POWERFACTORY

PowerFactory 2021

Technical Reference

DC Machine

ElmDcm, ElmDcmbi

POWER SYSTEM SOLUTIONS

MADE IN GERMANY

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1 General Description

Many classical industrial applications use DC machines due to their variable speed capability and simplicity in control. To represent the DC machine behaviour a dedicated model Although the DC machines are not as widely used as synchronous machines in power systems, their modelling is also very important for the power system analysis.

The *DC Machine* element (*ElmDcm*) can be used to represent a direct-current generator or a direct-current motor.This one-port element can be connected to dc terminals only. The *ElmDcm* has been implemented in *PowerFactory* according to the references [1] and [2].

The default parameters of the machine type *TypDcm* are used from [1].The *DC Machine* element is relevant for Load Flow and DC Short-Circuit calculation and RMS and EMT simulations.

The *ElmDcm* element supports five different models:

- Separately Excited model;
- Shunt-Connected model;
- Series-Connected model;
- Compound-Connected model with a shunt located ahead of the series field;
- Compound-Connected model with a shunt located behind of the series field.

The equations and parameters of the *DC Machine* element are documented in the following sections.

In addition, this document describes the models of the DC Machine with two terminals *ElmDcbi*.

2 DC Machine

2.1 Load Flow Analysis

The *DC machine* is a direct-current element and therefore it is only being considered for AC balanced and unbalanced Load Flow calculations. The equations for balanced and unbalanced Load Flow are the same.

2.1.1 AC Load Flow

The DC machine is represented as a constant active power model for the load flow analysis irrelevant of the machine type. The power of the machine p is calculated using the Active Power parameter *pini* and the Number of Parallel Machines *ngnum* as described in Equation (1):

$$P = pini \cdot ngnum \tag{1}$$

$$P = U_{DC} \cdot I_{DC} \tag{2}$$

The loading (in $\%$) is calculated according to Equation (3).

$$loading = \frac{|pini|}{\frac{pgn}{effic/100}} \cdot 100 \tag{3}$$

2.1.2 Calculation parameters

The calculation parameters used in the Load Flow model are presented in Table 2.1.

Table 2.1: Calculation parameters (AC Load Flow)

Name	Symbol	Unit	Description
p		W	Active power
pgn		kW	Rated mechanical power
$loading$		$\%$	Loading of the element

2.2 Short-Circuit Analysis

The short-circuit analysis on the DC elements in general has been the scope of interest for the many power engineering branches. Since the DC elements can be both sources and loads it might be useful to know how the DC or even the AC network behaves in such fault conditions. All DC machines can be both generators and motors, which means they might have different impact on the connected network and different contribution to the total fault current. This Section details the DC short-circuit analysis for the DC machine element.

2.2.1 DC Short-Circuit

For fault conditions, as in the case of a short-circuit, the DC machine shall contribute with the DC components of its current and voltage to the connected network and to the fault location. The DC short-circuit can be defined according to the IEC 61660 and the ANSI/IEEE 946 standards. Each standard is treated separately with respect to the DC Short-Circuit contribution of the DC machine element.

IEC 61660 According to IEC 61660 only DC motors with separate or independent excitation are considered for DC short-circuit analysis.

The quasi steady-state short-circuit current of the motor, I_{kM} is given as in equation (4) and is valid when the motor speed $n = n_n = const.$

$$I_{kM} = \frac{L_F}{L_{OF}} \cdot (\frac{U_{rM} - R_M \cdot I_{rM}}{R_{MBr}}) \tag{4}$$

Otherwise, when the speed is decreasing, which is the most probable case, $n \to 0$ then the quasi steady-state short-circuit current is $I_{kM} = 0$.

The peak short-circuit current i_{pM} is as in equation (5).

$$i_{pM} = X\kappa_M \cdot \frac{U_{rM} - R_M \cdot I_{rM}}{R_{MBr}} \tag{5}$$

The calculation parameters used in the presented equations are explained in the provided table 2.2.

Table 2.2: Calculation parameters (IEC 61660)

Name	Unit	Description
R_M	Ω	resistance of the armature circuit including the brushes
L_M	H	inductance of the armature circuit including the brushes
L_F	H	equivalent saturated inductance of the field circuit at short circuit
L_{OF}	H	equivalent unsaturated inductance of the field circuit at no load
R_{MBr}	Ω	total resistance of the motor branch up to the fault location
L_{MBr}	H	total inductance of the motor branch up to the fault location
U_{rM}	V	rated voltage of motor
I_{rM}	A	rated current of motor
n_n	s^{-1}	nominal speed of motor
n_0	s^{-1}	no-load speed of motor
κ_M		factor for the peak short-circuit current
J	$kg{\cdot}m^2$	moment of inertia of the whole rotating part
M_r	$N \cdot m$	rated torque of the motor

The DC motor time constants (in seconds) relevant to the short-circuit are calculated as follows:

a) time constant of the armature circuit up to the short-circuit location, τ_M (6):

$$\tau_M = \frac{L_{MBr}}{R_{MBr}} \tag{6}$$

b) mechanical time constant, τ_{mec} (7):

$$\tau_{mec} = \frac{2 \cdot \pi \cdot n_0 \cdot J \cdot R_{MBr} \cdot I_{rM}}{M_r \cdot U_{rM}} \tag{7}$$

c) field circuit time constant, τ_F (8):

$$\tau_F = \frac{L_F}{R_F} \tag{8}$$

d) time to peak, t_{pM} (9):

$$t_{pM} = k_{1M} \cdot \tau_M \tag{9}$$

e) rise-time constant, τ_{1M} (10), for decreasing or nominal speed with $\tau_{mec} \geq 10 \cdot \tau_F$:

$$\tau_{1M} = k_{2M} \cdot \tau_M \tag{10}$$

or for decreasing speed with $\tau_{mec} < 10 \cdot \tau_F$:

$$\tau_{1M} = k_{3M} \cdot \tau_M \tag{11}$$

f) decay-time constant, τ_F (12), for decreasing or nominal speed with $\tau_{mec} \geq 10 \cdot \tau_F$:

$$\tau_{2M} = k \cdot \tau_M \tag{12}$$

or for decreasing speed with $\tau_{mec} < 10 \cdot \tau_F$:

$$\tau_{2M} = k_{4M} \cdot \tau_M \tag{13}$$

The value of κ_M or k-factors can be found in the corresponding standard figures (refer to the Figures 17. - 21., IEC 61660:1997).

ANSI/IEEE 946 The ANSI/IEEE 946:1992 does not provide any calculation details on the DC short-circuit calculation for DC machines, but instead suggests some estimated values for the fault current. However, the standard provides a reference which is related to the General Electric's guidance "Industrial Power Systems Data Book", 1956, where the short-circuit characteristic of DC motors and generators is being specified. The equations below are extracted from this book and apply for the ANSI/IEEE 946 calculations of the DC machine element during DC Short Circuit Analysis.

A complete expression for the short-circuit current i_a if it occurs on the machine terminals is provided by equation (14). The current is time dependent.

$$i_a = \frac{e_0}{r'_d} \cdot (1 - \exp^{-\sigma_a \cdot t}) - (\frac{e_0}{r'_d} - \frac{e_0}{r_d}) \cdot (1 - \exp^{-\sigma_f \cdot t}) \tag{14}$$

The peak short-circuit current is given in equation (15).

$$i'_a = \frac{e_0}{r'_d} \tag{15}$$

And (15) can be rewritten and expressed in terms of amperes as in equation (16).

$$i'_a = I_a \cdot \frac{e_0}{r'_d} \tag{16}$$

The steady state-current I_k is calculated by means of the usual calculation approach for the machine current as in equation (17).

$$I_k = \frac{V_n - EMF}{R_a} \tag{17}$$

The initial rate of rise of the short-circuit current is given by equation (18).

$$RR = \frac{di_a}{dt} = V_1 \cdot \frac{e_0}{L'_a} \tag{18}$$

The calculation parameters used in the equations above are explained in the Table2.3.

Table 2.3: Calculation parameters (ANSI/IEEE 946)

Name	Unit	Description
i_a	$p.u.$	short-circuit current of the DC machine in the time domain
i'_a	$p.u.$	peak short-circuit current of the DC machine
I_a	A	rated DC machine current
I'_a	A	peak short-circuit current of the DC machine
e_0	$p.u.$	internal emf prior the fault conditions
V_1	V	rated DC machine voltage
V_n	V	rated DC network voltage
EMF	V	back electromotive force of the machine
r_d	$p.u.$	steady-state effective resistance of the machine
r'_d	$p.u.$	transient effective resistance of the machine
L'_a	H	machine armature circuit unsaturated inductance
R_a	Ohm	machine armature resistance
R_f	Ohm	machine field resistance
L_{ff}	H	machine saturated field self-inductance
RR	A/s	rate of rise of the short-circuit current
σ_a	s^{-1}	armature circuit decrement factor
σ_f	s^{-1}	field circuit decrement factor
T_M	s	machine time constant
N_1	rpm	machine nominal speed
P	rpm	machine pole number
C_x		inductance factor

The decrement factor σ_a is calculated according to equation (19).

$$\sigma_a = \frac{r'_d \cdot 2 \cdot \pi \cdot f}{C_x} \tag{19}$$

The decrement factor σ_f is calculated using the machine field resistance and inductance as in equation (20).

$$\sigma_f = \frac{R_f}{L_{ff}} \tag{20}$$

The machine time constant T_M is calculated using the machine field resistance and inductance as in equation (21).

$$T_M = \frac{L'_a}{R_a} \tag{21}$$

The value of L'_a is calculated by equation (22).

$$L'_a = \frac{19.1 \cdot C_x \cdot V_1}{P \cdot N_1 \cdot I_a} \tag{22}$$

Note: If the fault occurred on a distant terminal then the branch resistance and inductance up to the fault location must be added to the machine resistance and inductance, respectively.

2.3 RMS-Simulation

The equations for balanced and unbalanced RMS simulation are the same and are described in the following sections.

Depending on the connection type between stator and rotor, the *ElmDcm* element supports five different models:

- Separately Excited model;
- Shunt-Connected model;
- Series-Connected model;
- Compound-Connected model with a shunt located ahead of the series field;
- Compound-Connected model with a shunt located behind of the series field.

2.3.1 Common initialisation of all models (RMS-Simulation)

In this subsection the parameters are shown that have/use the same definition/initialisation for all RMS models.

The nominal angular velocity ω_n and the angular velocity ω are initialised as:

$$\omega_n = 2 \cdot \pi \cdot \frac{speednom}{60} \qquad \left[\frac{rad}{s}\right] \tag{23}$$

$$\omega = \omega_n \cdot speed \qquad \left[\frac{rad}{s}\right] \tag{24}$$

where:

- $speednom$ is nominal speed in rpm;
- $speed$ is speed in $p.u.$.

The rated mechanical torque of the element xmt_r is calculated using the rated mechanical power pgn and the nominal angular velocity w_n:

$$xmt_r = \frac{pgn}{\omega_n} \tag{25}$$

Some parameters of the *DC Machine* element are differently initialised depending if it is operated as a generator or as a motor.

If the *DC Machine* operates as a generator, the mechanical torque xmt, turbine power pt and external MDM $xmdm$ are initialised as follows:

$$xmt = xme + \frac{D \cdot \omega}{xmt_r} \qquad [p.u.] \tag{26}$$

$$pt = xmt \cdot speed \qquad [p.u.] \tag{27}$$

$$xmdm = 0 \qquad [p.u.] \tag{28}$$

where:

- xme is electrical torque in $p.u.$;
- D is friction coefficient in Nms;
- w is angular velocity in $\frac{rad}{s}$;
- xmt_r is rated mechanical torque in Nm.

If the *DC Machine* operates as a motor, the mechanical torque xmt, turbine power pt, proportional factor for internal MDM $mdmlp$ (if motor is connected and $speed > 0$) and external MDM $xmdm$ are initialised as follows:

$$xmt = -xme - \frac{D \cdot \omega}{xmt_r} \qquad [p.u.] \tag{29}$$

$$pt = 0 \qquad [p.u.] \tag{30}$$

$$mdmlp = \frac{xmt}{\omega^{mdmex}} \qquad [p.u.] \tag{31}$$

$$xmdm = \begin{cases} xmt & if\ external\ MDM\ is\ connected \\ 0 & if\ external\ MDM\ is\ not\ connected \end{cases} \tag{32}$$

where:

- xme is electrical torque in $p.u.$;
- D is friction coefficient in Nms;
- ω is angular velocity in $\frac{rad}{s}$;
- xmt_r is rated mechanical torque in Nm;
- $mdmex$ is exponent for internal MDM.

2.3.2 Model description

In this Section the equations describing the specific model types are presented.

Separately Excited DC Machine model (RMS-Simulation)
The equivalent circuit of the Separately Excited model is depicted in Figure 2.1. The field and armature windings of the Separately Excited DC Machine are excited from separate sources.

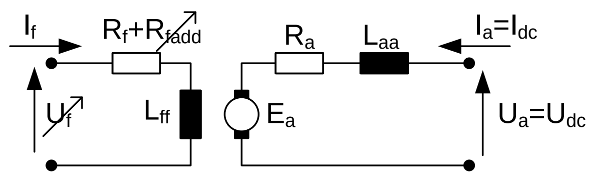

Figure 2.1: DIgSILENT Separately Excited DC Machine

The separately excited machine uses the parameters Initial Field Voltage $Ufinit$ and Initial Speed $speedinit$ that are defined on the RMS/EMT tab of the element window. Depending if the separately excited machine is connected or disconnected, there are two ways of initialising:

- If the machine is disconnected, $Ufinit$ is used for initialisation of the field current I_f and of the Field Winding Voltage U_f input signal:

$$U_f = U_{finit} \cdot 1000 \qquad [V] \tag{33}$$

$$I_f = \frac{U_f}{R_f} \qquad [A] \tag{34}$$

$$speed = 0 \qquad [p.u.] \tag{35}$$

- If the machine is connected, $speedinit$ is used for initialisation of the $speed$ and then the field current I_f is calculated from the induced voltage:

$$speed = speedinit \qquad [p.u.] \tag{36}$$

$$I_f = \frac{U_{dc} - I_{dc} \cdot R_a}{L_{af} \cdot \omega} \qquad [A] \tag{37}$$

$$U_f = R_f \cdot I_f \qquad [V] \tag{38}$$

The electrical torque xme and the induced voltage E_a are calculated as follows:

$$xme = -L_{af} \cdot I_f \cdot I_a / xmt_r \qquad [p.u.] \tag{39}$$

$$E_a = L_{af} \cdot I_f \omega \qquad [V] \tag{40}$$

The differential equations of the Separately Excited DC Machine model are:

$$U_{dc} = E_a + R_a \cdot I_a + L_{aa} \cdot \frac{dI_a}{dt} \qquad [V] \tag{41}$$

$$U_f = (R_f + R_{fadd}) \cdot I_f + L_f \frac{dI_f}{dt} \qquad [V] \tag{42}$$

The resistance of the field winding can be adjusted by modifying the R_{fadd} signal. This enables the adjustment of the field current and flux of the machine.

Model of a Shunt-Connected DC Machine (RMS-Simulation)

The connection of the field and armature windings in the case of the shunt-connected dc machine is shown in Figure 2.1.

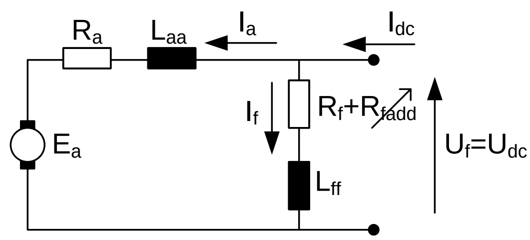

Figure 2.2: DIgSILENT Shunt-Connected DC Machine

The field current I_f and armature current I_a are initialised as follows:

$$I_f = \frac{U_{dc}}{R_f} \qquad [A] \tag{43}$$

$$I_a = I_{dc} - I_f \qquad [A] \tag{44}$$

The machine speed is initialised to:

$$speed = \frac{U_a - I_a \cdot R_a}{L_{af} \cdot I_f \cdot w_n} \qquad [p.u] \tag{45}$$

The electrical torque xme and the induced voltage E_a are calculated as follows:

$$xme = -L_{af} \cdot I_f \cdot I_a / xmt_r \qquad [p.u.] \tag{46}$$

$$E_a = L_{af} \cdot I_f \cdot \omega \qquad [V] \tag{47}$$

The differential equations of the Shunt-Connected DC Machine model are:

$$U_{dc} = E_a + R_a \cdot I_a + L_{aa} \cdot \frac{dI_a}{dt} \qquad [V] \tag{48}$$

$$U_{dc} = (R_f + R_{fadd}) \cdot I_f + L_{ff} \cdot \frac{dI_f}{dt} \qquad [V] \tag{49}$$

Model of a Series-Connected DC Machine (RMS-Simulation)

In the case of the series-connected dc machine the field winding is connected in series with the armature winding (Figure 2.3) which makes the field current to be equal with the armature current.

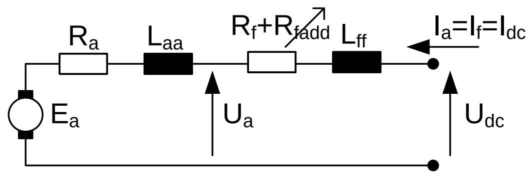

Figure 2.3: DIgSILENT Shunt-Connected DC Machine

The machine speed is initialised to:

$$speed = \frac{U_{dc} - I_{dc} \cdot (R_a + R_f)}{L_{af} \cdot I_f \cdot w_n} \qquad [p.u] \tag{50}$$

The electrical torque xme and the induced voltage E_a are calculated as follows:

$$xme = -L_{af} \cdot I_f \cdot I_a / xmt_r \qquad [p.u.] \tag{51}$$

$$E_a = L_{af} \cdot I_f \cdot \omega \qquad [V] \tag{52}$$

The differential equations of the Series-Connected DC Machine model are:

$$U_{dc} = E_a + I_{dc} \cdot (R_a + R_f + R_{fadd}) + (L_{aa} + L_{af}) \cdot \frac{dI_{dc}}{dt} \qquad [V] \tag{53}$$

$$I_f = I_{dc} \qquad [A] \tag{54}$$

Model of a Compound Connected DC Machine where Shunt is ahead of Series Field (RMS-Simulation)

The compound dc machine is equipped with both shunt and series field winding. The model used in *PowerFactory* is the so called cumulative connection and it is illustrated in Figure 2.4.

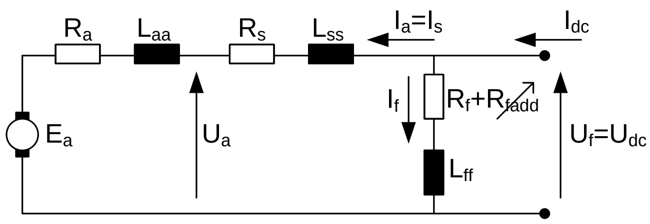

Figure 2.4: DIgSILENT Compound Connected DC Machine with Shunt ahead of Series Field

The field current I_f and armature current I_a are initialised as follows:

$$I_f = \frac{U_{dc}}{R_f} \qquad [A] \qquad (55)$$

$$I_a = I_{dc} - I_f \qquad [A] \qquad (56)$$

(57)

The machine speed is initialised to:

$$speed = \frac{U_{dc} - I_a \cdot (R_a + R_s)}{(L_{af} \cdot I_f + L_{as} \cdot I_s) \cdot w_n} \qquad [p.u] \qquad (58)$$

The electrical torque xme and the induced voltage E_a are calculated as follows:

$$xme = -\left(L_{af} \cdot I_a \cdot I_f + L_{as} \cdot I_a \cdot I_s\right) / xmt_r \qquad [p.u.] \qquad (59)$$

$$\mathrm{E_a} = (\mathrm{L_{af}} \cdot \mathrm{I_f} + \mathrm{L_{as}} \cdot \mathrm{I_s}) \cdot \omega \qquad [\mathrm{V}] \qquad (60)$$

The differential equations of the compound-connected dc machine model where the shunt is located ahead of the series field are:

$$U_{dc} = E_a + (R_a + R_s) \cdot I_a + (L_{aa} + L_{ss}) \cdot \frac{dI_a}{dt} + L_{fs} \cdot \frac{dI_f}{dt} \qquad [V] \qquad (61)$$

$$U_{dc} = (R_f + R_{fadd}) \cdot I_f + L_{ff} \cdot \frac{dI_f}{dt} + L_{fs} \cdot \frac{dI_a}{dt} \qquad [V] \qquad (62)$$

Model of a Compound Connected DC Machine where Shunt is behind of series field (RMS-Simulation)

The model of the compound-connected dc machine where the shunt is located behind of the series field is illustrated in Figure 2.5. For this model also the so called cumulative connection is being used.

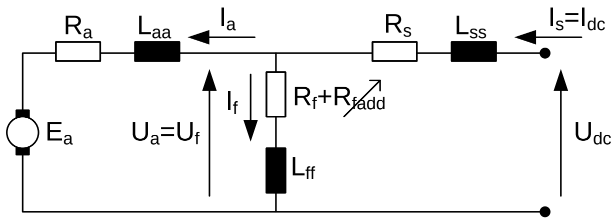

Figure 2.5: DIgSILENT Compound Connected DC Machine with Shunt behind of Series Field

The field current I_f and armature current I_a are initialised as follows:

$$I_f = \frac{U_{dc} - R_s \cdot I_{dc}}{R_f} \qquad [A] \qquad (63)$$

$$I_a = I_{dc} - I_f \qquad [A] \qquad (64)$$

The machine speed is initialised to:

$$speed = \frac{U_{dc} - I_a \cdot R_a - I_{dc} \cdot R_s}{(L_{af} \cdot I_f + L_{as} \cdot I_s) \cdot \omega_n} \qquad [p.u] \qquad (65)$$

The electrical torque xme and the induced voltage E_a are calculated as follows:

$$xme = -\left(L_{af} \cdot I_a \cdot I_f + L_{as} \cdot I_a \cdot I_s\right)/xmt_r \qquad [p.u.] \qquad (66)$$

$$E_a = (L_{af} \cdot I_f + L_{as} \cdot I_s) \cdot \omega \qquad [V] \qquad (67)$$

The differential equations of the compound-connected dc machine model where the shunt is located behind of the series field are:

$$U_{dc} = E_a + R_a \cdot I_a + L_{aa} \cdot \frac{dI_a}{dt} + R_s \cdot I_{dc} + L_{ss} \cdot \frac{dI_{dc}}{dt} + L_{fs} \cdot \frac{dI_f}{dt} \qquad [V] \qquad (68)$$

$$U_{dc} = (R_f + R_{fadd}) \cdot I_f + L_{ff} \cdot \frac{dI_f}{dt} + L_{fs} \cdot \frac{dI_s}{dt} + R_s \cdot I_{dc} + L_{ss} \cdot \frac{dI_{dc}}{dt} + L_{fs} \cdot \frac{dI_f}{dt} \qquad [V] \qquad (69)$$

2.3.3 Common calculation for all machine types (RMS-Simulation)

The mechanical torque and the speed derivative are calculated differently dependent if the dc machine is used as a generator or as a motor. These calculations are same for all dc machine types and therefore are presented in the following subsection.

The electrical torque has been set negative in the equations in order that we have consistency with the asynchronous machine. Therefore we have negative electrical torque for motors (Ia is positive for motors) and positive for generators (Ia is negative for generators). An additional calculation parameter has been added $xmem = -xme$ in order to be able to plot a positive electrical torque when working with motors.

DC Machine as a Generator (RMS-Simulation)

If the speed of the generator is higher than a certain threshold ($speed > 0.001$), the mechanical torque xmt is calculated using the turbine power pt and speed $speed$ as follows:

$$xmt = \frac{pt}{speed} \qquad [p.u.] \qquad (70)$$

If the speed of the generator is $speed \leq 0.001$ the speed derivative is set to 0, else it is calculated according to the following equation:

$$\frac{dspeed}{dt} = \frac{-\mathrm{xme} + \mathrm{xmt} - \mathrm{D} \cdot \mathrm{w}/xmt_r}{\omega_\mathrm{n} \cdot \mathrm{J}/xmt_r} \qquad [p.u.] \qquad (71)$$

DC Machine as a Motor (RMS-Simulation)

The mechanical torque xmt for the motor is calculated depending if the external signal MDM torque $xmdm$ is connected or not. If the external MDM is not connected, the internal MDM is being used:

$$xmt = \begin{cases} xmdm & if\ external\ MDM\ is\ connected \\ mdmlp \cdot speed^{mdmex} & if\ external\ MDM\ is\ not\ connected \end{cases} \tag{72}$$

If the speed of the motor is $speed \leq 0.001$ the speed derivative is set to 0, else it is calculated according to the following equation:

$$\frac{dspeed}{dt} = \frac{-\mathrm{xme} - \mathrm{xmt} - \mathrm{D} \cdot \mathrm{w}/xmt_r}{\omega_\mathrm{n} \cdot \mathrm{J}/xmt_r} \qquad [p.u.] \tag{73}$$

2.3.4 Signals

The signals used in the RMS model are presented in Table 2.4.

Table 2.4: Signals (RMS-Simulation)

Name	Symbol	Unit	Type	Description
$speed$		$p.u.$	STATE	Machine speed
If	I_f	A	STATE	Field current
pt		$p.u.$	IN	Turbine power
$xmdm$		$p.u.$	IN	MDM torque
Uf	U_f	kV	IN	Field winding voltage
$Rfadd$	R_{fadd}	Ohm	IN	Additional resistance for adjusting the field winding resistance
$xspeed$		$p.u.$	OUT	Machine speed
Xme		Nm	OUT	Electrical torque
Xmt		Nm	OUT	Mechanical torque

2.3.5 Calculation parameters

The calculation parameters used in the RMS model are presented in Table 2.5.

Table 2.5: Calculation parameters (RMS-Simulation)

Name	Symbol	Unit	Description
Ia	I_a	A	Armature current
Is	I_s	A	Series field current (only compound-connected machines)
Ea	E_a	V	Induced voltage
$speednoms$		rad/s	Nominal speed
$Ufinit$	U_{finit}	V	Initial field voltage (used for initialisation of U_f)
$speedinit$		$p.u.$	Initial speed (used for initialisation of $speed$)
xmt		$p.u.$	Mechanical torque
xme		$p.u.$	Electrical torque
$xmem$		$p.u.$	Electrical torque (Motor)
$mdmlp$		$p.u.$	Internal MDM proportional factor
$mdmex$			Internal MDM exponent
pgn		kW	Rated mechanical power
J		Kgm^2	Inertia
D		Nms	Friction coefficient
Ra	R_a	Ohm	Armature winding resistance
Rf	R_f	Ohm	Field winding resistance
Rs	R_s	Ohm	Series field winding resistance (only compound-connected machines)
Laa	L_{aa}	H	Armature winding self-inductance
Lff	L_{ff}	H	Field winding self-inductance
Lss	L_{ss}	H	Series field winding self-inductance (only compound-connected machines)
Laf	L_{af}	H	Mutual field-armature inductance
Las	L_{as}	H	Mutual series field-armature inductance
Lfs	L_{fs}	H	Mutual series-shunt field windings inductance

2.4 EMT-Simulation

The model equations for the EMT-Simulation are same with the equations used for the RMS-Simulation. Please refer to Section 2.3 of this document.

3 DC Machine with Two Terminals

The *DC machine with two terminals* is a direct-current element and therefore it is only being considered for AC balanced and unbalanced Load Flow calculations. The equations for balanced and unbalanced Load Flow are the same.

3.0.1 AC Load Flow

The models described in Section 2.1.1 are also valid for the two terminals model. The only difference is the calculation of the dc voltage, which is considered as follows:

$$U_{DC} = U_{T(+)} - U_{T(-)} \tag{74}$$

3.1 Short Circuit Analysis

The battery with two terminals is ignored for the short circuit calculation.

3.2 RMS-Simulation

The models described in Section 2.3 are also valid for the two terminals model.

3.3 EMT-Simulation

The models described in Section 2.4 are also valid for the two terminals model.

A References

[1] P. Krause. *Analysis of Electric Machinery*. McGraw-Hill, 1987.

[2] F. Milano. *Power System Modelling and Scripting*. Springer, 2010.

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