Steady-State Analysis and Control of Double Feed Induction Motor

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Abstract—This paper explores steady-state characteristics of grid-connected doubly fed induction motor (DFIM) in case of unity power factor operation. Based on the synchronized mathematical model, analytic determination of the control laws is presented and illustrated by various figures to understand the effect of the applied rotor voltage on the speed and the active power. On other hand, unlike previous works where the stator resistance was neglected, in this work, stator resistance is included such that the equations can be applied to small wind turbine generators which are becoming more popular. Finally the work is crowned by integration of the studied induction generator in a wind system where an open loop control is proposed confers a remarkable simplicity of implementation compared to the known methods.

Keywords—DFIM, equivalent circuit, induction machine, steady state

I. INTRODUCTION

URING the last years the induction machine is the most used to produce electrical energy in wind power projects. A common configuration for large wind turbines is based on doubly fed induction generator (DFIG) with back to back converter between the AC grid and the rotor winding. The mean advantage of the DFIG is the ability of variable speed operation with only 20-30% of the generated power having to pass through the power converter. This yield considerable reduction in the converter size which translates to substantial system cost benefit. Therefore, the power extraction from the wind can be optimized since the rotating speed can be changed proportionally to the wind speed. Many control strategies of the DFIG have been proposed in the literature. Most are based on the transient state model of the machine and leads to an easy open loop control of the DFIM. The proposed control doesn’t need any sensors but ensure a zero reactive power.

At the end, analytical expressions, derived from the steady state model, are given which lead to an easy open loop control of the DFIM. Furthermore, many authors was examined the Stability of the DFIG by considering only the steady state model [7].

II. STEADY STATE DFIM MODELS

A. Dynamic Equations of DFIM

The DFIM consist of a wound rotor induction machine connected to a converter. The stator is supplied by the grid so that the rotor’s side frequency superimposed with the rotor speed result a synchronously rotating field. Only the fundamental components of the voltage and currents are considered for stator and rotor. Core losses are neglected in the general analysis.
Using the \(dq\) reference frame, the general full order dynamic model of DFIM is given by:

\[
\begin{align*}
V_{sd} &= R_s I_{sd} + \frac{d\phi_{sd}}{dt} - \omega_r \phi_{sq} \\
V_{sq} &= R_s I_{sq} + \frac{d\phi_{sq}}{dt} + \omega_r \phi_{sd} \\
V_{rd} &= R_r I_{rd} + \frac{d\phi_{rd}}{dt} - \omega_r \phi_{rq} \\
V_{rq} &= R_r I_{rq} + \frac{d\phi_{rq}}{dt} + \omega_r \phi_{rd}
\end{align*}
\]

The rotor and stator fluxes are related to the current by:

\[
\begin{align*}
\phi_{sd} &= L_s I_{sd} + L_m I_{rd} \\
\phi_{sq} &= L_s I_{sq} + L_m I_{rq} \\
\phi_{rd} &= L_r I_{rd} + L_m I_{sq} \\
\phi_{rq} &= L_r I_{rq} + L_m I_{sd}
\end{align*}
\]

The electromagnetic torque \(\Gamma_e\) can be expressed according to the stator flux and rotor current by:

\[
\Gamma_e = p \frac{L_m}{L_s} (I_{rd} \phi_{sq} - I_{rq} \phi_{sd})
\]

The variation of the mechanical speed is given by the following differential equation:

\[
\Gamma_e = J \frac{d\omega}{dt} + f\omega + \Gamma_i
\]

### B. Steady State Equations of DFIM

The steady state equations of the DFIG are obtained by cancelling the time derivatives in the dynamic equations (1) to (4). Moreover, by replacing the different flux by their respective equations given according to the stator and rotor currents, we obtain:

\[
\begin{align*}
V_{sd} &= R_s I_{sd} - L_s \omega_r I_{sq} - L_m \omega_r I_{rq} \\
V_{sq} &= R_s I_{sq} + L_s \omega_r I_{sd} + L_m \omega_r I_{rd} \\
V_{rd} &= R_r I_{rd} - L_r \omega_r I_{sq} - L_m \omega_r I_{rq} \\
V_{rq} &= R_r I_{rq} + L_r \omega_r I_{sd} + L_m \omega_r I_{rd}
\end{align*}
\]

The four equations (11) to (14) can be reduced to two: one at the rotor and another at the stator by introducing the voltages and currents space vectors \(\mathbf{V}_r, \mathbf{V}_s, \mathbf{I}_r, \mathbf{I}_s\) and \(\mathbf{I}_r\), defined by:

\[
\begin{align*}
\mathbf{V}_s &= \mathbf{V}_{sd} + j \mathbf{V}_{sq} \\
\mathbf{V}_r &= \mathbf{V}_{rd} + j \mathbf{V}_{rq} \\
\mathbf{I}_r &= \mathbf{I}_{rd} + j \mathbf{I}_{rq} \\
\mathbf{I}_s &= \mathbf{I}_{sd} + j \mathbf{I}_{sq}
\end{align*}
\]

By noting:

\[
\begin{align*}
X_s &= L_s \omega_r \\
X_r &= L_r \omega_r \\
X_m &= L_m \omega_r \\
\omega_r &= s \omega_r
\end{align*}
\]

Easy intermediate calculations makes possible to lead to two equations, one at the stator and the other at the rotor, which determinate the steady state operation of the DFIM. These two equations are given by:

\[
\begin{align*}
\mathbf{V}_s &= (R_s + jX_s) \mathbf{I}_s + jX_m \mathbf{I}_r \\
\mathbf{V}_r &= jX_m \mathbf{I}_r + \left(\frac{R_r}{s} + jX_r\right) \mathbf{I}_r
\end{align*}
\]

In matrix form we got:

\[
\begin{bmatrix}
\mathbf{V}_s \\
\mathbf{V}_r
\end{bmatrix} =
\begin{bmatrix}
R_s + jX_s & jX_m \\
 jX_m & \frac{R_r}{s} + jX_r
\end{bmatrix}
\begin{bmatrix}
\mathbf{I}_s \\
\mathbf{I}_r
\end{bmatrix}
\]

The equations (23) and (24) can be translated in equivalent circuit called: transformer equivalent circuit of DFIM given by Fig. 1.

The equivalent circuit of Fig. 1 is rarely used in the literature. It is preferable to adopt the equivalent circuit where all the sizes are referred to the stator. This representation would be obtained by introducing on the rotor quantities the transformation ratio defined by: \(a = X_s / X_m\).

Then we pose:

\[
\mathbf{V}_r = a \mathbf{V}_s : \text{Rotor voltage referred to the stator.} \\
\mathbf{I}_r = \mathbf{I}_s / a : \text{Rotor current referred to the stator.}
\]

By introducing this variable changes into (23) and (24) it gives:

\[
\begin{align*}
\mathbf{V}_s &= R_s \mathbf{I}_s + jX_s (\mathbf{I}_r + \mathbf{I}_s) \\
\mathbf{V}_r &= \frac{R_r}{s} \mathbf{I}_r + jX_r (\mathbf{I}_s + \mathbf{I}_r)
\end{align*}
\]
With:

\[ X'_l = a'^2 \sigma X'_c \]: Leakage Reactance referred to the stator
\[ R'_l = a'^2 R_s \]: Rotor resistance referred to the stator

The equations (26) and (27) can be written in the following matrix form:

\[
\begin{bmatrix}
V_s \\
\frac{\bar{V}_r}{s}
\end{bmatrix} =
\begin{bmatrix}
R_s + jX_s & jX_s & R'_s + jX'_s \\
-jX_s & jX_s & 
\end{bmatrix}
\begin{bmatrix}
\bar{I}_s \\
\frac{\bar{I}_r}{s}
\end{bmatrix}
\]

(28)

Then it possible to lead to an equivalent circuit which differs from the induction machine conventional circuit by the presence of the rotor voltage \( \bar{V}_r / s \):

![Fig. 2 Equivalent circuit of DFIG referred to the stator side](image)

**C. Analytical Expressions of \( \bar{I}_s \) and \( \bar{I}_r \)**

To find the expressions of the stator and rotor currents, \( \bar{I}_s \) and \( \bar{I}_r \), according to the voltages and the slip, it would be easier to apply the theorem of superposition. The \( \bar{I}_r \) current will be the superposition of two currents \( \bar{I}_{1r} \) and \( \bar{I}_{2r} \), which are respectively created by the source \( \bar{V}_r \), with \( \bar{V}_r / s \) null and by the source \( \bar{V}_r / s \) while keeping \( \bar{V}_s \) null. The same procedure will be applied to the current \( \bar{I}_s \).

1. \( \bar{I}_{1s} \) and \( \bar{I}_{1r} \) Computation

By short-circuiting the rotor side source \( \bar{V}_r \), one leads to the equivalent diagram of Fig. 3.

![Fig. 3 Superposed theorem applied to the equivalent circuit for \( \bar{I}_{1s} \) and \( \bar{I}_{1r} \) computation](image)

From Fig. 3 it is easy to write:

\[
\bar{I}_{1s} = \frac{\bar{V}_s}{R_s + (jX_s / R_s / s + jX'_s)}
\]

(29)

\[
\bar{I}_{1r} = \frac{\bar{V}_r / s}{R'_s / s + jX'_s}
\]

(30)

2. \( \bar{I}_{2s} \) and \( \bar{I}_{2r} \) Computation

By short-circuiting the stator side source \( \bar{V}_s \), one leads to the equivalent diagram of Fig. 4.

![Fig. 4 Superposed theorem applied to the equivalent circuit for \( \bar{I}_{2s} \) and \( \bar{I}_{2r} \) computation](image)

By using Fig. 4, it can be easily deduced that:

\[
\bar{I}_{2s} = \frac{\bar{V}_s / s}{(R_s / s + jX'_s) / (R_s / s)}
\]

(31)

\[
\bar{I}_{2r} = \frac{-jX'_s / s}{R'_s / s + jX'_s}
\]

(32)

Finally the currents \( \bar{I}_s \) and \( \bar{I}_r \) are given by the following expressions:

\[
\bar{I}_s = \bar{I}_{1s} + \bar{I}_{2s} = \frac{(R_s + jX_s + jX'_s) \bar{V}_s - jX_s \bar{V}_r}{sX'_s / s + (R_s + jX_s) / (R_s + jX'_s + jX'_s)}
\]

(33)

\[
\bar{I}_r = \bar{I}_{1r} + \bar{I}_{2r} = \frac{-jX'_s \bar{V}_s + (R_s + jX'_s) \bar{V}_r}{sX'_s / s + (R_s + jX'_s) / (R_s + jX'_s + jX'_s)}
\]

(34)
3. Modified Equivalent Circuit of the DFIM

The equivalent diagram of Fig. 3 can be modified, to become more realistic, by giving a physical interpretation for the fictitious source $\tilde{V}_r/s$, fictitious resistance $R_r/s$, and by reasoning on the power having to pass through the rotor.

According to the equivalent circuit of Fig. 2, we can conclude that the electromagnetic power $P_e$, transmitted to the stator, is equal to the active power provided by the $\tilde{V}_r/s$ source minus the Joule losses dissipated in the fictitious resistance $R_r/s$:

$$P_e = \text{Re}(\tilde{V}_r\tilde{I}_r) - \frac{R_r}{s}|\tilde{I}_r|^2$$ \hspace{1cm} (35)

On the other hand, the electromagnetic power $P_e$ is the sum of the active power $P_a$, provided by the real source $V_r$, plus the mechanical power $P_m$ minus the Joule losses dissipated in the real resistance $R_r$:

$$P_e = \text{Re}(V_r\tilde{I}_r) + P_m - R_r|\tilde{I}_r|^2$$ \hspace{1cm} (36)

Making member to member the equality between (35) and (36), we lead to the following mechanical power expression:

$$P_m = \frac{1}{s}(1-s)\text{Re}(\tilde{V}_r\tilde{I}_r) - \frac{1}{s}R_r|\tilde{I}_r|^2 = \frac{1}{s}(P_e - R_r|\tilde{I}_r|^2)$$ \hspace{1cm} (37)

It can be seen according (37) that the mechanical power $P_m$ is made up of two terms: the first term, $(1-s)P_e/s$, part of the active power provided by the source $\tilde{V}_r$, which converted into mechanical power. The second term $-\frac{1}{s}R_r|\tilde{I}_r|^2/s$ represents the mechanical power provided from the outside. By taking account of the losses in the resistance $R_r$, we lead finally to the modified equivalent circuit shown at Fig. 5:

![Fig. 5 Modified equivalent circuit of the DFIM](image)

III. CHARACTERISTICS OF THE DFIG IN THE CASE OF UNITY POWER FACTOR OPERATION

The rotor of a DFIG is generally supplied by a PWM inverter. The DC bus voltage is maintained constant by an adequate control of a PWM rectifier which is fed by the grid via a three-phase transformer. Moreover, the control of the grid side rectifier ensures a unity power factor so that the rotor side reactive power can be considered as null. The DFIG reactive power $Q_{\text{gen}}$ is defined as only that passing through the stator:

$$Q_{\text{gen}} = Q_i$$

![Fig. 6 DFIG connected to the grid](image)

A. Stator Reactive Power Characteristics

The reactive power $Q_i$ swapped between the stator and the grid is given by the following relation:

$$Q_i = \text{Im}(\tilde{V}_r\tilde{I}_r)$$ \hspace{1cm} (38)

By taking the stator voltage vector $\tilde{V}_r$ as origin of the phases we are able to write $\tilde{V}_r = V_{rd} + jV_{rq} = V_{sd} = V_r$, moreover, by substituting the current $\tilde{I}_r$ given by (33) the reactive power $Q_i$ is given by:

$$Q_i = V_r\text{Im}(\tilde{I}_r) = V_r \left[ \frac{(R_{V_{rd}} + V_{rd}X_{\sigma})(sR_{X_{\sigma}} + sR_{X_r} + R_{X_r})}{(sR_{X_{\sigma}} + sR_{X_r} + R_{X_r})^2 + (R_{R_{\sigma}} - sX_{\sigma}X_{\sigma})} \right] - \frac{(sV_{X_{rd}} + sV_{X_r}X_{rd} - V_{rd}X_{\sigma})}{(sR_{X_{\sigma}} + sR_{X_r} + R_{X_r})^2 + (R_{R_{\sigma}} - sX_{\sigma}X_{\sigma})}$$ \hspace{1cm} (39)

To have $Q_i$ constantly null, the following equality should be satisfied:

$$\left[ (R_{V_{rd}} + V_{rd}X_{\sigma})(sR_{X_{\sigma}} + sR_{X_r} + R_{X_r}) - (sV_{X_{rd}} + sV_{X_r}X_{rd} - V_{rd}X_{\sigma})(R_{R_{\sigma}} - sX_{\sigma}X_{\sigma}) \right] = 0$$ \hspace{1cm} (40)

From (40) we deduce that if we want to operate at zero reactive power, the rotor voltage component $V_{rq}$ must be calculated according $V_{rd}$ by the following relation:

$$V_{rq} = \frac{(sV_{X_{rd}} + sV_{X_r}X_{rd} - V_{rd}X_{\sigma})(R_{R_{\sigma}} - sX_{\sigma}X_{\sigma})}{X_{\sigma}(sR_{X_{\sigma}} + sR_{X_r} + R_{X_r})} - \frac{R_{V_{rd}}V_{rd}}{X_{\sigma}}$$ \hspace{1cm} (41)

Fig. 7 shows the DFIG rotor voltage $V_{rq}$ against the slip $s$ as variation in $V_{rd}$. Note that the operating characteristics ensure a zero reactive power at the stator side.
By supposing the reactive power equal to zero, it results:

\[ Q_s = \text{Im}(\bar{V}_s, \bar{I}_s) = V_s \text{Im}(I_{sd} - jI_{sq}) = 0 \Rightarrow I_{sq} = 0 \]  

(42)

It is deduced that the stator current does not have an imaginary component; the space vector \( \bar{I}_s \) merges with the real component \( I_{sd} \):

\[ \bar{I}_s = I_{sd} = I_s \]  

(43)

By using the relation given by (33) combined with the fundamental relation of (40) we find that the current \( \bar{I}_s \) is given by:

\[ I_s = \frac{sV_iX_{sd} + sV_iX_{sq} - V_{sd}X_{sd}}{sR_iX_{sd} + sR_iX_{sq} + R_iX_{sd}} \]  

(44)

The active power \( P_s \) passing through the stator is given by the following relation:

\[ P_s = \text{Re}(\bar{V}_s, \bar{I}_s) = V_s I_s \]  

(45)

Fig. 8 shows the modulus of the rotor current versus the slip as \( V_{sd} \) increases from -0.4pu to 0.4pu. It is noted that the current is still different from zero because of the needed magnetizing reactive power passing only through the rotor.

D. Electromagnetic Torque Characteristics

The electromagnetic power \( P_e \), passing through the rotor towards the stator, across the air gap, is equal to the power provided by the stator to the grid increased by the joules losses in the \( R_s \) resistance. With the adopted conventions, it is written:

\[ P_e = (P_s - R_sI_{sd}^2) = R_sI_{rd}^2 - P_s \]  

(50)

\[ = R_s \left( \frac{sV_iX_{sd} + sV_iX_{sq} - V_{sd}X_{sd}}{sR_iX_{sd} + sR_iX_{sq} + R_iX_{sd}} \right)^2 - V_s \left( \frac{sV_iX_{sd} + sV_iX_{sq} - V_{sd}X_{sd}}{sR_iX_{sd} + sR_iX_{sq} + R_iX_{sd}} \right) \]

C. Rotor Current Characteristics

The rotor current \( \bar{I}_r \), with the adopted Conventions, is the difference between the magnetizing current \( \bar{I}_{m} \) passing through \( X_s \) and the stator current:

\[ \bar{I}_r = \frac{V_s - R_sI_{rd}}{jX_s} - I_s = j \frac{R_sI_{rd} - V_s}{X_s} - I_s = I_{rd} + jI_{sq} \]  

(47)

With:

\[ I_{rd} = I_s = \frac{sV_iX_{sd} + sV_iX_{sq} - V_{sd}X_{sd}}{sR_iX_{sd} + sR_iX_{sq} + R_iX_{sd}} \]  

(48)

\[ I_{sq} = \frac{R_sI_{rd} - V_s}{X_s} \]  

(49)
The electromagnetic torque is consequently given by:

\[ \Gamma_e = \frac{P_r - P_i}{\Omega_s} \]  

(51)

One can observe, in Fig. 10, the electromagnetic torque characteristics versus the slip as variation in \( V_{rd} \). It is noted that the electromagnetic torque has a line equation if the torque not exceed the rated value. It is easy to give an explanation if \( R_s \) is made equal to zero in (50):

\[ \Gamma_e = \frac{V^2_i (X'_s + X_s)}{R_s X_s} \]  

(52)

From (52), note that electromagnetic torque vary with a negative and constant slope: \( -V^2_i (X'_s + X_s) / R_s X_s \). This justifies the characteristics given on Fig. 10.

E. Reactive and Active Rotor Powers Characteristics

The reactive power \( Q_r \) provided by the rotor side inverter is used to magnetize the machine since the stator reactive power \( Q_s \) is imposed null. This last is given by:

\[ Q_r = \text{Im}(V_r I_r^*) = \text{Im}(V_{rd} + jV_{rq})(-I_s + j\frac{R_s I_s - V_s}{X_s}) \]  

(53)

\[ = V_{rq} I_s + \frac{V_{rd}}{X_s} (V_s - R_s I_s) \]

The rotor side inverter provides to the rotor an active power given by:

\[ P_r = \text{Re}(V_r I_r^*) = \text{Re}(V_{rd} + jV_{rq})(-I_s + j\frac{R_s I_s - V_s}{X_s}) \]  

(54)

\[ = -V_{rd} I_s + \frac{V_{rq}}{X_s} (V_s - R_s I_s) \]

F. Global DFIM Active Power Characteristics

The active power of the generator \( P_{DFIM} \) was defined as being the sum of the power exchanged with the grid side stator and the inverter side rotor:

\[ P_{DFIM} = P_s + P_i = (V_s - V_{rd}) I_s + \frac{V_{rq}}{X_s} (V_s - R_s I_s) \]  

(55)

IV. SAFETY OPERATING RANGES OF THE DFIM

To avoid the excessive heating of the machine's windings, it should be taken care that stator and rotor currents are below or equal to their rating values. Owing to the fact, the expression of the stator current is simpler; we give the limitation strategy by acting of the stator current.

A. Limitation by the Rotor Voltage

We suppose that the machine operates at a given slip, we thus calculate the voltage \( V_{rd} \) to be applied to the rotor so that the machine stays within the acceptable limits of operation.

To answer the put question, it should be solved the following inequality:
The Resolution of this inequality enables to find the range of \( V_{rd} \) to apply to the rotor to avoid overloading the machine. It is found that:

\[
V_{rd\min} \leq V_{rd} \leq V_{rd\max}
\]

With:

\[
V_{rd\min} = \frac{1}{X_s} \left[ s(V_i + R_i I_{s\max})(X_s + X' \sigma) + R_i I_{s\max} \right]
\]

\[
V_{rd\max} = \frac{1}{X_s} \left[ s(V_i - R_i I_{s\max})(X_s + X' \sigma) - R_i I_{s\max} \right]
\]

The safety operating range is subdivided into two parts by a line corresponding to a null value of the stator current which admits as equation:

\[
V_{rd(0)} = \frac{V_i (X_s + X' \sigma)}{X_s} \cdot s
\]

### B. Limitation by the Slip

The safety operating area of the DFIM can also be defined by acting on the slip \( s \) instead of the voltage \( V_{rd} \). By solving the inequality given by (60) it is found:

\[
s_{\min} \leq s \leq s_{\max}
\]

With:

\[
s_{\min} = \frac{X_i (V_i - R_i I_{s\max})}{(X_s + X' \sigma)(V_i + R_i I_{s\max})}
\]

\[
s_{\max} = \frac{X_i (V_i + R_i I_{s\max})}{(X_s + X' \sigma)(V_i - R_i I_{s\max})}
\]

Fig. 13 shows the acceptable operating range of the DFIM according to voltage \( V_{rd} \) and the slip \( s \). This range area is delimited by two lines: one corresponds to the maximum voltage \( V_{rd\max} \) not to exceed and which coincides with generator operation. The other line delimits the minimal voltage \( V_{rd\min} \) from which one should not go down and corresponds to motor operation.

The safety operating range is subdivided into two parts by a line corresponding to a null value of the stator current which admits as equation:

\[
V_{rd(0)} = \frac{V_i (X_s + X' \sigma)}{X_s} \cdot s
\]

### V. OPEN LOOP CONTROL OF THE DFIM

In this section we propose an open loop control of the DFIM. The control has as a main aim to answer the following question: which is the value of the voltage to be applied to the rotor if we want to operate under a known applied torque and a desired mechanical speed? Moreover, the additional constraint to operate under a null reactive power must be verified. This open loop control doesn’t require any sensor as in the case of other known controls.

To check the validity of the proposed control, numerical simulation results are given where the control is applied to the dynamic \( dq \) model of the DFIM. Constraints such as the current limitation and mechanical frictions will be taken into account to supplement this study.

### A. Control Voltage Computation

Desired operating points can be imposed to the machine according to the rotor applied voltage. While placing in the case of the wind power system, to have an MPTT operation, the desired speed of the DFIG can be given by the measured wind speed. The applied torque can be known from the mechanical power available on the turbine shaft.

To find the voltage to be applied to the rotor, we proceed in two steps: to calculate initially the stator current \( I_s \) according to the applied torque then we calculate the voltage according to the slip and \( I_s \).
The electromagnetic torque equation is first written as:

$$\Gamma_{em} = \frac{P_{d}}{\Omega} = -\frac{P_{s} - R_{s}I_{s}^{2}}{\Omega} = \frac{V_{s}I_{s} - R_{s}I_{s}^{2}}{\Omega}$$  \hspace{1cm} (64)

To find the value of $I_{s}$ corresponding to each value of $\Gamma_{em}$, we solve the second order equation (64) and we lead to the following results:

$$I_{s1} = \frac{1}{2R_{s}}(V_{s} - \sqrt{V_{s}^{2} + 4\Gamma_{s}\Omega R_{s}})$$  \hspace{1cm} (65)

$$I_{s2} = \frac{1}{2R_{s}}(V_{s} + \sqrt{V_{s}^{2} + 4\Gamma_{s}\Omega R_{s}})$$  \hspace{1cm} (66)

The second solution, $I_{s2}$ given by (66) is to be rejected since it gives only negative values.

Knowing the value of the $I_{s}$ current, given by the equation (65), it is possible to deduce from (44) the voltage to be applied to the rotor according the desired mechanical speed:

$$V_{sd} = \frac{X_{s} + X_{d}'}{X_{s}}(R_{s}I_{s} - V_{s})s - R_{s}I_{s}$$  \hspace{1cm} (67)

By introducing the mechanical speed $\Omega$:

$$V_{sd} = -\frac{X_{s} + X_{d}'}{\Omega_{s}X_{s}}(R_{s}I_{s} - V_{s})(\Omega_{s} - \Omega) - R_{s}I_{s}$$  \hspace{1cm} (68)

Obtaining the supply rotor voltage and the steady state control can be summarized by the following diagram:

---

**B. Simulation and Results**

A numeric simulation was carried out using MATLAB-Simulink software under the following conditions: the machine being at a standstill ($s=1$), then we want that the DFIM start up and operates as generator and in sub-synchronous range. The applied torque is of 15 N-m and the desired slip is 0.3. The machine is connected to the grid; it is supplied with 220/380V balanced three-phase system and 50Hz of frequency. To avoid overflow of the currents, at the time of starting up, the reference slip is applied gradually using a weak negative slope. Remembered the proposed control ensures a null stator reactive power.

The simulation results shown at the Fig. 16 to 18 demonstrate that the desired operating point is well obtained and the reactive power is equal to zero. The proposed control is then validated.

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**Fig. 15 Steady state control of the DFIM assuring a null reactive power and without any sensors**

**Fig. 16 Simulated reference speed and DFIM speed**

**Fig. 17 Simulated stator active and reactive power**

**Fig. 18 Simulated stator current**
VI. CONCLUSION

In this work, it has been established the steady state characteristics of a DFIM under unity power factor operation. Driven from the forth synchronized model, it is given the relation between the rotor voltage components ensuring a zero reactive power at the stator. This assumption leads to very interesting analytical expression of the electromagnetic torque, the speed and the other sizes, permitting to understand the DFIM behaviors and to define the safety operating area. Moreover, the analytical expressions lead to a very interesting and easy open loop control of the DFIM without any sensors. The simplicity holds promise of greater reliability.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>STUDIED DFIM CARACTERISTICS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal power $P_n$</td>
<td>3Kw</td>
</tr>
<tr>
<td>Nominal supply voltage $V_Y$</td>
<td>220V/380V</td>
</tr>
<tr>
<td>Stator rated current $I_Y$</td>
<td>11A/6.3A</td>
</tr>
<tr>
<td>Stator resistance $R_s$</td>
<td>0.099</td>
</tr>
<tr>
<td>Stator cyclic inductance $L_s$</td>
<td>260mH</td>
</tr>
<tr>
<td>Leakage coefficient $\sigma$</td>
<td>0.0872</td>
</tr>
<tr>
<td>Rotor constant $T_r$</td>
<td>0.72</td>
</tr>
<tr>
<td>Rotor resistance $R_r$</td>
<td>1.5Ω</td>
</tr>
<tr>
<td>Transformation ratio $a=L_s/L_o$</td>
<td>2.02</td>
</tr>
</tbody>
</table>

REFERENCES


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