POWERFACTORY

PowerFactory 2021

Technical Reference

Doubly-Fed Induction Machine

ElmAsmsc, TypAsmo

PF2021

POWER SYSTEM SOLUTIONS

MADE IN GERMANY

Publisher:
DIgSILENT GmbH
Heinrich-Hertz-Straße 9
72810 Gomaringen / Germany
Tel.: +49 (0) 7072-9168-0
Fax: +49 (0) 7072-9168-88
info@digsilent.de

Please visit our homepage at:
https://www.digsilent.de

January 28, 2021
PowerFactory 2021
Revision 2

Contents

1 General Description 1

2 Load Flow Analysis 3

2.1 DFIG . . . 3

2.2 DFIG with integrated rotor-side PWM . . . 3

3 Short-Circuit Calculation 5

4 Harmonics 6

5 Stability/Electromagnetic Transients (RMS/EMT Simulation) 7

5.1 General . . . 7

5.2 DFIG . . . 8

5.2.1 Rotor protection . . . 8

5.3 DFIG with integrated rotor-side PWM . . . 8

5.3.1 Rotor Protection . . . 9

6 Input/Output Definitions of Dynamic Models 10

List of Figures 13

List of Tables 14

1 General Description

The doubly-fed induction generator (DFIG) is a rotor-voltage controlled, slip-ring induction machine. The PWM converter connected to the slip-rings controls the rotor voltage in magnitude and phase angle, why active and reactive power output of the DFIG can be controlled.

There are two different models in *PowerFactory*, one is without and the other one with integrated PWM converter. The doubly-fed induction machine model without an integrated rotor-side converter is a model with two AC terminals and is shown in Figure 1.1. The doubly-fed induction machine model with an integrated rotor-side converter is a model with AC and a DC terminal and is shown in Figure 1.2.

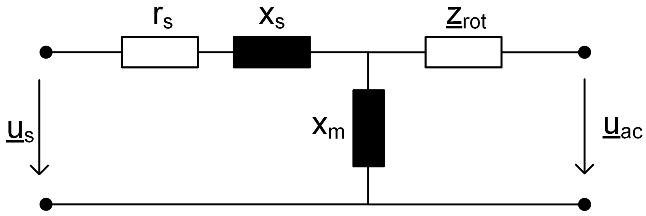

Figure 1.1: Equivalent Circuit of the DFIG Model

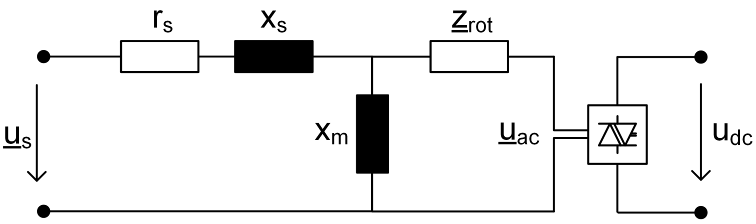

Figure 1.2: Equivalent Circuit of the DFIG model with integrated PWM

The rotor-side converter according to Figure 1.3 is modelled by a fundamental frequency approach. The AC- and the DC-voltages are related to each other by the modulation index $\underline{P}m$. It is assumed that the modulation corresponds to a sinusoidal pulse-width modulation (PWM). The PWM converter model is lossless and the active power flowing through the rotor is equal to the active power through the converter.

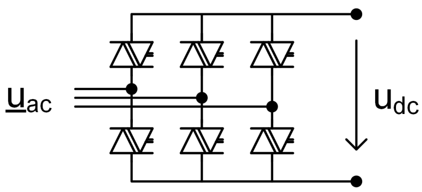

Figure 1.3: Rotor-Side PWM-Converter

If relevant, switching losses can be considered as no-load losses by an equivalent resistance connected between the DC-node and ground. The detailed PWM-converter model (*ElmVsc-mono*) of *PowerFactory* integrates no-load losses and it is recommended to consider all switching losses in the grid-side converter model.

The winding ratio between stator and rotor is directly calculated from the open-loop rotor voltage without considering the voltage drop across the leakage reactance due to no-load currents.

If the winding ratio and the actually measured nominal rotor voltage are available, the input parameter $Urot$ (*Rated Slip Ring Voltage*) should be calculated from the winding ratio.

The induction machine model is identical to the standard induction machine model of *PowerFactory*, including a very detailed approximation of the rotor impedance $\underline{z}_{rot}$ with up to three R-L ladder circuits. For more information on the rotor side model, please refer to the asynchronous machine technical reference document.

All resistances and reactances of the model need to be entered for $slip = 0$ in $p.u.$ values. Additionally, all rotor resistances and reactances need to be referred to the stator side. If the rotor impedance referred to the stator is in absolute value, the base impedance for converting to $p.u.$ values is $Z_b = ugn^2/sgn$ where ugn is the nominal voltage of the machine and sgn is the nominal apparent power.

2 Load Flow Analysis

The rated voltage of the stator side is taken from the asynchronous machine type parameter ugn and the rated rotor voltage from the input parameter $Urot/1000$ (*Rated Slip Ring Voltage*).

2.1 DFIG

The DFIG model without integrated PWM requires the input of the steady state slip $slipset$ for load flow calculations. The control of the active and reactive power is done using an external PWM. Therefore, load flow equations for the element are simple:

$$\begin{aligned} \underline{i}_R &= \frac{\underline{u}_R - \underline{u}_m \cdot slipset/100}{\underline{z}_{rot}} \\ \underline{i}_S + \underline{i}_R &= \frac{\underline{u}_m}{\jmath x_m} \end{aligned} \tag{1}$$

where:

- $\underline{u}_S$ and $\underline{i}_S$ are stator voltage and current;
- $\underline{u}_R$ and $\underline{i}_R$ are rotor voltage and current;
- $\underline{u}_m = \underline{u}_S - (r_{str} + \jmath\, x_{str}) \cdot \underline{i}_S$ and $\underline{x}_m$ are magnetising voltage and magnetising reactance;
- $\underline{r}_{str}$ and $\underline{x}_{str}$ are stator resistance and reactance;
- $\underline{z}_{rot}$ is rotor impedance;
- $slipset$ is slip setpoint.

2.2 DFIG with integrated rotor-side PWM

For load flow analysis, active and reactive power and steady state slip need to be specified. All other variables, including the corresponding modulation index are calculated during the load flow iterations.

The active and reactive power inputs define the stator active and reactive power and not the total power of the doubly-fed induction machine. For many applications, it is useful to specify the power at a different point, e.g. at the HV-side of a three-winding transformer fed by a DFIG.

The following are the load flow equations from which also the voltage source voltage $\underline{u}_{ac} = usr + \jmath\, usi$ is determined:

$$\begin{aligned} \underline{i}_R &= \frac{usr + \jmath\, usi - \underline{u}_m \cdot slipset/100}{\underline{z}_{rot}} \\ \underline{i}_S + \underline{i}_R &= \frac{\underline{u}_m}{\jmath x_m} \\ p_R &= u_{dc} \cdot i_{dc} \end{aligned} \tag{2}$$

where:

- $\underline{u}_{dc}$ and $\underline{i}_{dc}$ are stator voltage and current;
- p_R is the active power of the rotor.

The pulse-width modulation indexes are calculated as:

$$
\begin{aligned}
Pmr &= \frac{2 \cdot \sqrt{2}}{\sqrt{3}} \cdot \frac{usr}{u_{dc}} \cdot \frac{Urot/1000}{u_{dc\ nom}} \\
Pmi &= \frac{2 \cdot \sqrt{2}}{\sqrt{3}} \cdot \frac{usi}{u_{dc}} \cdot \frac{Urot/1000}{u_{dc\ nom}}
\end{aligned}
\tag{3}
$$

where $u_{dc\ nom}$ is the nominal voltage of the connected DC terminal.

3 Short-Circuit Calculation

The short-circuit model for doubly-fed induction generators is identical to the short-circuit model of the standard asynchronous machine with the *Doubly Fed Induction Machine* option set. Please refer to the Technical Reference of the asynchronous machine (*ElmAsm*) for more details.

Note: Short-circuit contributions will be provided by the stator-side connection. The connection to the rotor side is neglected.

---

4 Harmonics

For harmonic analysis, the doubly-fed induction machine model is based on the subtransient model and is the same as the standard asynchronous machine model with DFIG option selected. For more details please refer to the asynchronous machine technical reference document.

5 Stability/Electromagnetic Transients (RMS/EMT Simulation)

5.1 General

The common properties of the DFIG and the DFIG with integrated PWM models are described here. In the following subsections, the characteristics that are valid for the separate models will be given.

The DFIG machine model is very similar to the model used for the asynchronous machine part when the DFIG option is used (without the simplified power converter). The differences compared to the standard asynchronous machine model will be presented here for better comparison and readability. More information on the standard asynchronous machine with and without the DFIG option can be found in the asynchronous machine technical reference document.

Considering the rotor voltage of the rotor side terminal (voltage source) $\underline{u}_{ac} = u_{sr} + \jmath u_{si}$, the following rotor voltage equation is obtained:

$$\underline{\mathbf{u}}_{\mathbf{ac}} = \mathbf{r_R} \cdot \underline{\mathbf{i}}_R + \frac{1}{\omega_n} \cdot \frac{d\underline{\mathbf{\Psi}}_R}{dt} + j\,\frac{\omega_{ref} - \omega_R}{\omega_n} \cdot \underline{\mathbf{\Psi}}_R \tag{4}$$

If the option *Effect of frequency variation* (available on the *Advanced* tab of the *RMS-Simulation* page of the *TypAsmo* edit dialog) is disabled, it is assumed that the frequency changes are small and don't have a big effect on the stator voltage (the frequency is kept constant $\omega_{ref} = \omega_n$. Else, the effect of frequency variation on the stator voltage is taken into account.

The variables of the machine (currents, voltages,...) are expressed in a synchronous reference frame rotating with the global system reference (usually fixed to the rotor of the reference machine). The variables can be expressed in the rotor reference frame by shifting them using the rotating angle phi_m (as in Equation 8) . This angle is initialised to zero, and its rotation depends on the speed of the machine i.e. its derivative is initialised and calculated as:

$$\frac{d\;phi_m}{dt} = 2 \cdot \pi \cdot f_{nom} \cdot (speed - f_{ref}) \tag{5}$$

where:

- f_{ref} is the speed (frequency) of the reference machine;
- f_{nom} is the nominal frequency.

The variables are shifted to this reference frame by multiplying them with the transformation $e^{-\jmath \cdot phi_m}$.

The output signals ird and irq are calculated using the internal rotor currents $\underline{i}_R$ as:

$$ird + \jmath\; irq = \underline{i}_R \cdot e^{-\jmath \cdot phi_m} \tag{6}$$

The calculation quantities urd and urq are similarly calculated as:

$$urd + \jmath\; urq = (usr + \jmath\; usi) \cdot e^{-\jmath \cdot phi_m} \tag{7}$$

The phase currents and voltages ira, irb, irc, ura, urb and urc are calculated from ird, irq, urd and urq using the inverse Clarke transformation.

The DFIG model does not support neutral connections for both RMS and EMT simulations. The zero sequence equations remain the same. For the unbalanced RMS simulation, the negative sequence impedance $\underline{z}_2$ is slip dependent and calculated same as for the asynchronous machine (with slip of $2 - slip$).

5.2 DFIG

The configuration of the doubly fed induction machine without integrated PWM is shown in Figure 5.1.

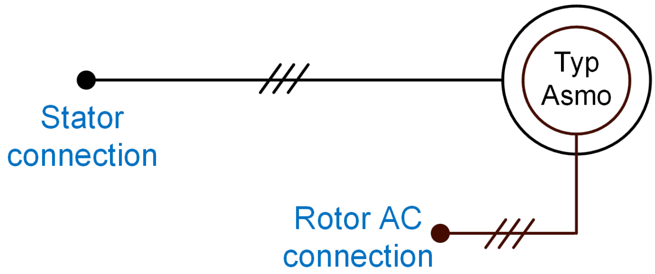

Figure 5.1: Configuration of the DFIG without integrated PWM

For this model an additional equation needs to be satisfied for the rotor-side current:

$$\underline{i}_{rot} = \underline{i}_R \cdot e^{-\jmath \cdot phi_m} \tag{8}$$

where $\underline{i}_R$ is the internal model rotor current and $\underline{i}_{rot}$ is the rotor-side current expressed in the rotor reference frame available from the simulation ($m\colon i1r\colon bus2$ and $m\colon i1i\colon bus2$).

The voltages of rotor-side connected terminal are also expressed in the rotor reference frame ($m\colon u1r\colon bus2$ and $m\colon u1i\colon bus2$).

In this model, the *Rated Slip Ring Voltage* is required only for calculating the parameters Ird and Irq (in A).

5.2.1 Rotor protection

For limiting the rotor current and for influencing the speed-torque characteristic of the machine, the rotor additional resistance and reactance can be included. These can be inserted by changing the values of the input parameter $rradd$ and calculation parameter $xradd$ using *Parameter-Events*.

5.3 DFIG with integrated rotor-side PWM

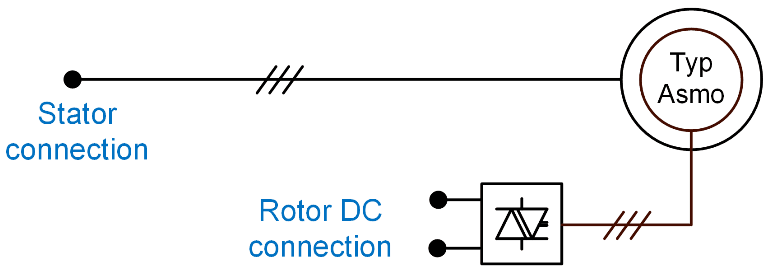

Figure 5.2: Configuration of the DFIG with integrated PWM

The converter is controlled by the pulse width modulation factors Pmd and Pmq (input signals) in the rotor reference frame . It is therefore necessary to convert the d-q output of a controller (usually expressed in a stator reference frame) to the rotor reference frame of the machine.

Internally first the modulation factors in the synchronous frame are being calculated:

$$Pmr + \jmath\, Pmi = (Pmd + \jmath\, Pmq) \cdot e^{\jmath \cdot phi_m} \tag{9}$$

The rotor voltage of the machine is then controlled using the modulation factors as:

$$\begin{aligned} usr &= \frac{\sqrt{3}}{2 \cdot \sqrt{2}} \cdot Pmr \cdot \frac{u_{dc} \cdot u_{dc\ nom}}{Urot/1000} \\ usi &= \frac{\sqrt{3}}{2 \cdot \sqrt{2}} \cdot Pmi \cdot \frac{u_{dc} \cdot u_{dc\ nom}}{Urot/1000} \end{aligned} \tag{10}$$

where $u_{dc\ nom}$ is the nominal voltage of the connected DC terminal. The same can be written in the rotor reference frame as :

$$\begin{aligned} urd &= \frac{\sqrt{3}}{2 \cdot \sqrt{2}} \cdot Pmd \cdot \frac{u_{dc} \cdot u_{dc\ nom}}{Urot/1000} \\ uri &= \frac{\sqrt{3}}{2 \cdot \sqrt{2}} \cdot Pmq \cdot \frac{u_{dc} \cdot u_{dc\ nom}}{Urot/1000} \end{aligned} \tag{11}$$

5.3.1 Rotor Protection

For protecting the rotor side PWM-converter against high rotor currents, the converter can be bypassed during fault conditions. The crowbar activation can be simulated by using *Parameter-Events* on set_bypass and $reset\_bypass$. When the bypass is set, the converter is bypassed (the voltages usr and usi are set to zero) and a series impedance consisting of the input parameters $rcrow$ and $xcrow$ is inserted in the rotor.

For limiting the rotor current and for influencing the speed-torque characteristic of the machine, an additional resistance and reactance can be included in the rotor circuit. These can be inserted by changing the values of the input parameter $rradd$ and calculation parameter $xradd$ using *Parameter-Events*.

Additional protection, e.g. protection against under- or over-voltage can be implemented using standard *PowerFactory* relay models.

6 Input/Output Definitions of Dynamic Models

The following per-unit systems are used:

-Rated Apparent Power, Rated Voltage:

$$S_r;\ V_r;\ Z_b = \frac{V_r^2}{S_r} \tag{12}$$

-Rated (Electrical) Active Power:

$$P_{er} = S_r \cdot \cos(\phi_r) \tag{13}$$

-Rated Mechanical Power:

$$P_{mr} = P_{er} \cdot \eta_r \tag{14}$$

where η_r is the motor rated efficiency.

-Rated Mechanical Torque:

$$M_{mr} = \frac{P_{mr}}{\omega_{mr}} = \frac{P_{mr}}{\frac{\omega_n}{p_z} \cdot (1 - s_n)} \tag{15}$$

where s_n is the nominal slip;
ω_n is the nominal electrical angular velocity in rad/s;
p_z is the number of pole-pairs.

Table 6.1: DFIG - dynamic model signals and state variables

Parameter	Symbol	Unit	I/O	Description
pt		p.u.	INPUT	Turbine power (rated to mechanical power)
xmdm	m_m	p.u.	INPUT	Mechanical load torque (rated to mechanical torque)
rradd		p.u.	INPUT	Additional rotor resistance
usr		p.u.	INPUT	Rotor voltage (voltage source converter)
usi		p.u.	INPUT	Rotor voltage (voltage source converter)
iqgrid		p.u.	INPUT	Reactive current of Grid-Side Converter
xspeed	$speed$	p.u.	OUTPUT	Mechanical speed (equal to speed)
pgt		p.u.	OUTPUT	Active power (rated to nominal active power)
xme	m_e	p.u.	OUTPUT	Electrical torque, based on rated mechanical torque
phi	phi	rad	OUTPUT	Rotating angle for transferring between dq and $\alpha\beta$ system (EMT only)
ird	ird	p.u.	OUTPUT	d-axis rotor current (referred to rotor angle)
irq	ird	p.u.	OUTPUT	q-axis rotor current (referred to rotor angle)
xphim	phi_m	p.u.	OUTPUT	Rotating angle with slip frequency
psis_r		p.u.	OUTPUT	Stator Flux, Real Part
psis_i		p.u.	OUTPUT	Stator Flux, Imaginary Part
psir_r		p.u.	OUTPUT	Rotor Flux, Real Part
psir_i		p.u.	OUTPUT	Rotor Flux, Imaginary Part
cosphim		p.u.	OUTPUT	cos(phim)
sinphim		p.u.	OUTPUT	sin(phim)
cosphi		p.u.	OUTPUT	cos(phi) (EMT only)
sinphi		p.u.	OUTPUT	sin(phi) (EMT only)
phim	phi_m	p.u.	STATE	Rotating angle with slip frequency
speed	$speed$	p.u.	STATE	Mechanical speed
psiA1_r	$\underline{\psi}_R$	p.u.	STATE	Flux of loop A1, real
psiA1_i	$\underline{\psi}_R$	p.u.	STATE	Flux of loop A1, imaginary
psiA2_r	$\underline{\psi}_R$	p.u.	STATE	Flux of loop A2, real
psiA2_i	$\underline{\psi}_R$	p.u.	STATE	Flux of loop A2, imaginary
psiB_r	$\underline{\psi}_R$	p.u.	STATE	Flux of loop B, real
psiB_i	$\underline{\psi}_R$	p.u.	STATE	Flux of loop B, imaginary

Table 6.2: DFIG with integrated PWM - dynamic model signals and state variables

Parameter	Symbol	Unit	I/O	Description
Pmd		p.u.	INPUT	d-axis-modulation index (referred to rotor angle)
Pmq		p.u.	INPUT	q-axis-modulation index (referred to rotor angle)
pt		p.u.	INPUT	Turbine power (rated to mechanical power)
xmdm	m_m	p.u.	INPUT	Mechanical load torque (rated to mechanical torque)
rradd		p.u.	INPUT	Additional rotor resistance
usr		p.u.	INPUT	Rotor voltage (voltage source converter)
usi		p.u.	INPUT	Rotor voltage (voltage source converter)
iqgrid		p.u.	INPUT	Reactive current of Grid-Side Converter
xspeed	$speed$	p.u.	OUTPUT	Mechanical speed (equal to speed)
pgt		p.u.	OUTPUT	Active power (rated to nominal active power)
xme	m_e	p.u.	OUTPUT	Electrical torque, based on rated mechanical torque
phi	phi	rad	OUTPUT	Rotating angle for transferring between dq and $\alpha\beta$ system (EMT only)
ird	ird	p.u.	OUTPUT	d-axis rotor current (referred to rotor angle)
irq	ird	p.u.	OUTPUT	q-axis rotor current (referred to rotor angle)
xphim	phi_m	p.u.	OUTPUT	Rotating angle with slip frequency
psis_r		p.u.	OUTPUT	Stator Flux, Real Part
psis_i		p.u.	OUTPUT	Stator Flux, Imaginary Part
psir_r		p.u.	OUTPUT	Rotor Flux, Real Part
psir_i		p.u.	OUTPUT	Rotor Flux, Imaginary Part
cosphim		p.u.	OUTPUT	cos(phim)
sinphim		p.u.	OUTPUT	sin(phim)
cosphi		p.u.	OUTPUT	cos(phi) (EMT only)
sinphi		p.u.	OUTPUT	sin(phi) (EMT only)
phim	phi_m	p.u.	STATE	Rotating angle with slip frequency
speed	$speed$	p.u.	STATE	Mechanical speed
psiA1_r	$\underline{\psi}_R$	p.u.	STATE	Flux of loop A1, real
psiA1_i	$\underline{\psi}_R$	p.u.	STATE	Flux of loop A1, imaginary
psiA2_r	$\underline{\psi}_R$	p.u.	STATE	Flux of loop A2, real
psiA2_i	$\underline{\psi}_R$	p.u.	STATE	Flux of loop A2, imaginary
psiB_r	$\underline{\psi}_R$	p.u.	STATE	Flux of loop B, real
psiB_i	$\underline{\psi}_R$	p.u.	STATE	Flux of loop B, imaginary

Table 6.3: Additional parameters (calculation parameters)

Parameter	Unit	Description
slip	%	Slip
xmem	p.u.	Electrical torque (inverted sign), based on rated mechanical torque
xmt	p.u.	Mechanical Torque, based on rated mechanical torque
xradd	p.u.	Additional rotor reactance
addmt	p.u.	Additional mechanical torque, based on rated mechanical torque

List of Figures

1.1 Equivalent Circuit of the DFIG Model 1

1.2 Equivalent Circuit of the DFIG model with integrated PWM 1

1.3 Rotor-Side PWM-Converter 1

5.1 Configuration of the DFIG without integrated PWM 8

5.2 Configuration of the DFIG with integrated PWM 8

List of Tables

6.1 DFIG - dynamic model signals and state variables 11
6.2 DFIG with integrated PWM - dynamic model signals and state variables 12
6.3 Additional parameters (calculation parameters) 12