POWERFACTORY

PowerFactory 2021

Technical Reference

Complex Load

ElmLod,TypLodind

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

Copyright © 2020 DIgSILENT GmbH
All rights reserved. No part of this
publication may be reproduced or
distributed in any form without written
permission of DIgSILENT GmbH.

December 1, 2020
PowerFactory 2021
Revision 1

Contents

1 General Description

In power systems, electrical load consists of various different types of electrical devices, from incandescent lamps and heaters to large arc furnaces and motors. It is often very difficult to identify the exact composition of static and dynamic loads in the network.

In most cases the general load model (see Technical Reference Manual for the General Load) is sufficient to model the static and dynamic load characteristic for load-flow and dynamic simulations. Although for modelling industrial loads with a large portion of induction motors the general load model might not be adequate. Therefore a second load model is available, which is representing a composition of a static load and an induction motor.

The complex load model diagram is shown in Figure 1.1.

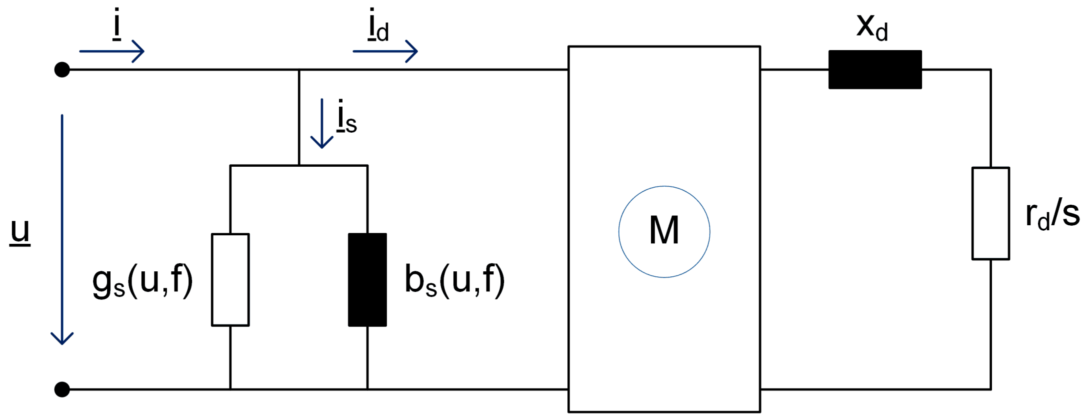

Figure 1.1: *PowerFactory* Complex Load Model

2 Load-Flow Model

The current flowing in the load (Equation 1) is the sum of the currents flowing in the static and in the dynamic part of the load (Figure 1.1). The percentage of the dynamic relative to the static load can be defined using the parameter t_{m0}.

$$\underline{i} = \underline{i}_s + \underline{i}_d \tag{1}$$

The complex load model is used only if the *Load Flow* option *Consider Voltage Dependency of Loads* is used. Without this option, the load model used is a constant PQ model (without a voltage dependent static part and the dynamic part is completely not taken into account $i_d = 0$).

2.1 Static part of the load

The static part of the load is defined using an 'extended' polynomial representation of the voltage dependency and is described by Equation 2.

$$\begin{aligned} p = p_0 \cdot k_p = p_0 \cdot \left(aP \cdot \left(\frac{u}{u_0}\right)^{e\_aP} + bP \cdot \left(\frac{u}{u_0}\right)^{e\_bP} + (1 - aP - bP) \cdot \left(\frac{u}{u_0}\right)^{e\_cP} \right) \\ q = q_0 \cdot k_q = q_0 \cdot \left(aQ \cdot \left(\frac{u}{u_0}\right)^{e\_aQ} + bQ \cdot \left(\frac{u}{u_0}\right)^{e\_bQ} + (1 - aQ - bQ) \cdot \left(\frac{u}{u_0}\right)^{e\_cQ} \right) \end{aligned} \tag{2}$$

where aP, bP, cP, aQ, bQ, cQ are the proportional coefficients of the static part of the load, e_aP, e_bP, e_cP, e_aQ, e_bQ, e_cQ are the exponential coefficients of the static part of the load and u is the magnitude of the busbar voltage. u_0 is the voltage input parameter (*ElmLod*) and u is the absolute voltage where the load is connected.

The active and reactive power p_0 and q_0 are defined as:

$$\begin{aligned} p_0 = p_{lini} \cdot scale_0 \cdot scale_{zone} \cdot scale_{lf} \\ q_0 = q_{lini} \cdot scale_0 \cdot scale_{zone} \cdot scale_{lf} \end{aligned} \tag{3}$$

where p_{lini}, q_{lini} and $scale_0$ are the active power, reactive power and the scaling factor of the load defined in *ElmLod*. Furthermore, $scale_{zone}$ is the zone load scaling factor and $scale_{lf}$ is the load scaling factor defined in the *Load Flow* settings. Note that p_{lini} and q_{lini} have the same absolute and per-unit values since the base is $1MVA$.

By selecting certain values for the proportional and exponential coefficients, different exponential and polynomial models can be defined.

Changing the load type to constant power, current or impedance can be accomplished by modifying the exponential coefficients of the load according to Table 2.1.

Table 2.1: Selection of exponent value for different load model behaviour

Load model type	**Exponential coefficient** (e_aP, e_bP, e_cP)
Constant power	0
Constant current	1
Constant impedance	2

The current of the static part of the load can be described using the following equation:

$$\underline{i}_s = \underline{u} \cdot (g_s \cdot k_p + \jmath \cdot b_s \cdot k_q) \cdot \frac{u_0^2}{u^2} \tag{4}$$

where k_p and k_q are the coefficients defined in Equation 2 and the admittance (conductance and susceptance) of the static part of the load is defined as:

$$g_s = \frac{p_0}{u_0^2} \cdot \left(1 - \frac{t_{m0}}{100}\right) \tag{5}$$

$$b_s = -\frac{q_0 - p_0 \cdot \dfrac{t_{m0}}{100} \cdot \dfrac{s_0}{s_{cr}}}{u_0^2} \tag{6}$$

where u_0 is the voltage input parameter (*ElmLod*), s_0 is the normal operating slip in %, s_{cr} is the critical slip in % and t_{m0} is the percentage of dynamic compared to static load.

Please note that the second term of equation 6 uses the dynamic part input data. This is done so that the reactive power consumption of the dynamic part is compensated in order to get the desired reactive power operating point from the complex load.

2.2 Dynamic part of the load

The dynamic part of the load is actually a simplified asynchronous machine model and the current is calculated using the impedance and the normal operating slip of the asynchronous machine:

$$\underline{i}_d = \frac{\underline{u}}{\underline{z}_d} = \frac{\underline{u}}{\dfrac{r_d}{s_0/100} + \jmath \cdot x_d} \tag{7}$$

where:

$$\begin{aligned} x_d &= \frac{u_0^2}{p} \cdot \frac{100}{t_{m0}} \cdot \frac{s_0 \cdot s_{cr}}{s_0^2 + s_{cr}^2} \\ r_d &= x_d \cdot \frac{s_{cr}}{100} \end{aligned} \tag{8}$$

2.3 Model for unbalanced calculation

The positive sequence equation of the *Load Flow* model of the *Complex Load* is given by Equation 1.

In addition to the positive sequence equation, the unbalanced *Load Flow* calculation requires a model in the zero and in the negative sequence. The zero sequence impedance is set to infinite so that there is no flow of zero sequence current and the negative sequence model uses the negative sequence impedance:

$$\underline{i}_0 = 0 \tag{9}$$

$$\underline{i}_2 = \frac{\underline{u}_2}{\underline{z}_2} \tag{10}$$

where the negative sequence impedance is defined using the admittances of the static and dynamic part of the load:

$$\underline{z}_2 = \frac{1}{g_s + \jmath \cdot b_s + \underline{y}_d} \tag{11}$$

3 Short-Circuit Analysis

Short circuit calculations according to IEC 60909, VDE102/103 or ANSI C37 generally neglect loads.

The *complete* short circuit method utilises constant impedance.

4 Harmonic Analysis

In the type data of the complex load model, the harmonic load model can only be specified as constant impedance or with frequency dependent impedance characteristics for the dynamic and the static part individually.

5 RMS Simulation

The voltage dependency of the static part of the load is the same as described for the *Load Flow* Model.

5.1 Calculation of variables

The current flowing in the complex load is the sum of the currents flowing in the static and dynamic parts:

$$\underline{i} = \underline{i}_s + \underline{i}_d \tag{12}$$

5.1.1 Static part of the load

The current of the static part of the load can be described using the following equation:

$$\underline{i}_s = \underline{u} \cdot (g_s \cdot k_p \cdot dP_f + \jmath \cdot b_s \cdot k_q \cdot dQ_f) \cdot \frac{u_0^2}{u^2} \cdot k_{approx} \tag{13}$$

where the frequency dependency parameters are defined using the frequency factor P (kpf) and Q (kqf) as:

$$\begin{aligned} dP_f &= 1 + kpf \cdot (f_e - 1) \\ dQ_f &= 1 + kqf \cdot (f_e - 1) \end{aligned} \tag{14}$$

A voltage range is defined for the static part of the load by the variables u_{min} and u_{max}. Outside this voltage range, the power is adjusted according to the graph shown in Figure 5.1 and the load equations of the static load representing the full voltage range can be expressed using the following equations:

$$\begin{aligned} P &= k_{approx} \cdot P_{out} \\ Q &= k_{approx} \cdot Q_{out} \end{aligned} \tag{15}$$

where:

$$k_{approx} = \begin{cases} 1 & u_{\min} < u < u_{\max} \\ \dfrac{2 \cdot |u|^2}{u_{\min}^2} & 0 < u < \dfrac{u_{\min}}{2} \\ k = 1 - 2 \cdot \left(\dfrac{|u| - u_{\min}}{u_{\min}} \right)^2 & \dfrac{u_{\min}}{2} < u < u_{\min} \\ k = 1 + (|u| - u_{\max})^2 & u > u_{\max} \end{cases} \tag{16}$$

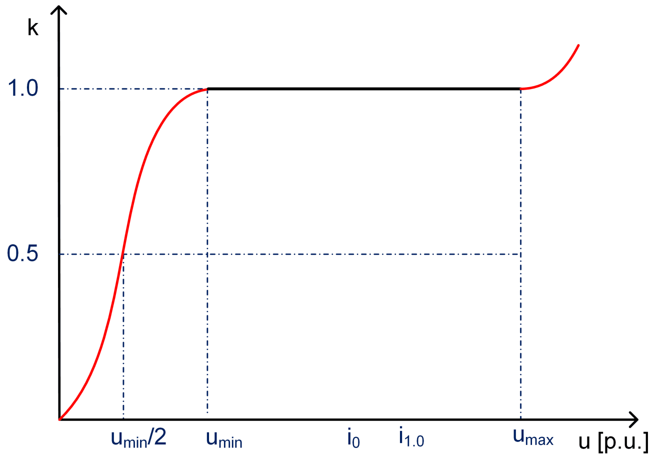

Figure 5.1: Low/High voltage approximations used in the non-linear dynamic load model

5.1.2 Dynamic part of the load

The current flowing in the dynamic part of the load (rotor current) is calculated as:

$$\underline{i}_d = \frac{\underline{\psi}_s - \underline{\psi}_r}{x_d} \tag{17}$$

where the stator flux is being calculated as:

$$\underline{\psi}_s = -\jmath \cdot \underline{u}/f_e \tag{18}$$

In addition, for the dynamic part of the load, a rotor voltage equation has to be satisfied:

$$0 = -r_d \cdot \underline{i}_d + \jmath \cdot s \cdot \underline{\psi}_r - \frac{1}{2 \cdot \pi \cdot F_{nom}} \cdot \frac{d\,\underline{\psi}_r}{dt} \tag{19}$$

The slip is calculated as:

$$s = f_e - speed \tag{20}$$

where f_e is the electrical frequency and the speed derivative of the machine is calculated using the following equation:

$$\frac{d\ speed}{dt} = \frac{xme - xmt}{T_j} \tag{21}$$

where:

- xmt is the mechanical torque in $[p.u.]$;
- xme is the electrical torque in $[p.u.]$;
- T_j is the acceleration time constant in $[s]$

The electrical torque is calculated using the stator flux and rotor current as:

$$xme = \frac{\underline{\psi}_s.r \cdot \underline{i}_d.i - \underline{\psi}_s.i \cdot \underline{i}_d.r}{p_0 \cdot t_{m0}/100} \qquad [p.u.] \tag{22}$$

If the signal $xmdm$ is connected, the mechanical torque takes its value. If it is not connected, the following equation is used:

$$xmt = xmt0 \cdot \left(\frac{speed}{speed0}\right)^{tm1} \tag{23}$$

where $xmt0$ is the initial mechanical torque, $speed0$ is the initial speed and $tm1$ is the *Mechanical Torque Exponent* input parameter.

For the unbalanced RMS simulation, the same from the load flow model applies (Chapter 2.3).

5.2 Initialising of variables

The speed and slip in $p.u.$ are initialised as:

$$\begin{aligned} speed &= 1 - s_0/100 \\ s &= s_0/100 \end{aligned} \tag{24}$$

The electrical torque, the initial mechanical torque and the MDM-torque are initialised as:

$$\begin{aligned} xme &= \frac{|u|^2}{u_0^2} \cdot \frac{s}{s_0/100} \cdot \frac{(s_0/100)^2 + s_{cr}/100)^2}{s^2 + (scr/100)^2} \\ xmt &= -xme \\ xmdm &= xmt \end{aligned} \tag{25}$$

The current flowing in the dynamic part of the load (rotor current) is initialised as:

$$\underline{i}_d = \frac{\underline{u}}{r_d/s + \jmath \cdot x_d} \tag{26}$$

6 EMT Simulation

The EMT model does not have the voltage and frequency dependent parts of the *Load Flow/RMS* model.

6.1 Calculation of variables

The phase currents flowing in the complex load is the sum of the phase currents flowing in the static and dynamic parts:

$$\begin{aligned} i_A &= i_{s\_A} + i_{d\_A} \\ i_B &= i_{s\_B} + i_{d\_B} \\ i_C &= i_{s\_C} + i_{d\_C} \end{aligned} \tag{27}$$

6.1.1 Static part of the load

The current of the static part of the load can be described using the following equation:

$$\begin{aligned} i_{s\_A} &= i_{L\_A} + c \cdot \frac{d\,u_A}{dt} \\ i_{s\_B} &= i_{L\_B} + c \cdot \frac{d\,u_B}{dt} \\ i_{s\_C} &= i_{L\_C} + c \cdot \frac{d\,u_C}{dt} \end{aligned} \tag{28}$$

$$\begin{aligned} u_A &= r \cdot i_{L\_A} + l \cdot \frac{d\,i_A}{dt} \\ u_B &= r \cdot i_{L\_B} + l \cdot \frac{d\,i_B}{dt} \\ u_C &= r \cdot i_{L\_C} + l \cdot \frac{d\,i_C}{dt} \end{aligned} \tag{29}$$

6.1.2 Dynamic part of the load

The variables for the dynamic part of the load are expressed in the dq rotating reference frame. To do this, first they are transferred to the stationary $\alpha\beta$ reference frame using the Clarke transformation and then to the dq rotating reference frame using the rotating angle $phiref$. The $phiref$ angle is initialised with $0\ rad$ and is rotating with the nominal angular frequency $\omega_n = \frac{d\ phi_{ref}}{dt} = 2 \cdot \pi \cdot F_{nom}$.

The flux derivative is being calculated as:

$$\frac{d\,\underline{\psi}_s}{dt} = 2 \cdot \pi \cdot F_{nom} \cdot (\underline{u} - \jmath \cdot \underline{\psi}_s) \tag{30}$$

In addition, for the dynamic part of the load, a rotor voltage equation has to be satisfied:

$$\frac{d\,\underline{i}_d}{dt} = \frac{2 \cdot \pi \cdot F_{nom}}{x_d} \cdot (-r_d \cdot \underline{i}_d + s \cdot \underline{u} - \jmath \cdot s \cdot x_d \cdot \underline{i}_d) \tag{31}$$

where the rotor flux is used in the following part of the equation $s \cdot \underline{u} - \jmath \cdot s \cdot x_d \cdot \underline{i}_d = \jmath \cdot s \cdot \underline{\psi}_r$ (for $f_e = 1$).

The slip is calculated as:

$$s = 1 - speed \tag{32}$$

where the speed derivative of the machine is calculated using the following equation:

$$\frac{d\ speed}{dt} = \frac{xme - xmt}{T_j} \tag{33}$$

where:

- xmt is the mechanical torque in $[p.u.]$;
- xme is the electrical torque in $[p.u.]$;
- T_j is the acceleration time constant in $[s]$

The electrical torque is calculated using the stator flux and rotor current as:

$$xme = \frac{\underline{\psi}_s.r \cdot \underline{i}_d.i - \underline{\psi}_s.i \cdot \underline{i}_d.r}{p_0 \cdot t_{m0}/100} \qquad [p.u.] \tag{34}$$

If the signal $xmdm$ is connected, the mechanical torque takes its value. If it is not connected, the following equation is used:

$$xmt = xmt0 \cdot \left(\frac{speed}{speed0}\right)^{tm1} \tag{35}$$

where $xmt0$ is the initial mechanical torque, $speed0$ is the initial speed and $tm1$ is the *Mechanical Torque Exponent* input parameter.

6.2 Initialising of variables

If the load is capacitative, then the inductance is set to zero and the capacitance and resistance are calculated as:

$$\begin{aligned} c &= \frac{b_s}{2 \cdot \pi \cdot F_{nom}} \\ r &= \frac{1}{g_s} \end{aligned} \tag{36}$$

If the load is inductive, then the capacitance is set to zero and inductance and resistance are calculated as:

$$\begin{aligned} \underline{z} &= \frac{1}{g_s + \jmath \cdot b_s} \\ l &= \frac{\underline{z}.i}{2 \cdot \pi \cdot F_{nom}} \\ r &= \underline{z}.r \end{aligned} \tag{37}$$

The conductance and susceptance are calculated same as for the load flow calculation.

The speed and slip in $p.u.$ are initialised as:

$$\begin{aligned} speed &= 1 - s_0/100 \\ s &= s_0/100 \end{aligned} \tag{38}$$

The electrical torque, the initial mechanical torque and the MDM-torque are initialised as:

$$
\begin{aligned}
xme &= \frac{|u|^2}{u_0^2} \cdot \frac{s}{s_0/100} \cdot \frac{(s_0/100)^2 + s_{cr}/100)^2}{s^2 + (scr/100)^2} \\
xmt &= -xme \\
xmdm &= xmt
\end{aligned}
\tag{39}
$$

6.3 Inputs/Outputs/State Variables of the Dynamic Model

6.3.1 Stability Model (RMS)

Table 6.1: Input Definition of the RMS-Model

Input Signal	Symbol	Description	Unit
xmdm		MDM-Torque	p.u.
fref	f_{ref}	Reference frequency	p.u.

Table 6.2: State Variables Definition of the RMS-Model

Parameter	Symbol	Description	Unit
speed	n	Speed	p.u.
psirr	$\underline{\psi}_r.r$	Rotor flux, real part	p.u.
psiri	$\underline{\psi}_r.i$	Rotor flux, imaginary part	p.u.

6.3.2 EMT-Model

Table 6.3: Input Definition of the RMS-Model

Input Signal	Symbol	Description	Unit
xmdm		MDM-Torque	p.u.

Table 6.4: State Variables Definition of the RMS-Model

Parameter	Symbol	Description	Unit
speed	n	Speed	p.u.
psir	$\underline{\psi}_s.r$	Stator flux, real part	p.u.
psii	$\underline{\psi}_s.i$	Stator flux, imaginary part	p.u.

Table 6.5: Output Definition of the EMT-Model

Parameter	Symbol	Description	Unit
phiref	phi_{ref}	Refernce angle used for conversion to the rotating dq frame	rad

List of Figures

List of Tables