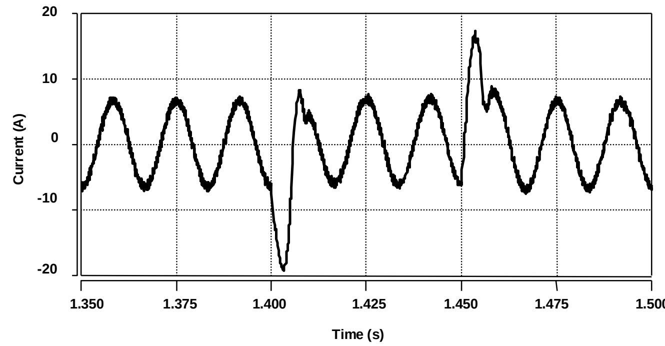

Fig. 18 – Simulated stator current.

V. CONCLUSIONS

The present paper present a detailed analysis of a doubly fed induction machine (DFIM) to be used as a variable speed synchronous condenser (VSSC). It was be shown that the VSCC can replace the conventional synchronous condenser in reactive power compensation with the advantage of being able to provide short time active power compensation. This system will be very important to guarantee electric energy quality in some points of the grid where high fluctuation of the load is present.

VI. ACKNOWLEDGEMENTS

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