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Research Article

Steady state analysis of DFIG wind turbine using Matlab#

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Abstract: In this paper the steady state electric circuit of the DFIG is developed, deriving the steady state model electric equations along with its physics. By means of these model equations, Matlab m-file for steady state calculations is developed. The modes of operation of the machine for different rotor speeds are presented and analyzed. Finally, based also on the Matlab calculations, a detailed performance evaluation of the DFIG is carried out, developing steady state performance curves that can reveal current, voltage, power balance, power losses, depending on the specific operating mode of the machine.

1. Introduction

Over the last years, there has been a strong penetration of renewal energy resources into the power system. Wind energy generation has played and will continue to play a very important role in electric energy sector for the coming years. Doubly fed induction generator (DFIG) based wind turbines have arisen as one of the leading technologies for wind turbine manufacturers, demonstrating that it is a cost effective, efficient, and reliable solution [1]. This machine, a key element of the wind turbine, is also known in the literature as the wound rotor induction machine, or asynchronous machine. It presents many similarities with the widely used and popular squirrel cage induction machine However, despite the parallelism of both machines, the DFIG requires its own specific study for an adequate understanding. DFIG used for wind turbines is basically a standard, wound rotor induction generator with a voltage source converter connected to the slip-rings of the rotor [2]. The stator winding are coupled directly to the grid and the rotor winding is connected to power converter as shown in figure 1. This configuration is especially attractive as it allows the power electronic converter to deal with approximately 30% of the generated power, reducing considerably the cost and the efficiency compared with full converter based topologies. Most manufacturers adjust the synchronous speed to be centred in the middle of the variable speed operation range 1500 rpm for two pole generators in wind turbines with a variable speed range from 1000 to 2000 rpm), which means that the machine, working at sub-synchronous and hyper-synchronous speeds with positive and negative torques, needs to be fed by a four-quadrant power electronic converter [3]. The standard power electronic converter used in this application is a back-to-back converter composed of two three-phase inverters sharing the DC bus. At present, most manufacturers uses two-level converters with standard IGBTs in order to reduce the cost for the 1.5 to 3 MW wind turbines; but for the most powerful offshore ones (3 to 10 MW), three-level converters are expected to be the best option.

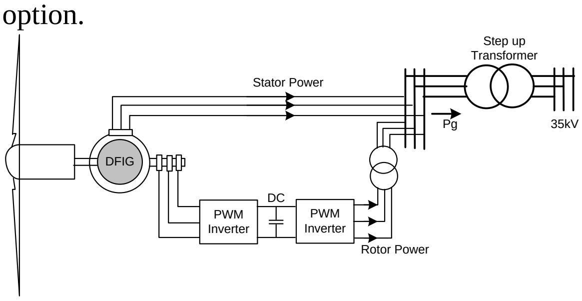

***Figure 1.** Double-Fed Induction Generator.*

2. Steady state DFIG model

To investigate the power balance and eficiency of DFIG in stady state operation regime the equivalent circuit shown in figure 2 can be used. The rotor quantities are referred to the stator. The reverse rotor current direction is used to facilitate the analysis of DFIG wind turbine, where the rotor circuit is connected to a power converter system with bidirectional power flow. The rotor side convertor is modeled as equivalent impedance. In developing model it is assumed that the induction generator is symmetrically structured and three phase are balanced, and the magnetic core of the stator and rotor is linear with negligible magnetic resistance. In this paper is considered the case that the generator operates with an Maximum Power Point Tracking scheme, and its mechanical torque is proportional to the square of the rotor speed [4,5].

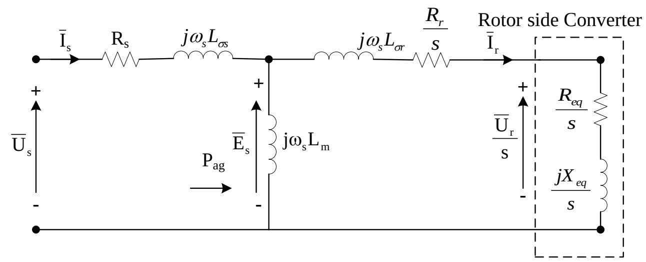

Figure 2. *Steady state equivalent circuit of the DFIG*

To investigate steady state analysis of DFIG we assumed that stator operates with $\cos\varphi = 1$.The air-gap power, stator current and magnetizing voltage branch of inductive generator can be calculated by expressions:

$$P_{ag} = \frac{\omega_s T_m}{p} = 3 \cdot (U_s - I_s R_s) \tag{1}$$

$$I_s = \frac{U_s \pm \sqrt{U_s^2 - \frac{4 R_s \omega_s T_m}{3p}}}{2R_s} \tag{2}$$

$$\bar{U}_m = \bar{U}_s - \bar{I}_s(R_s + j\omega_s L_{ls}) \tag{3}$$

For $\cos\varphi = 1$, where inductive machine operating in generation mode for the stator voltage and current we can write:

$$\bar{U}_s = U_s \angle 0^0 \text{ and } \bar{I}_s = I_s \angle 180^0 \tag{4}$$

The magnetizing current is given by:

$$\bar{I}_m = \frac{\bar{U}_m}{j\omega_s L_m} \tag{5}$$

The rotor current and voltage are given by:

$$\bar{I}_r = \bar{\bar{I}}_s - \bar{\bar{I}}_m \tag{6}$$

$$\bar{U}_r = s\bar{\bar{U}}_m - \bar{\bar{I}}_r(R_r + js\omega_s L_{lr}) \tag{7}$$

The equivalent impedance of rotor side converter can be calculated by:

$$\frac{\bar{U}_r}{\bar{I}_r} = R_{eq} + jX_{eq} \tag{8}$$

3. Matlab m-file for power balance analysis of DFIG in steady state operation regime

. We considered 5 MW, 950 V, 50 Hz, 1170 rpm, wind turbine of DFIG type which parameters are shown in table 1. The purpose of this example is to assess specific numerical calculations and graphical presentation of the impact of the rotor slip, to the electrical and mechanical variables as well as the power balance, power losses of DFIG-s. Application program Matlab is used for the calculation and graphical and numerical presentation [7]. For this case the specific m-file in Matlab is developed based on 5 MW DFIG parameters and from steady state equations obtained by the equivalent model of DFIG shown in figure 2. The m-file program automatically calculate and graphically present the diagrams of selected complex variables versus of rotor speed ωr which changes in the range (600- 11200) rpm with speed increment of $\Delta\omega_r = 1$ rpm. This program can also be used for DFIG with different size and capacity, if we know in advance its parameters.

Table 1. *5 MW, 950 V, 50 Hz DFIG parameters[4]*

Generator Type	DFIG, 5.0 MW, 950 V
Rated mechanical power	5 MW
Rated stator voltage, U_s	950 V
Rated stator current, I_s	2578.4 A
Rated rotor current, I_r	3188.7 A
Rated Rotor Speed	1170 rpm
Nominal Rotor Speed	670 – 1170 rpm
Rated Slip	-0.17
Number of Pole Pairs, p	3
Rated Mechanical Torque T_m	40.809 kNm
Stator Winding Resistance, R_s	1.552 mΩ
Rotor Winding Resistance, R_r	1.446 mΩ
Stator Leakage Inductance, L_{ls}	1.2721 mH
Rotor Leakage Inductance, L_{lr}	1.1194 mH
Magnetizing Inductance, L_m	5.5182 mH

Bellow is presented m-file script for steady state calculations of DFIG in Matlab:

```
% MATLAB m-file  for steady state analysis of 5MW, 950V,50Hz DFIG wind turbine
 Ub=950/sqrt(3); Ib=3118.7;  % Base [V] and  [A]
Us_=548.5+0i;  % Stator phase to ground  [V]
Rs=0.001552; Rr=0.001446;    % Stator and rotor winding resistance [ohm]
ws=2*pi*50;p=3;     % Stator frequency [rad/s] and number of poles
Los=0.0012721;Lor=0.0011194;     % Stator and rotor leakage inductance  [H]
Lm=0.0055182;     % Magnetizing inductance [H]
wrt=600:1:1200;  % Range and Step time calculation
wr=2*pi*p*wrt/60;   %angular electrical frequency of rotor  [rad/s]
Tmn=-(1000/1150)^2*40809; % Rated mechanical torque for s=0 [Nm]
s=(ws-wr)/ws      % slip
Tm=(wr/ws).^2*Tmn   % Mechaniqal torque  [Nm]
Is_=-(Us_-sqrt(Us_.^2-(4*Rs*ws*Tm)/(3*p)))/
(2*Rs)*exp(i*pi)        % Stator  current [A]
Is=abs(Is_)      % Magnitude [A]
Ispu=Is/Ib       % Stator current pu.
thetaIs_=angle(Is_)*180/pi    % stator current angle [degree]
Um_=Us_-Is_*(Rs+i*ws*Los)    % Magnetizing branch voltage [V]
Um=abs(Um_)       % Magnitude [V}
thetaUm=angle(Um_)*180/pi       % Magnetizing branch voltage [degree]
Im_=Um_/(i*ws*Lm)    % Magnetizing current [A]
Im=abs(Im_)        % Magnitude [A]
thetaIm=angle(Im_)*180/pi  % Magnetizing current angle [degree]
Ir_=Is_-Im_      % Rotor current [A]
Ir=abs(Ir_)      % Magnitude [A]
Irpu=Ir/Ib       % Rotor current [pu.]
thetaIr=angle(Ir_)*180/pi  % Rotor current [degree]
s1=s;
Ur_=s1.*Um_-Ir_.*(Rr+i*s1*ws*Lor)    % Rotor voltage phase to ground [V]
Ur=abs(Ur_)        % Magnitude [V}
Urpu=Ur/Ub        % Rotor voltage [pu.]
thetaUr=angle(Ur_)*180/pi  % Rotor voltage angle [degree]
Zeq_=Ur_./Ir_ % Zeq of Rotor S.Conv. [ohm]
Req=real(Ur_./Ir_)
Xeq=imag(Ur_./Ir_)
powfac_rot=angle(Zeq_)*180/pi    % Rotor power factor angle [degree]

%POWER BALANCE
Prot=(3*(Ir).^2).*Req      % Rotor power [W]
Pstator=3*Us_.*abs(Is_).*cos(angle(Us_)-angle(Is_))  % Stator power [W]
deltaProt=3*(Ir).^2*Rr  % Rotor power losses [W]
deltaPstator=3*(Is).^2*Rs  % Stator losses [W]
Pg=Pstator-Prot     % Pg of 5 MW  DFIG [W]
Pmek=Pg+abs(deltaProt)+abs(deltaPstator)   % Rotor mechanical power [W]

%Graphical results
subplot(5,1,1);plot(s,thetaUr,s,thetaIr,s,powfac_rot);
subplot(5,1,2);plot(s,Irpu,s,Ispu,s,Urpu);
subplot(5,1,3);plot(s,Req,s,Xeq);
subplot(5,1,4);plot(s,deltaProt,s,deltaPstator);
subplot(5,1,5);plot(s,-Prot,s,Pstator,s,Pg);
```

4. Simulation results and discussion discussions

After m-file MATLAB execution we have the graphical results and numerical results as shown in figures 3,4, 5 and table 2

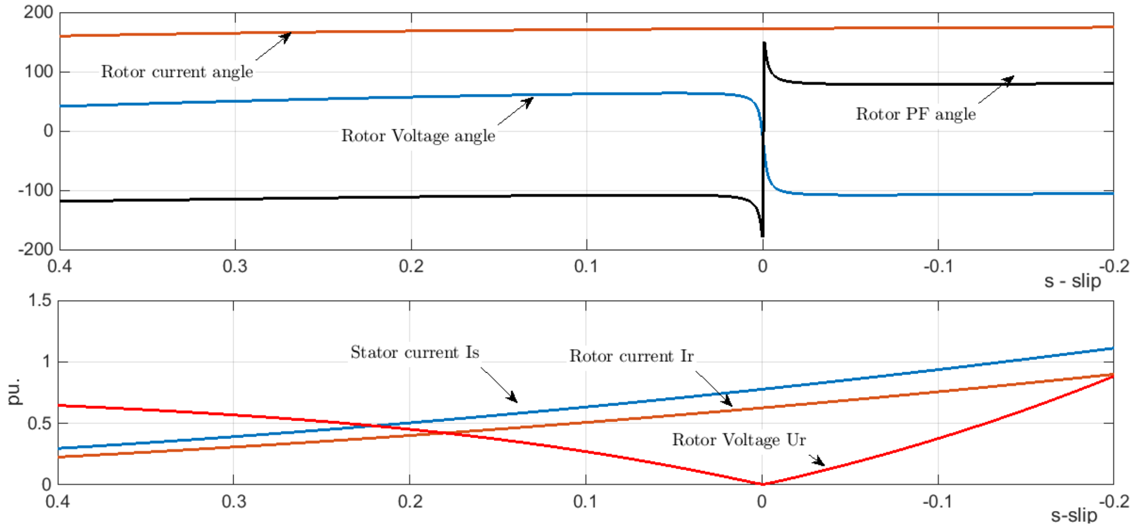

***Figure 3** Voltage and currents versus generator slip s.*

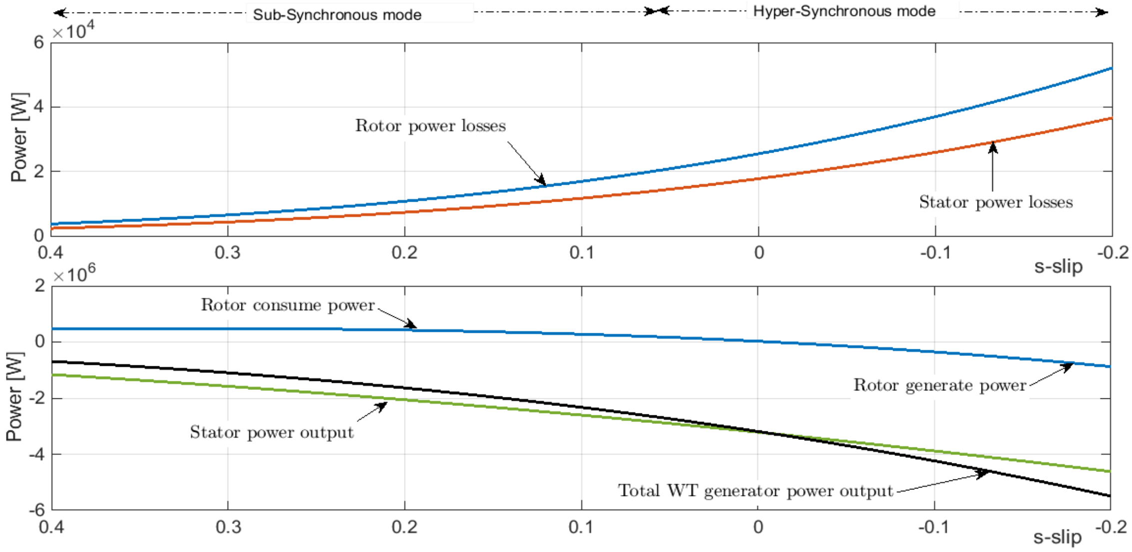

Figure 4 *Rotor, stator and generator power versus generator slip (s) for* $cos\varphi = 1$

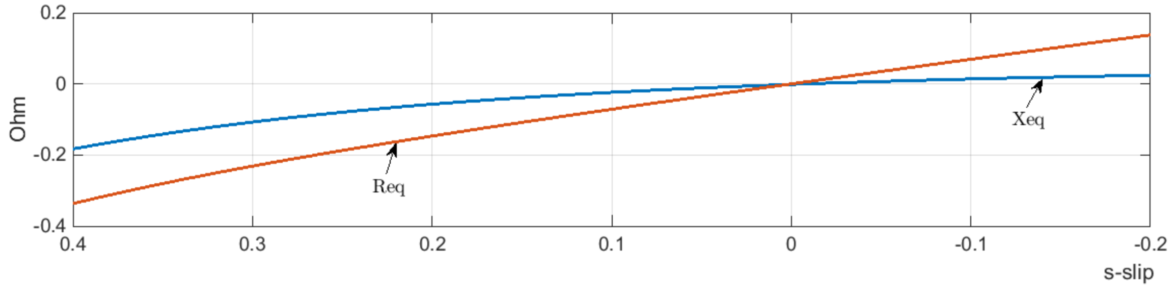

Figure 5 *Rotor side converter equivalent impedance versus generator slip (s) for* $cos\varphi = 1$

Table 2 *Power output, losses and efficiency of DFIG for different rotor speeds*

Speed [rpm]	s-slip	Pg [kW]	ΔP_r [kW]	ΔP_S [kW]	Efficienc [%]
1170	-0.17	5000	43	47	98.4
1000	0	3188	17.8	25.5	98.6
800	0.2	1636	7.3	10.7	98.8
670	0	963	5.5	3.6	99.0

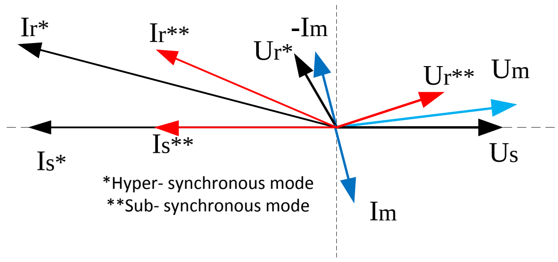

Figure 6 *Phase diagram of DFIG obtained by table 2 results*

Table 3 *Voltage and current phases of DFIG for different rotor speeds*

Speed [rpm]	Us [V]	Ur [V]	Is [kA]	Ir [A]
1170	$548e^{j0}$	$398e^{-j105}$	$2668e^{j57}$	$3298e^{j174}$
1000	$548e^{j0}$	$3.5e^{-j7}$	$1953e^{j180}$	$2424e^{j172}$
800	$548e^{j0}$	$248e^{j57}$	$1252e^{j180}$	$1573e^{j168}$
670	$548e^{j0}$	$326e^{j47}$	$248e^{j57}$	$1127e^{j163}$

It is essential to note that the generator slip s, respectively, the rotational speed of wind turbine determines operating character of DFIG. Analysing the graphical and numerical results, from figure 3 it can be shown that with the increase of the rotor angular speed from 600 rpm (s = 0.4) to the synchronous speed 1000 rpm (s = 0), the rotor voltage U_r decreases gradually near to the zero, and above synchronous speed the rotor voltage increases almost linearly to the certain value. It should be noted that the rotor calculated values of current and voltage are referred to the stator, which means that the real values of voltage and current in the rotor for the given 5 MW DFIG , should be transformed through rotor/stator winding ratio u = U_{rn}/ U_{sn}=381/548.48=0.694.

In figure 3 is shown also the phase angle of rotor voltage, rotor current and rotor power factor angle. In sub-synchronous mode of operation the power factor angle of rotor is negative, indicating that the rotor absorbs power from the grid, while in the hyper-synchronous mode of operation rotor inject power to the grid.

When DFIG operates at synchronous speed (s = 0) induction generator behave like synchronous generator. The rotor absorbs only small amount of power which is needed for excitation, and practically does not share power with the grid as is shown in figure 4. For s=0 the rotor leakage reactance and equivalent reactance of RSC are both zero. In this case the DFIG generated power is transferred through stator.

The rotor and stator losses increase proportionally to the square of the rotor and stator currents. In the sub-synchronous mode of operation the DFIG generated power Pg < Ps, due to the rotor power consumption, while in the hyper-synchronous operation both rotor and stator generate power and Pg > Ps The results presented above confirm the advantages of the DFIG wind turbine concept. In contrast to the constant speed wind turbine, DFIG generates power even for s > 0.

In figure 5 is shown the diagram of the equivalent resistance and reactance of the rotor side converter in dependence to the slip s. When the DFIG operates in the sub-synchronous mode the equivalent resistance of RSC is negative, indicating that rotor absorbs active power from RCS, while when DFIG operates in hyper-synchronous mode equivalent resistance is positive, meaning that an active power is delivered from rotor to the RSC, respectively to the grid. The negative sing of equivalent impedance of RSC is not a physical concept, but mathematically shows the change of rotor power flow direction.

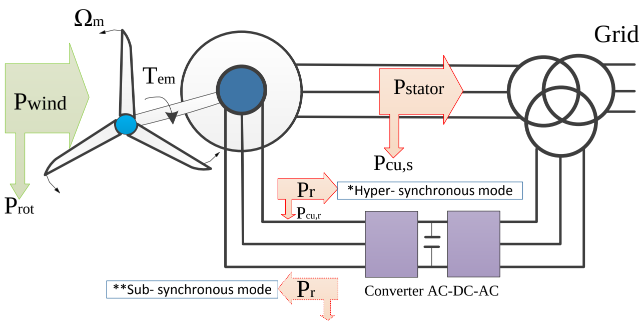

Figure 7 *Power balance illustration of DFIG based on different operational modes*

In table 3 are presented numerical results of DFIG power balance, and figure 6 shows phase diagrams of current and voltages obtained by table 2 numerical results corresponding to the operation modus of DFIG.

Figure 7 illustrates power balance of DFIG depending of operational regime in regard with sub or hyper synchronous mode.

5. Conclusion

In this paper, the steady state equivalent circuit for DFIG is presented and analysed, and the rotor side converter (RSC) is modeled by an equivalent impedance. The operating principle of the doubly fed induction generator (DFIG) with unit power factor operation are presented and analyzed. For the study case the 5 MW DFIG wind turbine is selected and based on the mathematical equations the Matlab m-file is developed. Finally, based on the Matlab calculations, a detailed performance evaluation of the DFIG is carried out, developing steady state performance curves of current, voltage, power balance, depending on the specific operating mode of the machine.

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