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Reactive power relation of Doubly Fed Induction Machine (DFIM) at super-synchronous speeds

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Abstract

This paper discusses the equivalent circuit of doubly fed induction machine in relevance to reactive power flow from the rotor. In particular, consistency of the traditional circuit model at super-synchronous speed is studied. It is proven that, while the existing model is valid for all rotor speeds, care is necessary when expressing rotor reactive power using the steady-state phasor and the dynamic *dq* models. Detailed simulation results of the DFIM under different operating modes are presented to validate the proposed method.

Keywords: Doubly Fed Induction Machine (DFIM), dynamic model, phasor diagram, reactive power, super-synchronous speed

Introduction

Wind energy conversion systems using Doubly Fed Induction Machine (DFIM) are by far the most common topology in the world [1]. This is due to many advantages of DFIMs including decoupled control of active and reactive powers, using a partial scale converter leading to lower cost and losses, etc. There has been great research on this topology for both grid-connected and stand-alone applications and the mathematical relations of the machine are well-established [2-4].

A study of the steady-state operation of the machine is vital to obtain its characteristics at steady-state and also establish the initial conditions for simulation of the dynamic performance. Therefore, a consistent equivalent circuit applicable to different operating modes must be obtained. It has been reported in [5,6] that the traditional steady-state equivalent circuit has shortcomings when applied to super-synchronous mode of operation. A modified model is then proposed that should be used for the super-synchronous speeds instead of the well-established DFIM model. In effect, these references emphasize that the equivalent circuit structure is dependent on the rotor slip. The rationale behind this claim is the change in the phase sequence of rotor variables at super-synchronous speeds which affects the reactive power exchanged at rotor the side. The authors apply their proposed model with an iterative approach for load flow analysis of wind farms equipped with Doubly Fed Induction Generator (DFIG) [7,8] Resorting to the claim arisen by [5,6] stating that the equivalent circuit changes significantly depending on the operating speed, a new unbalanced steady-state model for DFIG operating at different speeds is presented in [9].

In this paper, the strategy given in [5,6] is criticized in several aspects. First, the proposed circuit for super-synchronous speeds differs from the well-established DFIM circuit derived in any course of electric machinery analysis for wound rotor induction machines [10] and well-established context on DFIM modelling and control [2-4]. The second reason that using two different circuit models based on the operating slip is questionable is the extra complexity introduced in the modelling as one equivalent circuit may not apply for some value of slip. Also, the authors in [5,6] have not presented corrective measures to be taken when dealing with the dynamic *dq* model of the machine; in fact, their study is confined to steady-state phasor analysis of the machine. In the current paper, it is shown while there is a necessity of modifying some equations when the machine operates at super-synchronous speeds, it is neither necessary nor suggested that the well-established model be modified based on the operating speed: the same stator-referred equivalent circuit as for sub-synchronous speed can be used. The phasor diagram is then built based on the equivalent circuit, taking the negative slip into account. For the actual voltages and currents of the rotor side, it then suffices to consider that when having a negative slip, thus having negative rotor angular frequency ($s<0 \Rightarrow \omega_r < 0$), the direction of rotation of rotor phasors is reversed with respect to the direction of rotation of stator phasors (taking the normal direction to be anti-clockwise, the direction of rotation of rotor phasors for super-synchronous speeds will be clockwise). Therefore, only rotor reactive power relations based on steady-state and dynamic equations should take the sign of rotor slip into account.

This paper is organized as follows. Firstly, super-synchronous operation is investigated for the very special case of pure capacitive load at rotor terminals to shed some light on the problem. The general load case is then investigated, which gives an insight into rotor reactive power expression based on the operational speed. Afterwards rotor reactive power under dynamic conditions is studied. Simulation results and discussions are then given and conclusions are drawn.

Voltage-current relation for capacitive load

For a better illustration of the concept, consider first as a special case a pure capacitive load connected to rotor terminals of a DFIM rotating at super-synchronous speed. Under such loading conditions, the actual rotor phase voltage and current are related by the equation:

$$\bar{V}_r = \frac{-j}{C\omega_r}\bar{I}_r \tag{1}$$

Considering the negative sign of ω_r due to negative slip, the phasor diagram can be drawn, as shown in Figure 1.

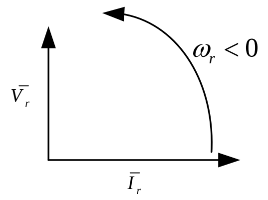


Figure 1. Pure capacitive load phasor diagram for super-synchronous speed

The phasors rotate at a rate corresponding to the rotor frequency. It might seem at a first glance that the rotor voltage phasor leads the rotor current phasor in the figure (which is misleading as the load is pure capacitive), but taking the actual direction of rotation of phasors, as expected for a capacitive load, the rotor current phasor is still leading the rotor voltage phasor, both rotating clockwise. The situation can be shown better by Figure 2.

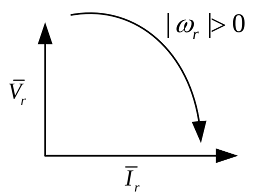


Figure 2. Phasor diagram taking the actual direction of phasors rotation

For better clarification, time variations of rotor phase-a voltage and current are expressed. Assuming phase-a voltage at rotor terminals to be:

$$v_r(t) = V_{mr}\cos(\omega_r t) = V_{mr}\cos(s\,\omega_e t) \quad (2)$$

The rotor phase-a current turns out to be:

$$i_r(t) = C\frac{dv_r(t)}{dt} = cs\omega_e V_{mr}\cos(s\omega_e t + \frac{\pi}{2}) \quad (3)$$

As the slip has been taken negative, rotor voltage and current are expressed in an alternative way so that there appears positive frequency and the negative multiplier of the cosine term in the rotor ($cs\omega_e < 0$) becomes positive:

$$v_r(t) = V_{mr}\cos(|s|\,\omega_e t), i_r(t) = c\,|s|\,\omega_e V_{mr}\cos(|s|\,\omega_e t + \frac{\pi}{2}) \quad (4)$$

This verifies the fact that rotor current leads rotor voltage.

It is now instructive to refer the rotor circuit to the stator (by frequency and turns-ratio transformations). The result is:

$$\frac{\bar{V}'_r}{s} = -\frac{j}{C's^2\omega_e}\bar{I}'_r \quad (5)$$

The above relation guarantees the current of a pure capacitive load leads its voltage in the stator-referred equivalent circuit, for both sub-synchronous and super-synchronous rotor speeds. Also, the magnitude of reactive power is amplified on the stator side compared to the reactive power on the rotor side; this reactive power amplification can be attributed to the division of frequency by slip, when referred from the rotor to the stator side.

The reactive power produced by the capacitive load in the rotor circuit is:

$$Q_r = 3|\bar{V}_r||\bar{I}_r| \quad (6)$$

Reactive power is also produced by the stator-referred load, and its value is given by:

$$Q'_r = 3\left|\frac{\bar{V}'_r}{s}\right||\bar{I}'_r| = 3\frac{|\bar{V}'_r||\bar{I}'_r|}{|s|} = 3\frac{|\bar{V}_r||\bar{I}_r|}{|s|} = \frac{Q_r}{|s|} \quad (7)$$

The last expression shows that the reactive power produced by the capacitive reactance is amplified when the reactance is referred from its actual position (i.e. rotor) to the stator side. This can be justified by considering the expression of capacitive reactive power:

$$\begin{cases} Q_r = \dfrac{I_r^{\,2}}{C_r|\omega_r|} \\ Q'_r = \dfrac{I'^2_r}{C'_r\omega_e} = \dfrac{I_r^{\,2}}{C_r|s||\omega_r|} \end{cases} \Rightarrow Q'_r = \frac{Q_r}{|s|} \quad (8)$$

Voltage-current relation for general load case

It was assumed in the previous derivation that a pure capacitive load is connected to the rotor terminals of DFIM working at super-synchronous speed. Now a general case is taken into account. The relation between rotor voltage and rotor current can be better visualized with the aid of phasor diagrams, showing the phasors of rotor voltage and current when in their actual rotor side, and when referred to the stator side.

Take the slip negative and assume that the rotor voltage and current phasors, when expressed in the actual rotor side, have a phase relation as shown in Figure 3.

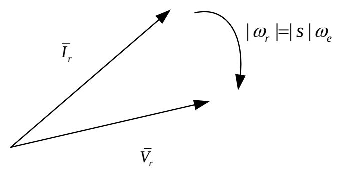


Figure 3. Rotor phasors at super-synchronous speed

The slip being negative, the phasors are rotating clockwise. Now the relative position of the stator-referred phasors, appearing in the equivalent circuit, is shown in Figure 4.

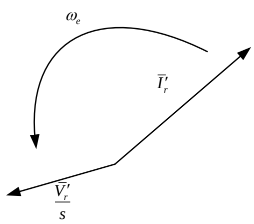
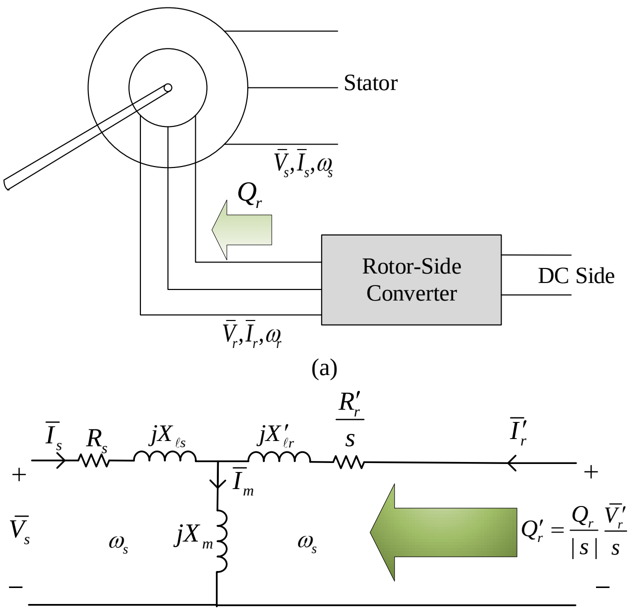


Figure 4. Stator-referred rotor phasors

The direction of rotation of the phasors is now reversed, and it is in the normal anti-clockwise direction. The referred rotor voltage phasor ($\frac{\bar{V}'_r}{s}$) is in the opposite direction with respect to rotor voltage phasor ($\bar{V}_r$) due to negative slip. It is clear that when rotor voltage phasor leads the rotor current phasor in the rotor side, the referred rotor voltage phasor in the equivalent circuit (that is: $\frac{\bar{V}_r'}{s}$) also leads the referred rotor current phasor ($\bar{I}_r'$), irrespective of the sub/super-synchronous operation.

It is observed that the relative position of the two phasors is not altered if care is taken regarding the direction of rotation of the corresponding phasors.

This explanation verifies the intuitive expectation that the sign of reactive power from the rotor-side converter (RSC) to the rotor is the same as the sign of reactive power from the stator-referred rotor voltage source ($\frac{\bar{V}_r'}{s}$) to the stator-referred equivalent circuit, irrespective of the operating mode, motoring or generating, sub-synchronous or super-synchronous speeds. This is shown schematically in Figure 5, where the two reactive powers shown always have the same sign, and they only differ in their magnitudes ($Q_r' = \frac{Q_r}{|s|}$).



(a)

(b)

Figure 5. (a): actual reactive power fed into the rotor windings from RSC, (b): reactive power fed into the stator-referred equivalent circuit

Reactive power using the dynamic model

Up to now, the emphasis has been only on the reactive power terms at steady-state, resorting to phasor equations and the steady-state equivalent circuit. To obtain insight into the conditions that prevail under transient conditions, it is helpful to express the equations in the synchronous *dq* reference frame. To investigate the relation between the actual rotor side and stator-referred reactive powers, the *dq* transformation is incorporated. As the primary goal here is deciding on the relative signs of reactive powers, the special steady-state case is considered. To be able to better compare the method in this paper with what has been given in [5,6] the same power invariant *abc* to *dq* transformation is used here.

Assuming balanced positive sequence rotor voltages, they are referred to the synchronous reference frame using (9).

$$\begin{bmatrix} v_{dr} \\ v_{qr} \\ v_{0r} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta_s-\theta_m) & \cos(\theta_s-\theta_m-\frac{2\pi}{3}) & \cos(\theta_s-\theta_m-\frac{4\pi}{3}) \\ -\sin(\theta_s-\theta_m) & -\sin(\theta_s-\theta_m-\frac{2\pi}{3}) & -\sin(\theta_s-\theta_m-\frac{4\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} \mathrm{V}_{rm}\cos(\omega_r t+\theta_0) \\ \mathrm{V}_{rm}\cos(\omega_r t+\theta_0-\frac{2\pi}{3}) \\ \mathrm{V}_{rm}\cos(\omega_r t+\theta_0-\frac{4\pi}{3}) \end{bmatrix} \quad (9)$$

where θ_s is the angle of the synchronous frame and θ_m is the rotor angle with respect to the stationary phase-a axis, both expressed in electrical radians. The slip angle can now be expressed as given in (10), where ω_r is the slip speed (which is also the angular frequency of the rotor voltages) in electrical radians/s.

$$\theta_s - \theta_m = \theta_r = \omega_r t \quad (10)$$

It should be recalled the rotor angular frequency has been assumed positive ($\omega_r > 0$) to have positive sequence rotor voltages.

The *dq* components of the rotor voltage can be simply obtained using (9), the result is:

$$v_{dr} = \sqrt{\frac{3}{2}} V_{rm}\cos(\theta_0), v_{qr} = \sqrt{\frac{3}{2}} V_{rm}\sin(\theta_0) \quad (11)$$

There will be no zero sequence component as the voltages have been assumed balanced ($v_{0r} = 0$).

The phasor corresponding to the rotor voltage can now be expressed using the d-axis and q-axis components in the synchronous reference frame, leading to:

$$\bar{V}_r = v_{dr} + jv_{qr} = \sqrt{\frac{3}{2}} V_{rm} e^{j\theta_0} \quad (12)$$

It is seen that for ($\omega_r > 0$), a three-phase positive sequence rotor voltage set is converted to DC values in the synchronous reference frame.

Now assuming each rotor phase current lags its corresponding phase voltage by an angle of φ, the three-phase rotor currents are expressed as:

$$\begin{cases} i_{ar} = I_{rm}\cos(\omega_r t + \theta_0 - \varphi) = I_{rm}\cos(\omega_r t + \gamma) \\ i_{br} = I_{rm}\cos(\omega_r t + \gamma - \frac{2\pi}{3}) \\ i_{cr} = I_{rm}\cos(\omega_r t + \gamma - \frac{4\pi}{3}) \end{cases} \quad (13)$$

where γ has been defined to be: $\gamma = \theta_0 - \varphi$.

The *dq* components of the rotor current are derived:

$$i_{dr} = \sqrt{\frac{3}{2}} I_{rm}\cos(\gamma),\ i_{qr} = \sqrt{\frac{3}{2}} V_{rm}\sin(\gamma) \quad (14)$$

Using (14), the rotor current phasor is expressed as follows:

$$\bar{I}_r = i_{dr} + ji_{qr} = \sqrt{\frac{3}{2}} I_{rm} e^{j(\theta_0-\varphi)} \quad (15)$$

As the transformation is power invariant, the active and reactive powers fed into the rotor are expressed by:

$$\begin{aligned} P_r &= real(\bar{V}_r \bar{I}_r^*) = (\frac{3}{2})V_{rm} I_{rm}\cos(\varphi) = \mathrm{v}_{dr}\, i_{dr} + v_{qr} i_{qr} \\ Q_r &= imag(\bar{V}_r \bar{I}_r^*) = (\frac{3}{2})V_{rm} I_{rm}\sin(\varphi) = v_{qr} i_{dr} - v_{dr} i_{qr} \end{aligned} \quad (16)$$

In the preceding derivations ((9)-(16)), sub-synchronous mode of operation corresponding to ($\omega_r > 0$) was assumed. Now the super-synchronous mode of operation is studied. In this mode corresponding to ($\omega_r < 0$), the rotor voltages with the same expression will appear as a negative sequence set:

$$\begin{cases} v_{ar} = V_{rm}\cos(\omega_r t + \theta_0) = V_{rm}\cos(|\omega_r t| - \theta_0) \\ v_{br} = V_{rm}\cos(\omega_r t + \theta_0 - \frac{2\pi}{3}) = V_{rm}\cos(|\omega_r t| - \theta_0 + \frac{2\pi}{3}) \\ v_{cr} = V_{rm}\cos(\omega_r t + \theta_0 - \frac{4\pi}{3}) = V_{rm}\cos(|\omega_r t| - \theta_0 + \frac{4\pi}{3}) \end{cases} \quad (17)$$

Transforming the above set of negative sequence voltages to the synchronous reference frame will yield exactly the same d-axis and q-axis voltage components and rotor voltage phasor as for positive sequence voltages ((12),(13)).

Now the rotor currents under super-synchronous speed are expressed in their *abc* reference frame and are then transformed to the synchronous reference frame. It is again assumed that any rotor phase current lags its corresponding phase voltage by an angle of φ.

$$\begin{aligned} & v_{ar} = V_{rm}\cos(\omega_r t + \theta_0) = V_{rm}\cos(|\omega_r|t - \theta_0) \Rightarrow \\ & i_{ar} = I_{rm}\cos(|\omega_r|t - \theta_0 - \varphi) = I_{rm}\cos(\omega_r t + \theta_0 + \varphi) \end{aligned} \quad (18)$$

Similarly:

$$\begin{aligned} & v_{br} = V_{rm}\cos(\omega_r t + \theta_0 - \frac{2\pi}{3}) = V_{rm}\cos(|\omega_r|t - \theta_0 + \frac{2\pi}{3}) \\ & \Rightarrow i_{br} = I_{rm}\cos(|\omega_r|t - \theta_0 + \frac{2\pi}{3} - \varphi) = ... \\ & I_{rm}\cos(\omega_r t + \theta_0 + \varphi - \frac{2\pi}{3}) \end{aligned} \quad (19)$$

And:

$$i_{cr} = I_{rm}\cos(\omega_r t + \theta_0 + \varphi - \frac{4\pi}{3}) \quad (20)$$

Defining ($\gamma = \theta_0 + \varphi$) the rotor currents are transformed to the synchronous reference frame, resulting to:

$$i_{dr} = \sqrt{\frac{3}{2}} I_{rm}\cos(\gamma),\ i_{qr} = \sqrt{\frac{3}{2}} V_{rm}\sin(\gamma) \quad (21)$$

Finally, the rotor current phasor is derived as follows:

$$\bar{I}_r = i_{dr} + j i_{qr} = \sqrt{\frac{3}{2}} I_{rm} e^{j(\theta_0 + \varphi)} \quad (22)$$

Considering (12) and (22) it is shown that for super-synchronous operation if the rotor phase currents are lagging (leading) with respect to their respective phase voltages by an angle of φ, the *dq* rotor currents will lead (lag) their corresponding *dq* rotor voltages by the same angle.

As the angular relation between the rotor phase voltage and current has not been altered (it can be assumed that there is a load connected to rotor terminals to fix the relative angles), it is expected that the active and reactive powers remain the same as they were when the rotor was rotating at sub-synchronous speed. Manipulation of the *dq* voltage and current (equations (11), (12), (21) and (22)) yields:

$$\begin{aligned} & P_r = (\frac{3}{2})V_{rm}I_{rm}\cos(\varphi) = real(\bar{V}_r\bar{I}_r^*) = v_{dr}i_{dr} + v_{qr}i_{qr} \\ & Q_r = (\frac{3}{2})V_{rm}I_{rm}\sin(\varphi) = -imag(\bar{V}_r\bar{I}_r^*) = -(v_{qr}i_{dr} - v_{dr}i_{qr}) \end{aligned} \quad (23)$$

Equation (23) shows that while the expression for rotor *active* power does not depend on the rotor sub-synchronous or super-synchronous mode of operation, for *reactive* power fed into the rotor, care should be taken whether the speed is sub-synchronous (where (16) is valid) or super-synchronous (where (23) is valid).

The equivalent circuit referred to the stator and the phasor diagram based on this circuit are better not to be altered based on the operating speed of the machine; instead, while other relations remain the same for super-synchronous speed, the expression for reactive power fed into the rotor of the DFIM from RSC should be modified. The following general rotor reactive power expression is proposed, to be used under all operating speeds:

$$Q_r = sign(s) * imag(\bar{V}_r\bar{I}_r^*) = sign(s) * (v_{qr}i_{dr} - v_{dr}i_{qr}) \quad (24)$$

The coefficient ($sign(s)$) takes care of sub-synchronous (positive slip, hence $sign(s) = 1$) or super-synchronous (negative slip, hence $sign(s) = -1$) speeds.

Results and Discussion

In order to show the efficacy of the proposed rotor reactive power relation given by (24), a DFIM with the parameters given in Table 1 is simulated in Matlab® Simulink under vector control with reference values of rotor speed and stator reactive power. The mechanical torque is taken as the input to the system. This can be load torque for a motor or turbine torque for a generator.

As motoring convention has been adopted, positive mechanical torque and stator active power represent motoring operation and negative values of these quantities represent generation.

Table 1. Parameters of the simulated DFIM

Stator resistance (pu)	0.05	Rotor leakage inductance (pu)	0.1
Rotor resistance (pu)	0.02	Magnetizing inductance (pu)	5
Stator leakage inductance (pu)	0.1	Base frequency (Hz)	60

The reference stator reactive power is kept zero, in accordance with [5], so that the machine should be magnetized through the rotor; in other words, under this control scenario, there is a need of positive reactive power supplied to the rotor in different operating modes. The reference speed is kept at 0.7 pu (i.e. sub-synchronous speed) for the first 15 seconds, then it changes to 1.3 pu (i.e. super-synchronous speed).

Figure 6 shows the active and reactive powers fed into the stator winding for motoring operation. This mode of operation has been simulated by simply taking a positive value of input torque (meaning load torque). As the goal of this paper is not control performance of the system, transients occurring in the waveforms are not of importance and emphasis is made on their steady-state values. Figure 7 shows variation of rotor *abc* currents for motoring mode under two operating speeds: for sub-synchronous speed (left side figure) the currents are positive sequence, while for super-synchronous speed (right side figure) the currents are negative sequence.

The same phase reversal phenomenon is also observed for rotor voltages (Figure 8).

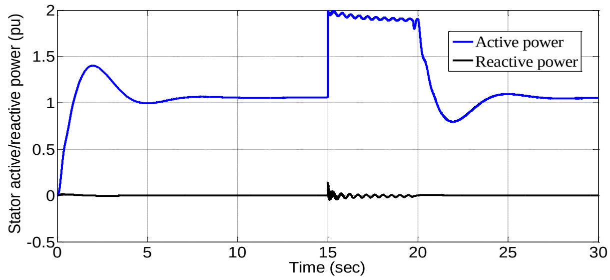


Figure 6. Stator active and reactive powers for positive input torque (motoring operation)

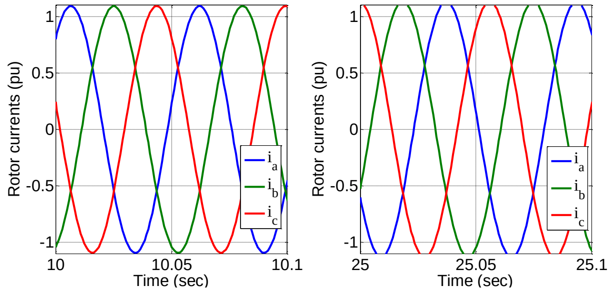


Figure 7. Rotor phase currents for motoring mode (left: sub-synchronous, right: super-synchronous)

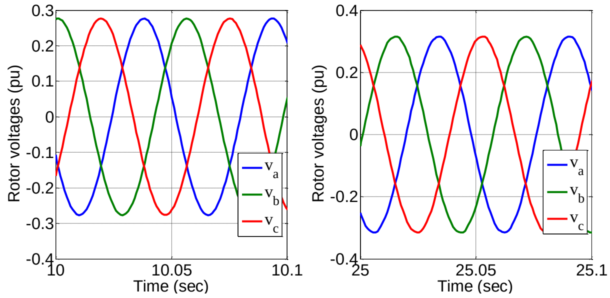


Figure 8. Rotor phase voltages for motoring mode (left: sub-synchronous, right: super-synchronous)

In Figure 9 relative time displacement of rotor phase-a voltage and current is illustrated for motoring operation under sub-synchronous speed (left) and super-synchronous speed (right). It is interesting that under both rotor speed operating modes, the rotor current lags the rotor voltage. This was expected because the stator reactive power being kept at zero, the DFIM should be magnetized through the rotor, so from the viewpoint of RSC, the rotor is inductive. For sub-synchronous speed (left), the rotor current lags the rotor voltage by an angle greater than 90 degrees, meaning that the rotor active power is negative (power fed from the rotor into RSC) while for super-synchronous speed (right), the rotor current lags the rotor voltage by an angle less than 90 degrees, meaning that rotor active power is positive (power fed from RSC into the rotor). This is in accordance with what has been reported in the literature [2].

A comparison is made in Figure 10 between the traditional rotor reactive power relation (equation 16) and the modified relation (equation 24). It is clear that the rotor reactive power at steady-state should be positive to magnetize the machine. While both expressions yield similar results for sub-synchronous speeds, the correct rotor reactive power for super-synchronous speeds is obtained using the modified relation derived in this paper.

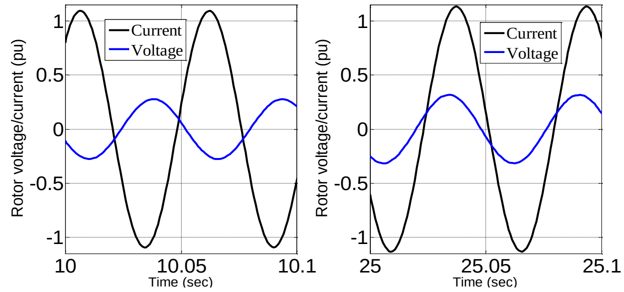


Figure 9. Relative time displacement of rotor voltage and current for motoring mode (left: sub-synchronous, right: super-synchronous)

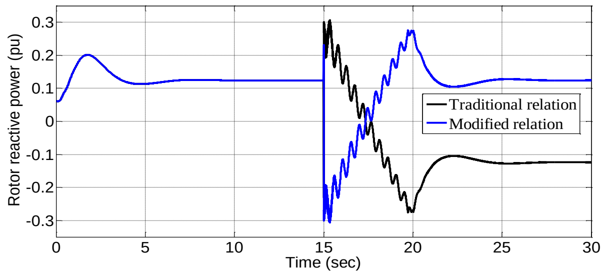


Figure 10. Rotor reactive power using traditional and modified relations (motoring operation)

Variation of stator active and reactive powers for generating operation is depicted in Figure 11. This mode of operation is implemented by keeping the input torque negative (meaning turbine torque). Variation of rotor *abc* currents for generating mode is shown in Figure 12, where the phase sequence of rotor currents changes when the speed goes from sub-synchronous (left) to super-synchronous (right). This phenomenon was also observed for motoring operation (Figure 7). This phase reversal also occurs for rotor voltages when the speed changes from sub-synchronous to super-synchronous (Figure 13).

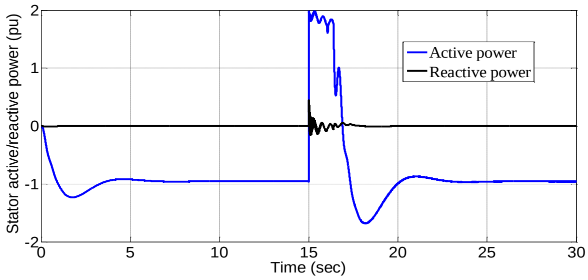


Figure 11. Stator active and reactive powers for negative input torque (generating operation)

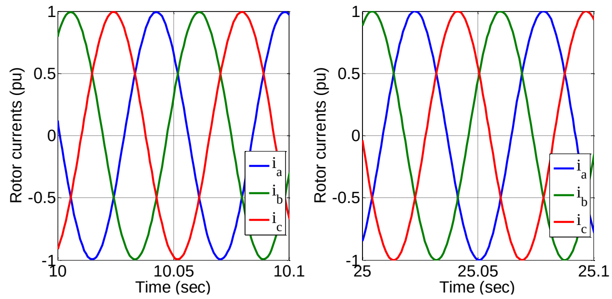


Figure 12. Rotor phase currents for generating mode (left: sub-synchronous, right: super-synchronous)

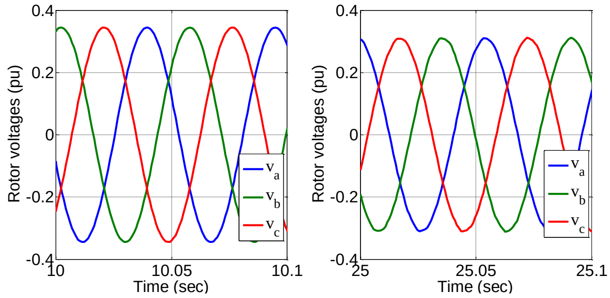


Figure 13. Rotor phase voltages for generating mode (left: sub-synchronous, right: super-synchronous)

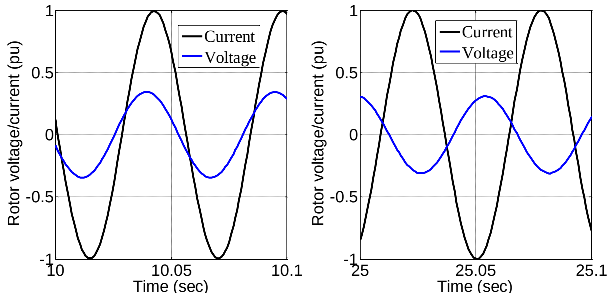


Figure 14. Relative time displacement of rotor voltage and current for generating mode (left: sub-synchronous, right: super-synchronous)

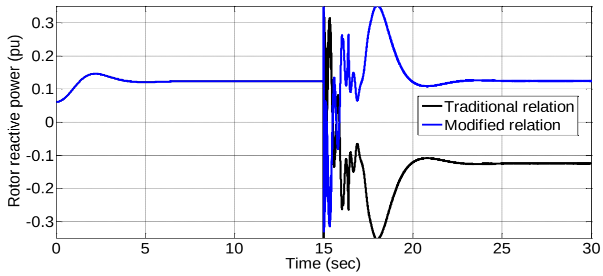


Figure 15. Rotor reactive power using traditional and modified relations (generating operation)

Variation of rotor phase-a voltage and current for generating operation is illustrated in Figure 14 for both sub-synchronous (left) and super-synchronous (right) speeds. Similar to Figure 9, rotor current lags rotor voltage under both conditions for the same reason. For sub-synchronous generating operation, active power should be supplied to the rotor windings, which necessitates a phase angle difference of less than 90 degrees between rotor voltage and current (left); on the other hand, active power is drawn from the rotor to RSC for super-synchronous generating operation, meaning that the phase angle difference between rotor voltage and current should be greater than 90 degrees (right). This is again in accordance with [2]. As was done for the motoring mode, the traditional and modified rotor reactive power relations are compared for generating mode in Figure 15. It is again clear that both relations give the same results for sub-synchronous speed conditions, but only the modified relation gives the correct sign of reactive power for super-synchronous speeds.

Conclusions

In this paper, the effect of super-synchronous operation of DFIM on rotor reactive power was investigated in detail. Under such operating conditions, the slip is negative, leading to a negative value of rotor frequency. It is obvious that a negative rotor frequency does not have a physical meaning but it implies a change of the phase sequence of rotor voltages/currents.

It has been shown that the well-established stator-referred equivalent circuit of DFIM is valid for both sub-synchronous and super-synchronous speeds; yet, care must be taken when dealing with phasor diagrams drawn for super-synchronous speeds, where the actual rotor quantities rotate in opposite direction to the stator-referred quantities. Also, calculation of rotor reactive power using *dq* rotor quantities necessitates modification of the traditional relation to take the sign of slip into account.

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