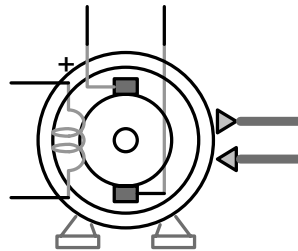


DC machine device



DCM1

DC machine device	1
1 Description	1
1.1 The DC-machine symbol	1
1.2 Variables used to define the DC-machine model	2
1.3 Theoretical summary	2
1.3.1 Main model equations	2
1.3.2 Mechanical equations	3
2 Parameters	5
2.1 Main Data	5
2.2 Mechanical data	5
2.3 Control	6
2.4 Observe/Scope	6
2.5 Precision	6
2.6 How to control the external mechanical torques	6
2.7 Base quantities	7
3 Rules	7
4 Netlist format	7
5 Load-Flow model	9
6 Steady-state model	9
7 Initial conditions	9
8 Frequency Scan model	9
9 Time-domain representation	9

1 Description

1.1 The DC-machine symbol

The DC-machine device is a 1-phase device. The following figure presents available device pins.

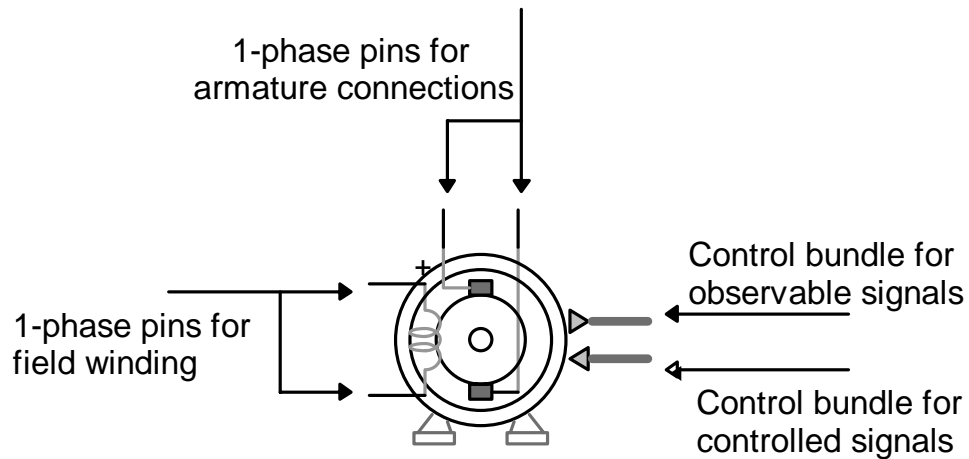


Figure 1 DC machine

1.2 Variables used to define the DC-machine model

The variables used in this model are defined in the following table.

Symbol	Description
v_a	Armature winding voltage
v_f	Field winding voltage
i_a	Armature winding current
i_f	Field winding current
R_a	Armature winding resistance
R_f	Field winding resistance
L_{ff}	Self-inductance of the field winding
L_{aa}	Self-inductance of the armature winding
L_{af}	Mutual inductance between the field and the rotating armature coils
ω_{rm}	Mechanical speed
ω_{bm}	Base mechanical speed
P_b	Rated power of the machine (W)
T_e	Electromagnetic torque (Nm)

1.3 Theoretical summary

1.3.1 Main model equations

Two voltage equations define the machine model.

The field voltage equation in time-domain is:

$$\frac{di_f}{dt}(t) = -\frac{R_f}{L_{ff}}i_f(t) + \frac{1}{L_{ff}}v_f(t) \quad (1)$$

The armature voltage equation is :

$$\frac{di_a}{dt}(t) = -\frac{R_a}{L_{aa}}i_a(t) - \frac{L_{af}}{L_{aa}}i_f(t)\omega_{rm}(t) + \frac{1}{L_{aa}}v_a(t) \quad (2)$$

where L_{ff} and L_{aa} are the self-inductances of the field and armature windings respectively. The rotor speed is denoted as ω_{rm} , and L_{af} is the mutual inductance between the field and the rotating armature coils. The above equations correspond to the equivalent circuit shown in Figure 2.

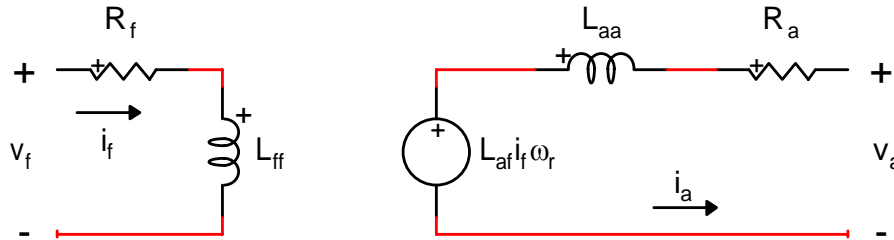


Figure 2 Equivalent circuit of a DC-machine

The electromagnetic torque developed by a DC machine is given by :

$$T_e = L_{af}i_f i_a \quad (3)$$

The equivalent circuit for the steady state solution is the same as the circuit shown in Figure 2, only now phasor (frequency domain) quantities are used.

1.3.2 Mechanical equations

The simplest model for the mechanical part is the single mass representation as used in stability studies:

$$J \frac{d\omega_{rm}}{dt} + D\omega_{rm} = T_e - T_{turbine} \quad (4)$$

where:

- J is the moment of inertia of rotating turbine-generator mass
- ω_{rm} is the mechanical speed
- D is the damping coefficient for viscous and wind friction
- $T_{turbine}$ is the torque input to turbine
- T_e is the electromagnetic torque of the generator

Modeling the mechanical part of a DC-machine with a single mass representation is not sufficiently accurate in some situations. Unlimited number of masses can be specified to define the rotor shaft. Each major element is considered to be a rigid mass connected to adjacent elements by mass less springs. An external torque can be applied on each individual mass. Figure 3 shows a typical 6-mass model.

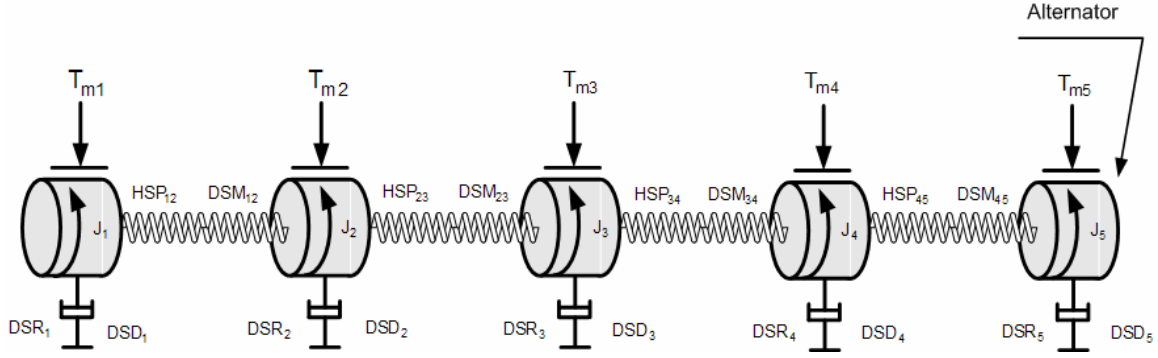


Figure 3 Diagram of the turbine/alternator assembly of the mechanical part

The n-spring-connected rotating masses are then described by the rotational form of Newton's second law:

$$\mathbf{J} \frac{d\boldsymbol{\omega}_{rm}}{dt} + \mathbf{D} \boldsymbol{\omega}_{rm} + \mathbf{HSP} \boldsymbol{\theta}_{rm} = \mathbf{T}_e - \mathbf{T}_{turbine} \quad (5)$$

where:

\mathbf{J} is the diagonal matrix of moments of inertia (J_1 to J_5 in Figure 3)

$\boldsymbol{\omega}_{rm}$ is the vector of mechanical speeds

$\boldsymbol{\theta}_{rm}$ is the vector of angular positions

\mathbf{HSP} is the tridiagonal matrix of stiffness coefficients

\mathbf{D} is the tridiagonal matrix of damping coefficients

$\mathbf{T}_{turbine}$ is the vector of torques applied to the turbine stages (see T_{m1} to T_{m4} in Figure 3)

\mathbf{T}_e is the vector of electromagnetic torques of generator (see T_{m5} in Figure 3)

The moment of inertia and the stiffness coefficients are normally available from design data. The spring action of the shaft section between masses $i-1$ and i creates a torque which is proportional to the angle twist $\theta_{rm\ i-1} - \theta_{rm\ i}$. The proportionality factor is the stiffness coefficient or spring constant $HSP_{i\ i+1}$. This spring action torque acts in opposite directions on masses $i-1$ and i :

$$T_{spring\ i-1} = -T_{spring\ i} = HSP_{i-1\ i} (\theta_{rm\ i-1} - \theta_{rm\ i}) \quad (6)$$

From equation (6) it can be seen that the \mathbf{HSP} matrix has the following form (3 masses case):

$$\mathbf{HSP} = \begin{bmatrix} HSP_{12} & -HSP_{12} & 0 \\ -HSP_{12} & HSP_{12} + HSP_{23} & -HSP_{23} \\ 0 & -HSP_{23} & HSP_{23} \end{bmatrix} \quad (7)$$

Three damping effects are included with the damping coefficients, namely the absolute speed self damping DSD_i of mass i , the mutual damping coefficient $DSM_{i\ i+1}$ and the mutual damping coefficient $DSM_{i-1\ i}$. The damping torque acting on mass i is therefore:

$$T_{damping\ i} = DSD_i \omega_{rm\ i} + DSM_{i-1\ i} (\omega_{rm\ i} - \omega_{rm\ i-1}) + DSM_{i\ i+1} (\omega_{rm\ i} - \omega_{rm\ i+1}) \quad (8)$$

From equation (8) it can be seen that \mathbf{D} has the same structure as \mathbf{HSP} except that the diagonal element is now $DSD_i + DSM_{i-1\ i} + DSM_{i\ i+1}$, as shown in this 3 masses example:

$$\mathbf{D} = \begin{bmatrix} DSD_1 + DSM_{12} & -DSM_{12} & 0 \\ -DSM_{12} & DSD_2 + DSM_{12} + DSM_{23} & -DSM_{23} \\ 0 & -DSM_{23} & DSD_3 + DSM_{23} \end{bmatrix} \quad (9)$$

Another damping coefficient, named speed deviation self damping for a given mass (DSR), is also available. By definition:

$$T_i = DSR_i (\omega_{rm\ i} - \omega_{bm}) \quad (10)$$

where ω_{bm} is the base mechanical (synchronous) speed.

It is difficult to obtain realistic values for these damping coefficients. Fortunately, they have very little influence on the peak torque value during transient disturbances.

2 Parameters

2.1 Main Data

- **Rated voltage:** Rated stator terminal voltage of the machine. Used in the definition of base values upon which pu machine parameters are to applied.
- **Rated power:** Power rating of the machine. Used in the definition of base values upon which pu machine parameters are to applied.
- **Rated speed:** Rated mechanical speed (ω_{rm}) of the machine. Used in the definition of base values upon which pu machine parameters are to applied.
- **Electrical parameters:** Electrical parameters that define the machine model. When pu units are specified the rated values above are used for conversion.
- **Initialization method:** The machine can start from no initial conditions (option none) or from a steady-state computations (option steady-state). If the steady-state option is chosen, the steady-state field and armature currents are required. The steady-state speed is also required. EMTP automatically calculates the steady-state torque. This constant torque will be taken as the external torque as long the "Controlled torque start time" is not exceeded when a mechanical torque control signal is available.

2.2 Mechanical data

- **Lock rotor shaft for negative speed:** This option allows locking the rotor shaft if the external torque tends to make the rotor speed negative.
- **Number of masses:** allows specifying the number of masses to model the mechanical shaft. The rotor mass is included in this number.
- **Index of rotor mass:** allows specifying the mass number of the generator or motor rotor within the interconnected mass-spring shaft system. This number must be positive and smaller or equal to the number of masses.
- **Mechanical parameters for the shaft system:** parameters that describe the masses and connections between masses. See the above section "Mechanical equations" for more details on the damping coefficients. It is allowed to specify the fraction (%) of the total external mechanical torque which is associated with the given mass. If the total is greater than 100% a scaling factor will be applied.
- **Use inertia constant H (s) instead of Moment of inertia:** If this option is unchecked the moment of inertia of the selected mass is specified in kgm^2 . Otherwise the moment of inertia of the mass is specified through the inertia constant in s. This constant is defined as the ratio of the kinetic energy of the rotating mass at base speed to the rated power :
$$H = \frac{J\omega_{bm}^2}{2P_b} \quad (11)$$
- **Observe, scope and control selections:** allows selecting the mechanical variables that need to be observed by a control system, or need to be available under the machine scopes, or need to be controlled by an external control system.
 - The mechanical angle of each mass (in rad) can be selected for scope and observe.

- The mechanical speed (in rad/s) of each mass can be selected for scope and observe.
- The torque (in Nm) between the different sections of the shaft can be selected for scope and observe.
- The shaft torque $T_{m_i_j}$ is the torque on the shaft section connecting masses i and $j=i+1$.
- The steady-state mechanical torque applied on mass i can only be observed. The external torque applied on mass i can be controlled.
- **Use pu for Scope variables units:** allows obtaining all the scope signals in pu.
- **Use pu for Observe and Control variables units:** allows obtaining and generating all observe and control signals in pu.

2.3 Control

- **Total mechanical torque:** If this option is chosen the total torque applied on the mechanical shaft is controlled. If this option is selected the independent mechanical torque applied on each mass of the shaft system (specified in the mechanical data form) is no more available.
- **Use pu for Control variables units:** allows using controls signals in pu.

2.4 Observe/Scope

- If the Observe option is selected, the corresponding signal becomes automatically available in the observe signal bundle of the machine.
- If the Scope option is selected, the selected variable will become available under machine scopes.
- **Use pu for Scope variables units:** allows obtaining all the scope signals in pu.
- **Use pu for Observe variables units:** allows obtaining all the observe signals in pu.

2.5 Precision

- **Damping factor:** Ratio between built-in damping resistors and discretized inductive elements used in the machine model. Reduce this number when numerical stability problems are encountered.
- **Rotor speed tolerance:** Relative tolerance associated with the iterative solution of rotor speed at each solution time-point.
- **Voltage convergence tolerance:** Relative tolerance associated with the iterative solution of voltage at the machine terminals at each solution time-point. In most cases, when the connected network is not weak, a larger value of tolerance can be used.
- **Maximum iterations in the rotor speed computation:** Maximum number of iterations allowed in the calculation of rotor speed at each solution time-point

2.6 How to control the external mechanical torques

The external mechanical torque applied on each mass composing the mechanical shaft can be controlled in 2 ways: independent control on each mass or total control. If one option is chosen, the other is not available.

□ Independent control of the external mechanical torques

In this case the external mechanical torque applied on each mass can be controlled. The corresponding control signals are available in the control bundle of the dc-machine device if the torque control option Tm_i has been specified in the mechanical data form. These torques are negative for a generator and positive for a motor. If this option has been chosen and if no controlled torque signal has been selected for a mass i then no external torque is applied on this mass i.

□ Total control

The total mechanical torque applied on the mechanical shaft can be specified. The fraction of the total external mechanical torque which is associated with each mass in the mechanical data form is used to calculate the individual external torque applied on each mass.

If a steady-state initialization has been chosen the electromagnetic torque in steady-state is taken as the total external mechanical torque. In this case an external torque is applied on each mass in accordance with the fraction of total external mechanical torque associated with each mass. This constant torque will be taken as the total external torque as long the "Controlled Torque Start Time" is not exceeded.

2.7 Base quantities

Parameters of the DC-machine model can be specified in fundamental units or in per units (pu). The base quantities are as follows:

- Base voltage $V_b = V_{rated}$
- Base power $P_b = P_{rated}$
- Base current $I_b = \frac{P_b}{V_b}$
- Base impedance $Z_b = \frac{V_b^2}{P_b} = \frac{V_b}{I_b}$
- Base torque $T_b = \frac{P_b}{\omega_{b,m}}$
- Base flux $\Psi_b = \frac{V_b}{\omega_{b,m}}$

3 Rules

Since the symbol of this device is automatically redrawn to account for user specified configurations, it is not allowed to change it with the symbol editor, to delete pins and change pin or signal attributes.

4 Netlist format

This device allows method-based scripting. The object data and methods are described in the script file referenced by the device Script.Open.Dev attribute.

Example of data:

```
DCM;DCM2;5;5;s1,s2,s3,s4,s10Tm,  
240,3900,127.7,0.6,0.012,240,120,1.8,1,157.318,6.70393,0.8333,5,?m,9,  
MS=0 1 1,  
1 1 0 0 0 0  
0 0 0 0 0  
MSu=0 0 0,  
PR=100 1e-06 1e-06 300 0,  
CTRLu=0,
```

```
CTRL=1,
OBSu=1 0,
OBS=1 1 1 1 1 1 1 1 1,
```

Field	Description
DCM	Part name
DCM2	Instance name for the machine, any name.
5	Total number of pins
5	Number of pins given in this data section
s1	Signal name connected to k-pin of the armature, any name
s2	Signal name connected to m-pin of the armature, any name
s3	Signal name connected to k-pin of the field coil, any name
s4	Signal name connected to m-pin of the field coil, any name
s10Tm,	Signal names contained in the control bundle for Observe variables.
240	Rated voltage.
3900	Rated power.
127.7	Rated speed.
0.6	Armature resistance.
0.012	Armature inductance.
240	Field coil resistance.
120	Field inductance.
1.8	Armature Field mutual inductance.
1	Steady state initialization ?
157.318	Steady state speed
6.70393	Steady state armature current
0.8333	Steady state field current
5	Controlled torque start time
?m	Request for scopes, sent to scope group Machine, optional
9	Number of scope outputs
Ms=	Start mechanical parameters section
0 1 1	Lock rotor shaft for negative speed (1 for locking, 0 for don't lock) Number of masses Index of rotor mass
1 1 0 0 0 0 0 0 0 0 0 0	Mechanical data tables (2 masses in this example)
MSu=	Start mechanical parameters units specification section
0	Use H instead of moment of inertia
0	Use "pu" for mechanical scope variable units
0	Use "pu" for mechanical observe and control variable units
CTRLu=	Use "pu" for mechanical control variable units
CTRL=	Start total controlled torque section
1	Control total external torque when 1
PR=	Start precision control data section
100	Damping factor
1e-6	Rotor speed tolerance
1e-3	Voltage convergence tolerance
30	Maximum number of iteration in rotor speed computation
OBSu=	Start Scope and Observe in "pu" section
0	Use "pu" for scope variable units
1	Use "pu" for observe variable units
OBS=	Start Scope and Observe requests
2 1 2 0 2 0 1 0.....	Scope and Observe requests: 0 for none, 1 for scope request, 2 for observe request, 3 for scope and observe request.

5 Load-Flow model

This machine is disconnected in the Load-Flow solution.

6 Steady-state model

The steady-state equivalent circuit is shown in Figure 2.

The approach followed for the steady-state initialization of DC-machines is to require the user to specify the desired rotor speed, field and armature currents instead of the terminal voltage.

The steady-state solution is performed for a non-zero dc frequency (see "Frequency for dc representation" in the "EMTP Simulation Options"). This device is disconnected for all other frequencies in the steady-state superposition process.

When the steady-state initialization is used, a small transient can appear at the beginning of the simulation. This is related to the discretization method in time-domain equations.

The user can decrease the simulation time-step to reduce the small transient at the beginning of the simulation.

7 Initial conditions

Initial conditions are found from the steady-state solution and the given speed when the device is initialized in steady-state. State variables are automatically initialized for achieving quick steady-state in time-domain. The dc-machine can also start with no initial conditions.

8 Frequency Scan model

The DC-machine is disconnected from the rest of the network for a frequency scan solution.

9 Time-domain representation

The time-domain representation of the DC-machine has been already explained in the previous sections.

In the time-domain solution this device is a nonlinear function. It is solved through the iterative procedure of EMTP until convergence according to the relative tolerance option for the given device.

Two parameters controlling the iterative speed loop and the iterative voltage loop can be modified by the user. Figure 4 shows the iterative process for the dc-machine model.

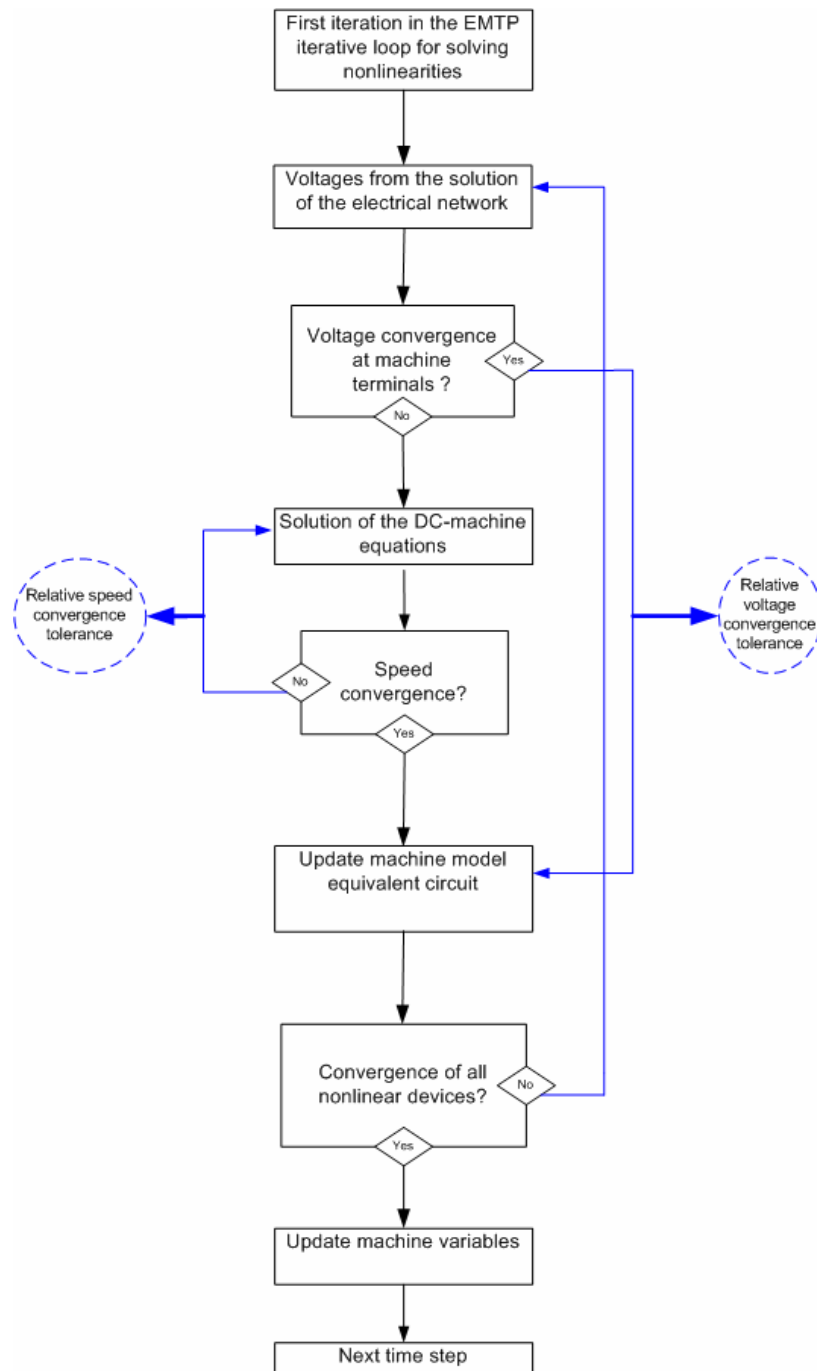


Figure 4 The iterative solution process: speed and voltage loops