POWERFACTORY

PowerFactory 2021

Technical Reference

General Load

ElmLod, TypLod

PF2021

POWER SYSTEM SOLUTIONS

MADE IN GERMANY

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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. The load composition can also vary depending on factors such as the season, time of day etc. Additionally, the term 'load' can be used for entire MV feeders in case of an HV system, or for LV feeders in the case of an MV system.

The *PowerFactory General Load* model can therefore represent:

- A complete feeder
- A combination of dynamic and static loads

A diagram of the general load model is provided in Figure 1.1.

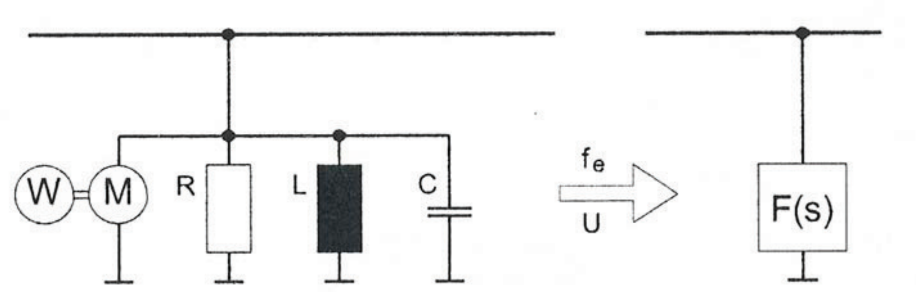

Figure 1.1: *DIgSILENT* general load model.

Note: The general load element in *PowerFactory* may be used in conjunction with the general load type. The load element contains all of the operational data associated with the particular load being modelled, and the type contains the non-specific data required for the modelling of that particular class of power system equipment. The terms 'element' and 'type' used throughout this document refer to these *PowerFactory* objects.

The option *Consider Load Transformer* has the following impact on the model:

- The rated power of the load transformer $Strat$ is used.
- Zero sequence impedance can be defined for 3PH PH-E and 3PH-'YN' models.
- Additional inductance is added to the harmonics model described in Section 4.3.

2 Load-Flow Analysis

The Load Flow tab available in the load element's dialogue allows the user to specify whether the load is balanced or unbalanced. Additionally, on the *Load Flow* tab the user can specify the input parameters for the load by using the *Input Mode* drop-down menu. Based on the load data available to the user, the appropriate combination of parameters can be selected from the following: *S* (apparent power), *P* (real power), *Q* (reactive power), *cos(phi)* (power factor) and *I* (current). For load flow analysis, it suffices to only specify the electrical consumption of the load.

Other data characterizing a load, such as the number of phases and the voltage dependency factors are defined in the general load type (i.e. the Type assigned to the load element). If no Type is specified on the Basic Data tab of the load element, a balanced, three-phase, constant impedance load is assumed.

Note: For a constant impedance load, the voltage dependency components are set to 2. For more detailed information see Section 2.3.

2.1 Balanced Load-Flow

The user is required to specify two input parameters depending on the selected *Input Mode*.

All loads specified as 2-phase or 1-phase loads are only considered in unbalanced load flow calculations. They are ignored when a balanced load flow is performed.

2.2 Unbalanced Load-Flow

When performing an unbalanced load flow (with a complete ABC-network representation), network unbalances resulting from either unbalanced loads or unbalanced branch elements can be considered. In this case, the additional data required to be specified for a general load is its *Technology*. This is done on the Basic Data page of the Type assigned to the load element.

Depending on the selected system type and load technology, the following load types can be defined:

- 3-phase loads (3PH-'D', 3PH PH-E, 3PH-'YN')

  The actual load per phase is entered on the Load Flow page of the load element dialogue. The user has the following choices:

  - Balanced load, only specifying the sum of all phases. In this case, it is assumed that the load is shared equally amongst the phases; or
  - Unbalanced load, specifying the load on a per-phase basis.

  These configurations are illustrated in Figure 2.1 - Figure 2.3.

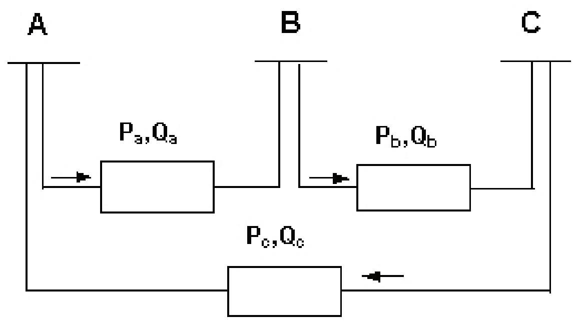

Figure 2.1: 3-phase, Technology 3PH 'D' load model

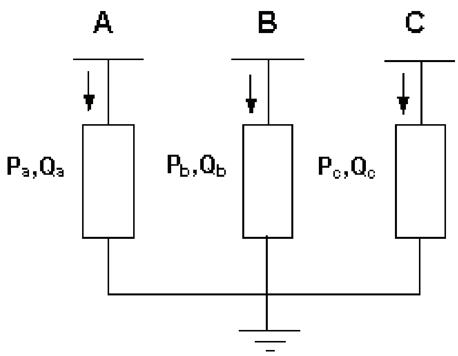

Figure 2.2: 3-phase, Technology 3PH PH-E load model

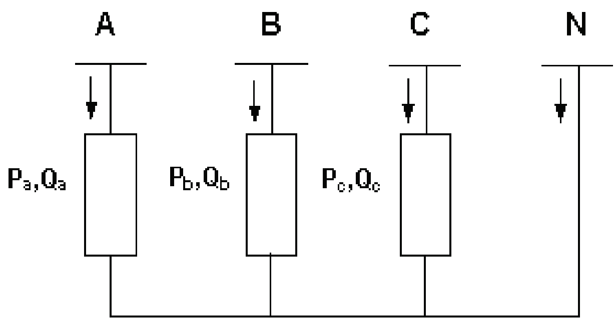

Figure 2.3: 3-phase, Technology 3PH 'YN' load model

- 2-phase loads (2PH PH-E, 2PH-'YN')

  This load type can be used for modelling loads in two-phase or bi-phase systems as shown in Figure 2.4 and Figure 2.5.

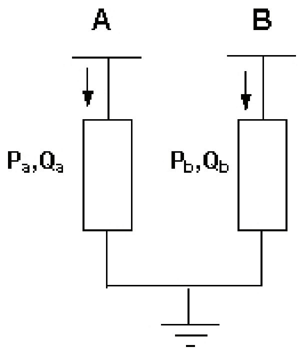

Figure 2.4: 2-phase, Technology 2PH PH-E load model

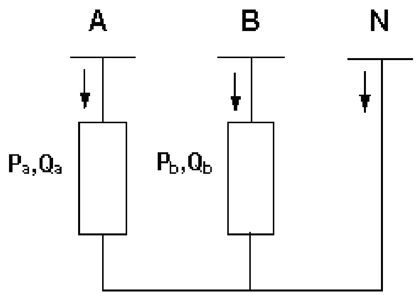

Figure 2.5: 2-phase, Technology 2PH-'YN' load model

- 1-phase loads (1PH PH-PH, 1PH PH-N, 1PH PH-E)

  The 1PH PH-PH load model can be used for representing single-phase loads connected between two phases (see Figure 2.6).

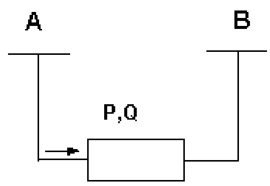

Figure 2.6: 1-phase, Technology 1PH PH-PH load model

  The 1PH PH-N load model can be used for a load connected between one phase and the neutral phase (see Figure 2.7).

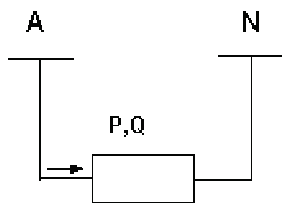

Figure 2.7: 1-phase, Technology 1PH PH-N load model

The 1PH PH-E load model can be used for a load connected between one phase and earth (see Figure 2.8).

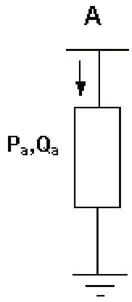

Figure 2.8: 1-phase, Technology 1PH PH-E load model

- DC loads

  DC loads are always single-phase, as shown in Figure 2.9. For load flow analysis, the DC load is characterized by the active power flow P. Inductive effects are only considered in dynamic simulations.

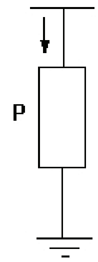

Figure 2.9: DC load model

2.2.1 Consider load transformer option

When the option *Consider Load Transformer* is selected for 3PH PH-E and 3PH-'YN' loads, a zero sequence impedance can be defined for the load transformer which is take into account for the zero sequence system:

$$\underline{z}0 = \frac{r0 + \jmath \cdot x0}{Strat} \tag{1}$$

2.3 Voltage dependency

The voltage dependency of loads is only considered if the parameter *Consider Voltage Dependency of Loads* is checked in the *Load Flow Calculation* command dialogue.

The voltage dependency of loads in *PowerFactory* is modelled using three polynomial terms:

$$\begin{aligned} P &= P_0 \cdot \left[aP \cdot \left(\frac{|\underline{u}|}{u_0}\right)^{e\_aP} + bP \cdot \left(\frac{|\underline{u}|}{u_0}\right)^{e\_bP} + (1 - aP - bP) \cdot \left(\frac{|\underline{u}|}{u_0}\right)^{e\_cP} \right] \\ Q &= Q_0 \cdot \left[aQ \cdot \left(\frac{|\underline{u}|}{u_0}\right)^{e\_aQ} + bQ \cdot \left(\frac{|\underline{u}|}{u_0}\right)^{e\_bQ} + (1 - aQ - bQ) \cdot \left(\frac{|\underline{u}|}{u_0}\right)^{e\_cQ} \right] \end{aligned} \tag{2}$$

where aP, bP, cP, aQ, bQ and cQ are the proportional coefficients and e_aP, e_bP, e_cP, e_aQ, e_bQ and e_cQ are the exponents. u_0 is the voltage input parameter (*ElmLod*) and $|\underline{u}|$ is the absolute voltage where the load is connected.

By selecting certain values for the proportional and exponential coefficients, different exponential and polynomial models can be defined. If a load needs to be described by one polynomial term, the coefficients aP, bP, aQ and bQ need to be set to zero. The relative proportion of each coefficient can be freely defined and the following is valid $1-aP-bP=cP$ and $1-aQ-bQ=cQ$.

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**
Constant power	0
Constant current	1
Constant impedance	2

2.4 Reference Voltage

The reference voltage u_0 in Equation 30 is the busbar voltage at which $P = P_0$ and $Q = Q_0$, and is therefore referred to as the nominal voltage of the load model. However, in *contingency analysis*, u_0 may be selected to be the busbar voltage in the base case. When executing a *contingency analysis*, this option can be enabled as follows:

- Select the option Allow different settings on the Multiple Time Phases tab in the *contingency analysis* command dialogue
- access the *Contingency Load Flow* on the same page, in order to select Consider Voltage Dependency of Loads in the *Load Flow Calculation* dialogue; and
- Select the option Use Base Case voltage as reference on the Advanced Options page of the *Load Flow Calculation* dialogue.

2.5 Load Scaling Factors

The active and reactive power P_0 and Q_0 are defined as:

$$\begin{aligned} P_0 &= p_{lini} \cdot scale \cdot scale_{lf} \cdot scale_{zone} \\ Q_0 &= q_{lini} \cdot scale \cdot scale_{lf} \cdot scale_{zone} \end{aligned} \tag{3}$$

where p_{lini} and q_{lini} are the active and reactive power and $scale$ is the scaling factor and $scale_0$ of the load defined in *ElmLod*. The *Scaling Factor* ($scale_0$) on the Load Flow page in the load element can be used to scale a load individually.

The load scaling factor $scale_{lf}$ is applied to all loads and can be adjusted in the *Load Flow* options (*Load/Generation Scaling*).

Using the zone scaling factor $scale_{zone}$ defined in the Zone element, all the loads belonging to a zone can be scaled. In the *Load Flow* options it can be selected if all loads should be scaled or only the loads that have the *Adjusted by Load Scaling* option enabled (defined in *ElmLod*). $scale_{zone} = 1$ if the load is not assigned to a zone.

2.6 Feeder Scaling

Loads in radial feeders can be scaled based on the total inflow into the feeder (option available in the Feeder element) as shown in Figure 2.10. The feeder load scaling function can be enabled or disabled globally using the corresponding Load Flow option *Feeder Load Scaling*. In addition, the option *Adjusted by Load Scaling* (defined in *ElmLod*) has to be enabled. When the feeder scaling is enabled, the scaling factor $scale$ is determined by the feeder scaling.

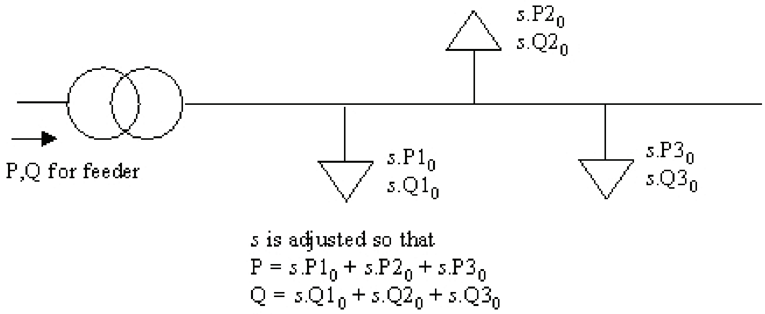

Figure 2.10: Load scaling to maintain feeder settings specified in the feeder definition

3 Short-Circuit Analysis

Short-circuit calculations according to IEC 60909, VDE102/103 or ANSI C37 generally neglect loads and only consider motor contributions. The IEC 61363 method ignores loads when calculating the short-circuit contribution, however if the calculation option *Preload Condition* (available on the Advanced Options page in the Short-Circuit Calculation dialogue) is set to use load flow initialization, loads are considered in the load flow calculation to calculate pre-fault voltages and currents. These pre-fault voltages and currents are then considered in the short-circuit calculation.

The Complete short-circuit method utilises constant impedance (Z) or constant current (I) load models for consideration of the load flow current. Z and I are calculated from a preceding load flow analysis. There are three different load models that can be selected on the Complete Short-Circuit tab of the load type *TypLod*:

- Load Model: Impedance, Model 1

  For a Load Model selected as Impedance, Model 1, the load is modelled as an impedance. Depending on whether the load is purely capacitive or purely inductive, either the resistance and inductance or the capacitance and conductance are calculated. The load admittance is calculated as follows:

$$Y_{load} = \frac{I(ldf)}{U(ldf)} \tag{4}$$

  where $I(ldf)$ is the load flow current, $U(ldf)$ is the load flow voltage, and the load current is set to zero $Iload = 0$.

  Figure 3.1 illustrates the constant impedance load in Y- and D-configurations.

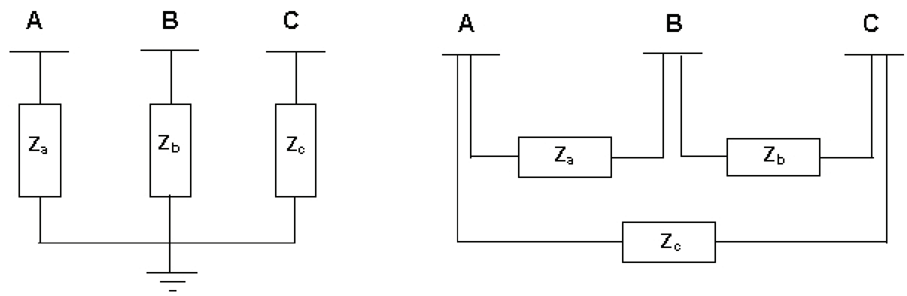

Figure 3.1: 3-phase constant impedance model, in Y- and D-connection, used by the Complete Short-Circuit calculation method

- Load Model: Impedance, Model 2

  This model is the same as the *Impedance, Model 1* model regarding the complete short-circuit calculation.

- Load Model: Current Source

  For a Load Model selected as Current Source, the load current is calculated as follows:

$$Iload = I(ldf) \tag{5}$$

  where $I(ldf)$ is the load flow current, and the load admittance is set to zero $Y_{load} = 0$.

Figure 3.2 illustrates the constant current load model in Y- and D-configurations.

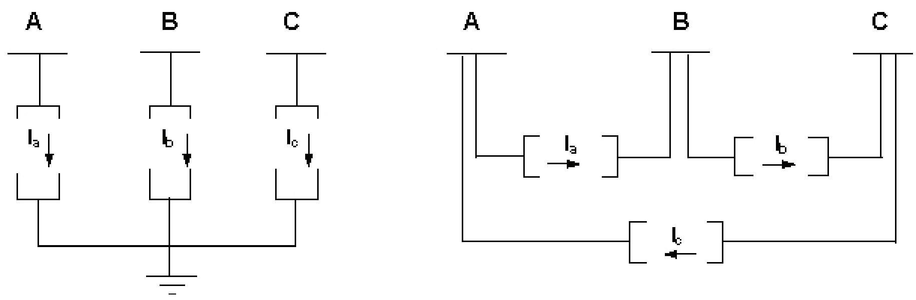

Figure 3.2: 3-Phase constant current load, in Y- and D-connection, used by the Complete Short-Circuit method

When the option *Consider Load Transformer* is selected for 3PH PH-E and 3PH-'YN' loads, a zero sequence impedance can be defined for the load transformer which is take into account for the zero sequence system:

$$\underline{z}0 = \frac{r0 + \jmath \cdot x0}{Strat} \tag{6}$$

3.1 Fault Contribution

The scalable and fixed fault contribution of a load can be entered via the load element's Complete Short-Circuit page. For consideration by the complete short-circuit method, the load is modelled as shown in Figure 3.3.

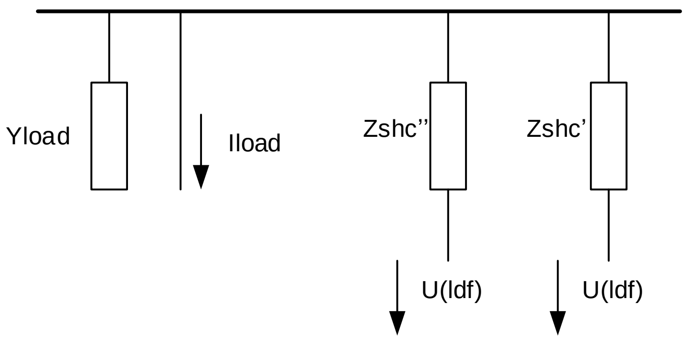

Figure 3.3: Load model used by the Complete Short-Circuit method

The following naming convention is used in Figure 3.3:

- $Yload$: Load admittance for Load Model selected as Impedance
- $Iload$: Load current for Load Model selected as Current Source
- $Zshc"$: Sub-transient short-circuit contribution

- $Zshc'$: Transient short-circuit contribution
- $U(ldf)$: Load flow voltage

The short-circuit contributions of a load are calculated as:

- Total sub-transient short-circuit contribution

$$Ishc'' = U'' \cdot Yload + Iload + \frac{U'' - U(ldf)}{Zshc''} \text{ (Load-oriented equation)} \tag{7}$$

where U'' is the sub-transient short-circuit voltage.
The calculation of the sub-transient short-circuit contribution impedance is as follows:

$$\begin{aligned} Zshc'' &= \frac{1}{Sk'' \cdot |p_{lini} \cdot scale \cdot scale_{zone} \cdot scale_{lf}| + Sksssfix} \\ Im(Zshc'') &= \frac{Zshc''}{\sqrt{1 + (R/X)^2}} \\ Re(Zshc'') &= R/X \cdot Im(Zshc'') \end{aligned} \tag{8}$$

where:

– Sk'' is the sub-transient short-circuit level in MVA/MW
– $Skssfix$ is the fixed sub-transient short-circuit level in MVA
– R/X is the R to X” ratio
– p_{lini} is the active power operating point
– $scale$ is the scaling factor $scale_0$ of the load defined in *ElmLod* or result from the feeder scaling (if feeder scaling is enabled)
– $scale_{zone}$ is the zone scaling factor defined in the Zone element ($scale_{zone} = 1$ if the load is not assigned to a zone)
– $scale_{lf}$ is the load scaling factor defined in *Load Flow* options

If load feeder scaling is enabled from the load, then the scaling is a result of the load flow calculation.

- Total transient short-circuit contribution

$$Ishc' = U' \cdot Yload + Iload + \frac{U' - U(ldf)}{Zshc'} \text{ (Load-oriented equation)} \tag{9}$$

where U' is the transient short-circuit voltage.
The calculation of the transient short-circuit contribution impedance is as follows:

$$\begin{aligned} Zshc' &= \frac{1}{Sk' \cdot |p_{lini} \cdot scale \cdot scale_{zone} \cdot scale_{lf}| + Sksfix} \\ Re(Zshc') &= R/X \cdot \frac{Zshc''}{\sqrt{1 + (R/X)^2}} = Re(Zshc'') \\ Im(Zshc') &= \sqrt{Zshc' \cdot Zshc' - Re(Zshc') \cdot Re(Zshc')} \end{aligned} \tag{10}$$

where:

– Sk' is the transient short-circuit level in MVA/MW
– $Sksfix$ is the fixed transient short-circuit level in MVA

- R/X is the R to X" ratio
- p_{lini} is the active power operating point
- $scale$ is the scaling factor $scale_0$ of the load defined in *ElmLod* or result from the feeder scaling (if feeder scaling is enabled)
- $scale_{zone}$ is the zone scaling factor defined in the Zone element ($scale_{zone} = 1$ if the load is not assigned to a zone)
- $scale_{lf}$ is the load scaling factor defined in *Load Flow* options

For the X/R ratio (X/R ratio break) calculation, only the short-circuit contribution is considered and the load impedance and load current are ignored.

4 Harmonic Analysis

In the general load model type (i.e. the *Type* assigned to the load element), the harmonic load model can be specified as either an impedance or a current source. Three different models are available.

When the option *Consider Load Transformer* is selected for 3PH PH-E and 3PH-'YN' loads, a zero sequence impedance can be defined for the load transformer which is take into account for the zero sequence system:

$$\underline{z}0 = \frac{r0 + \jmath \cdot x0}{Strat} \tag{11}$$

4.1 Load Model: Impedance, Model 1

The *Impedance, Model 1* load model is used in the harmonics calculation essentially as it is used in the short-circuit calculation, as described in Section 3.

In harmonics analysis however, the *Impedance, Model 1* load model offers the user the possibility of representing passive loads as *Purely Inductive/Capacitive* or *Mixed Inductive/Capacitive*. In the former case, R and L or C and G are calculated. In the latter case, the proportions of capacitive and inductive reactive power can be specified as a percentage. The active and reactive power is then recalculated into an admittance. Depending on the value of this admittance, the model will be more capacitive or more inductive.

Figure 4.1 shows the single-phase representations of a purely inductive and a purely capacitive load.

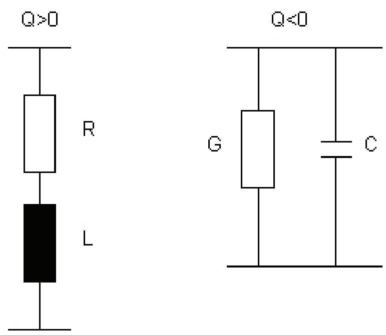

Figure 4.1: Purely inductive and purely capacitive load models used for harmonic analysis

The parameters R,L or G,C are calculated from a preceding load flow.

Figure 4.2 shows the single-phase load model for mixed inductive/capacitive load models (e.g. cables), used for harmonics analysis.

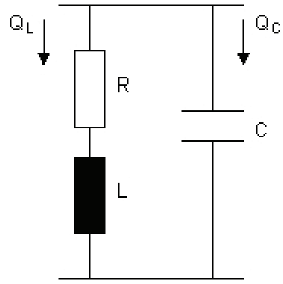

Figure 4.2: Mixed inductive/capacitive load model used for harmonics analysis

For purely inductive loads the parameters are calculated as:

$$
\begin{aligned}
\underline{Z}_{load} &= \frac{1}{\underline{Y}_{load}} \\
L &= Im(\underline{Z}_{load})/w_n \\
R &= Re(\underline{Z}_{load})
\end{aligned} \tag{12}
$$

For purely capacitive loads the parameters are calculated as:

$$
\begin{aligned}
C &= Im(\underline{Y}_{load})/w_n \\
R &= 1/Re(\underline{Y}_{load})
\end{aligned} \tag{13}
$$

For mixed inductive/capacitive loads the parameters are calculated as:

$$
\begin{aligned}
Q &= Q_L + Q_C \\
\frac{Q_c}{Q} &= \frac{Q_C}{Q_L + Q_C} = \frac{1}{\frac{Q_L}{Q_C} + 1} \\
C &= \frac{Im(\underline{Y}_{load})}{w_n \cdot (1 - \frac{Q_L}{Q_C}/100)} \\
\underline{Z}_{load} &= \frac{1}{Re(\underline{Y}_{load}) - \imath Im(\underline{Y}_{load}) \cdot \frac{\frac{Q_L}{Q_C}/100}{1 - \frac{Q_L}{Q_C}/100}} \\
L &= Im(\underline{Z}_{load})/w_n \\
R &= Re(\underline{Z}_{load})
\end{aligned} \tag{14}
$$

where Q_c is the capacitive reactive power, Q_L is the inductive reactive power, and Q is the total reactive power. ω_n is the nominal frequency, C is the capacitance and y is the admittance.

4.2 Load Model: Current Source

The *Current Source* load model is considered in the harmonics calculation as it is used in the short-circuit calculation. See Section 3 for details.

4.3 Load Model: Impedance, Model 2

The *Impedance, Model 2* load model is illustrated in Figure 4.3 and is an extension of the *Impedance, Model 1* model. It takes into consideration the impedance of the load transformer (if specified) on the Basic Data page of the load element dialogue, and also has user-definable static and dynamic portions on the Harmonics page of the load type.

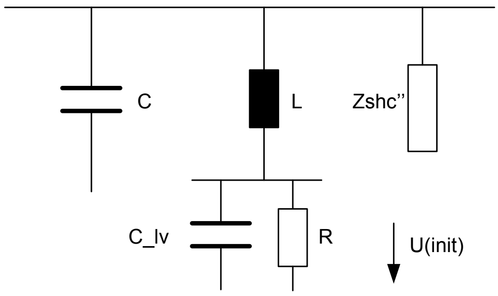

Figure 4.3: Equivalent circuit of Impedance, Model 2 model

The quantities in Figure 4.3 are calculated as follows:

$$R = \frac{1}{Prp/100 \cdot p_{lini} \cdot scale \cdot scale_{zone} \cdot scale_{lf}} \text{ (p.u. based on 1MVA)} \tag{15}$$

where Prp is the user-defined static portion of the load (in %), p_{lini} is the user-defined active power of the load, $scale$ is the load scaling factor, $scale_{zone}$ is the zone scaling factor and $scale_{lf}$ is the load scaling factor (specified via the load flow command, on the Load/Generation Scaling page).

The LV capacitance is calculated as follows:

$$C_{lv} = \frac{pfc/100 \cdot p_{lini} \cdot scale \cdot scale_{zone} \cdot scale_{lf} + Bc\_lv}{2\pi \cdot fnom} \text{ (p.u. based on 1MVA)} \tag{16}$$

where pfc is the power factor correction (in %), Bc_lv is the user-defined additional LV capacitance, and $fnom$ is the fundamental frequency.

The capacitance is calculated as:

$$C = \frac{Bc\_hv}{2\pi \cdot fnom} \text{ (p.u. based on 1MVA)} \tag{17}$$

where Bc_hv is the user-defined HV capacitance.

If the option *Consider Load Transformer* on the Basic Data tab of the load element dialogue is enabled, the inductance is calculated as follows:

$$L = \frac{xt/100}{Strat \cdot 2\pi \cdot fnom} \text{ (p.u. based on 1MVA)} \tag{18}$$

where xt is the user-defined reactance of the load transformer and $Strat$ is the user-defined rated apparent power of the load transformer. If the option Consider Load Transformer is disabled, the inductance is set to zero $L = 0$.

The load flow voltage is initialized as:

$$U(init) = u(ldf) \tag{19}$$

For *Impedance, Model 2*, an additional current source is modelled at the fundamental frequency (50Hz) to compensate the difference between the load flow current and the current calculated considering the load transformer. Depending on the size of this transformer, this difference between the two currents can be large.

This additional current infeed is calculated as follows:

$$\underline{i}_{comp} = \underline{i}(ldf) - \underline{u} \cdot \underline{y}1 \tag{20}$$

where $\underline{y}1$ is the admittance of the $C \parallel (L - (C\_lv \parallel R))$ part of the circuit shown in Figure 4.3.

4.4 Fault Contribution

The fault contribution is definable for harmonics analysis. It is considered in the harmonics calculation as it is in the short-circuit calculation. The harmonic current is calculated comprised of three components:

- the load voltage and impedance,
- the current injected by the current source,
- the current based on the short-circuit impedance.

Refer to Section 3.1 for further details regarding the calculation of the fault contribution.

4.5 Harmonic Current Injections

Non-linear loads are described by their harmonic current spectrum. A requirement for modelling current-injecting loads is to set the corresponding parameter on the harmonics page of the load type dialogue to *current source*.

Harmonic current injections in *PowerFactory* are defined via the use of the Harmonic Sources object. For balanced loads, only characteristic harmonics can be specified. Figure 4.4 shows the specification of the harmonic spectrum in the Harmonic Sources dialogue, for Balanced, Phase Correct sources. The current spectrum shown in Figure 4.4 is that of an ideal 6-pulse rectifier.

The angles of harmonic currents are defined with reference to the fundamental frequency phase angle (cosine reference). This way of entering phase angles allows the definition of the current waveform to be independent from the power factor at fundamental frequency.

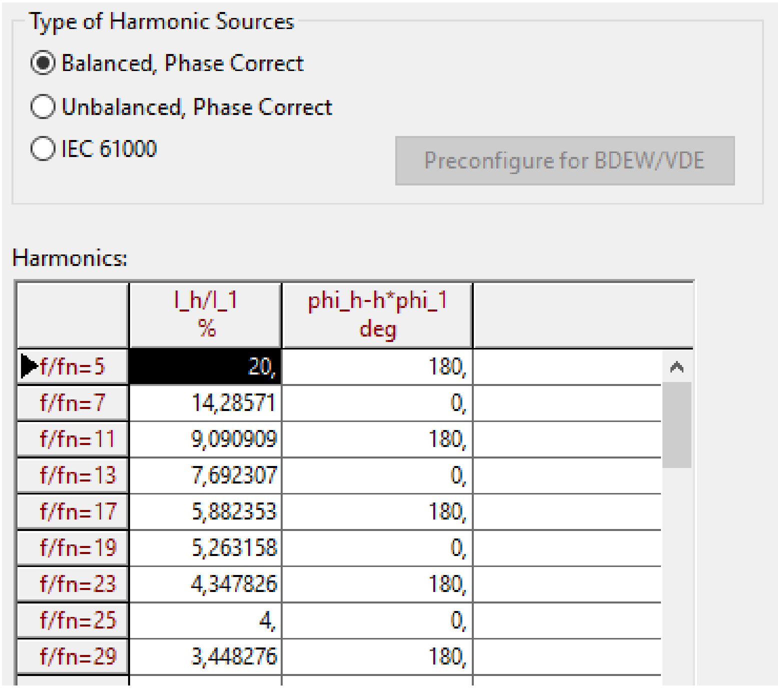

Figure 4.4: Specification of the harmonic current spectrum for balanced loads

In the case of unbalanced loads, the frequency, phase angle and magnitude of harmonic currents can be entered individually for each phase.

For Balanced, Phase Correct and Unbalanced, Phase Correct sources, the user can select whether the current magnitudes are to be calculated referred to fundamental or rated current.

For phase correct sources, if the harmonic injections are to be calculated referred to fundamental current, the harmonic current magnitudes are defined as:

$$|I_f| = k_f \cdot |I_{fn}| \tag{21}$$

where k_f is the user-defined harmonic current injection and $|I_{fn}|$ is the current magnitude at the nominal frequency. The phase angles of the harmonic currents are defined as:

$$\varphi_{(f)} = \varphi + \frac{f}{f_n} \cdot \varphi_1 \tag{22}$$

where φ_1 is the phase angle of the fundamental current.

If the harmonic injections are to be calculated referred to rated current, the harmonic current magnitudes are defined as:

$$|I_f| = k_f \cdot |I_{rated}| \tag{23}$$

where k_f is the user-defined harmonic current injection and $|I_{rated}|$ is the rated current. The phase angles of the harmonic currents are defined as:

$$\varphi_{(f)} = \varphi_{(ldf)} \tag{24}$$

where $\varphi_{(ldf)}$ is the bus voltage angle calculated by the load flow.

A source may instead be defined as an IEC 61000 harmonic source, according to the IEC 61000-3-6 standard. The input for this type of harmonic source allows odd- and even-order harmonics, as well as non-integer order harmonics. For this type of harmonic source, whether performing a balanced or an unbalanced load flow, harmonic injections at zero sequence orders and non-integer orders are considered in the positive sequence.

Note: All current magnitudes for IEC 61000 harmonic sources are calculated referred to rated current.

IEC harmonic injections are always calculated referred to rated current (never referred to fundamental current); hence the harmonic current magnitudes are defined in Equation 23. The phase angles of the harmonic currents in the case of IEC harmonic injections are defined as:

$$\varphi_{(f)} = \varphi_{(ldfini)} \tag{25}$$

where $\varphi_{(ldfini)}$ is the initial bus voltage angle calculated by the load flow.

5 RMS Simulation

For RMS simulations, a three-phase load can be modelled as a pure static or dynamic load or as a combination of static and dynamic loads (as illustrated in Figure 5.1). To the static load group belong ohmic, inductive or capacitive loads, and to the dynamic load group belong motor loads (especially induction motors).

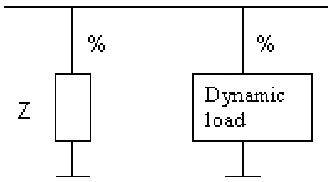

Figure 5.1: Representation of the mixture of static and dynamic loads used for stability studies

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

$$\begin{aligned} \underline{i} &= \underline{i}_s + \underline{i}_{dyn} \\ \underline{i}_s &= \underline{Y}load \cdot \underline{u} \\ \underline{i}_{dyn} &= \frac{(\underline{S}_{dyn})^*}{\underline{u}^*} \end{aligned} \tag{26}$$

Two-phase, single-phase and DC loads are generally modelled as constant impedance (admittance).

5.1 Static part of the load

The static part of the load is initialised from the load flow results:

$$\underline{Y}load = \frac{lodst}{100} \cdot \frac{I(ldf)}{U(ldf)} \tag{27}$$

5.2 Dynamic part of the load

The dynamic part of the load can be represented by one of the following dynamic loads dependent on voltage and frequency:

- Linear,
- Nonlinear voltage, linear frequency,
- Nonlinear and
- Nonlinear, regulated

Note: The voltage dependency coefficients and exponents of the dynamic part of the load are the same as used in the load flow model. The load flow model does not differentiate between static and dynamic part.

5.2.1 Dynamic models

The frequency dependency is enabled in all models if the frequency dependence parameters kpf and kqf are non-zero.

The structure of the *Nonlinear, regulated* load model cannot be further modified. However, the voltage and frequency dependency of the other loads can be additionally modified depending if the time constants are zero or not. If the following voltage dependence coefficients (calculated from input parameters) are zero or not has also influence on the other loads:

$$\begin{aligned} k_{put} &= aP \cdot e\_aP + bP \cdot e\_bP + (1 - aP - bP) \cdot e\_cP \\ k_{qut} &= aQ \cdot e\_aQ + bQ \cdot e\_bQ + (1 - aQ - bQ) \cdot e\_cQ \end{aligned} \tag{28}$$

5.2.1.1 Linear voltage and linear frequency dependence model

The dynamic linear load model is represented by the block diagram shown in Figure 5.2 where $\Delta f = f_e - 1 = F_e/F_{nom} - 1$, $\Delta u = |\underline{u}| - |\underline{u}_{ini}|$, $|\underline{u}|$ is the absolute value of the connected voltage and $|\underline{u}_{ini}|$ is the absolute value of the initial voltage. This model is based on [1].

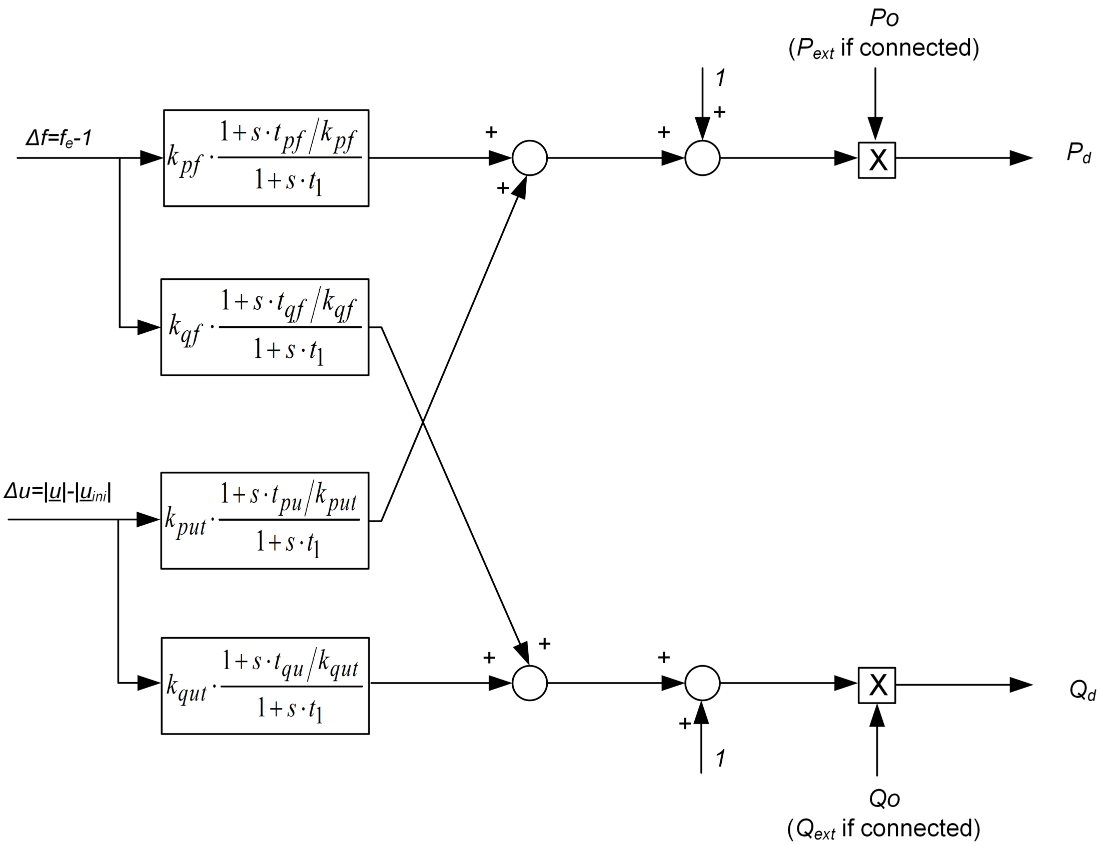

Figure 5.2: Model used to approximate the behaviour of the linear dynamic load

From the model structure it can be seen that the effects of the voltage and frequency linear dependence are summed and then multiplied by the initial load values.

If the frequency and voltage dependency disabled, the model becomes a constant power model.

The frequency dependency is enabled if the factors kpf and/or kqf are not zero. The first-order lead-lag (PD-T1) block is used if all time constants used in the block are not zero. If the frequency time constant is zero, the lead-lag block becomes a first-order delay (PT1) block. If the dynamic load time constant $t1$ is zero, the lead-lag block becomes a gain.

The voltage dependency is enabled if the factors k_{put} and/or k_{qut} are not zero. The first-order lead-lag (PD-T1) block is used if the time constants used in the block are not zero. If the voltage time constant is zero, the lead-lag block becomes a first-order delay (PT1) block. If the dynamic load time constant $t1$ is zero, the lead-lag block becomes a gain.

In [1], the transfer functions parameters are estimated based on measured data. The delay time constant is very small and is calculated using the slip and the acceleration time constant of a machine as $t_1 = slip/100 \cdot T_{ag}$ ($t_1 = 0.1s$ for a machine with $T_{ag} = 5s$ and $slip = 2\%$). The identified parameters in [1] are as follows: $(k_{pf} + s \cdot t_{pf})/(1 + s \cdot t_1) = (1.19 + s)/(1 + s \cdot 0.1)$, $(k_{qf} + s \cdot t_{qf})/(1 + s \cdot t_1) = -(1.82 + s \cdot 1.59)/(1 + s \cdot 0.1)$, $(k_{put} + s \cdot t_{pu})/(1 + s \cdot t_1) = (1.17 + s \cdot 0.14)/(1 + s \cdot 0.1)$ and $(k_{qut} + s \cdot t_{qu})/(1 + s \cdot t_1) = (1.92 + s \cdot 0.18)/(1 + s \cdot 0.1)$.

5.2.1.2 Nonlinear voltage and linear frequency dependance model

This dynamic load model is represented by the block diagram shown in Figure 5.3 where $\Delta f = f_e - 1 = F_e/F_{nom} - 1$, $\Delta u = |\underline{u}| - |\underline{u}_{ini}|$, $|\underline{u}|$ is the absolute value of the connected voltage and $|\underline{u}_{ini}|$ is the absolute value of the initially connected voltage.

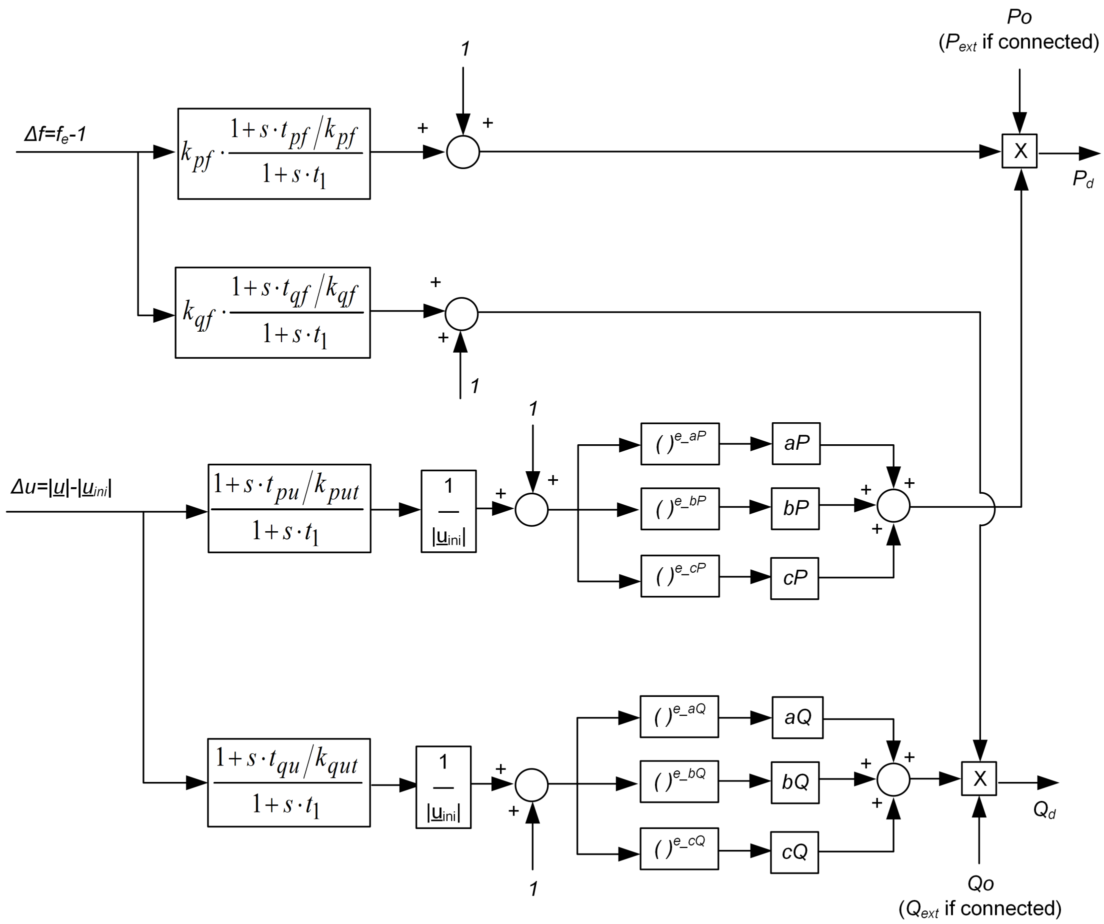

Figure 5.3: Model used to approximate the behaviour of the non-linear dynamic load

The model has a nonlinear voltage and a linear frequency dependence. Therefore, it is valid for deviations close to nominal frequency.

The frequency dependency is enabled if the factors kpf and/or kqf are not zero. The first-order lead-lag (PD-T1) block is used if all time constants used in the block are not zero. If the frequency time constant is zero, the lead-lag block becomes a first-order delay (PT1) block. If the dynamic load time constant $t1$ is zero, the lead-lag block becomes a gain.

The voltage dependency is enabled if the factors k_{put} and/or k_{qut} are not zero. The first-order lead-lag (PD-T1) block is used if the time constants used in the block are not zero. If the voltage time constant is zero, the lead-lag block becomes a first-order delay (PT1) block. If the dynamic load time constant $t1$ is zero, the lead-lag block becomes a gain (having a value of 1). In this case, the voltage dependency gets the same form (using three polynomial terms) as in Equation 30.

By putting all the time constants of the model to zero, $e\_aP = e\_aQ = 2$, $e\_bP = e\_bQ = 1$ and $e\_cP = e\_cQ = 0$, we get a model that has exponential voltage dependency (ZIP) and frequency dependency:

$$\begin{aligned} P_d &= P_0 \cdot \left[aP \cdot \left(\frac{|\underline{u}|}{|\underline{u}_{ini}|} \right)^2 + bP \cdot \frac{|\underline{u}|}{|\underline{u}_{ini}|} + cP \right] \cdot (1 + kpf \cdot \Delta f) \\ Q_d &= Q_0 \cdot \left[aQ \cdot \left(\frac{|\underline{u}|}{|\underline{u}_{ini}|} \right)^2 + bQ \cdot \frac{|\underline{u}|}{|\underline{u}_{ini}|} + cQ \right] \cdot (1 + kqf \cdot \Delta f) \end{aligned} \tag{29}$$

5.2.1.3 Nonlinear voltage and nonlinear frequency model

The dynamic nonlinear voltage and nonlinear frequency load model is represented by the block diagram shown in Figure 5.4.

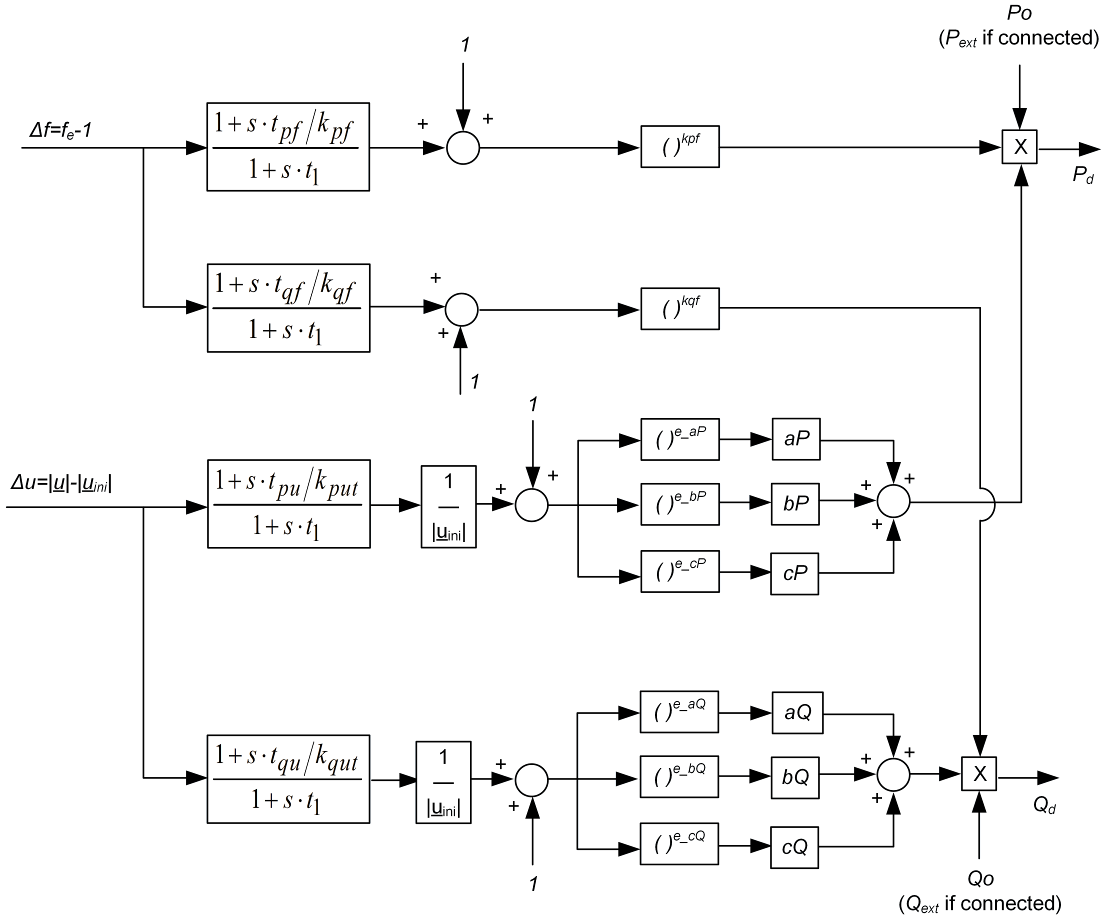

Figure 5.4: Model used to approximate the behaviour of the non-linear dynamic load

The difference to the *Nonlinear voltage and linear frequency dependance model* is that this model has also an exponential frequency dependency (the coefficients are now used as exponents on the frequency).

By putting all the time constants and the voltage dependence coefficients aP, bP, aQ and bQ to zero we get a model that has exponential voltage and exponential frequency dependency:

$$\begin{aligned} P_d &= P_0 \cdot \left(\frac{|\underline{u}|}{|\underline{u}_{ini}|}\right)^{e\_cP} \cdot \left(\frac{f_e}{1}\right)^{kpf} \\ Q_d &= Q_0 \cdot \left(\frac{|\underline{u}|}{|\underline{u}_{ini}|}\right)^{e\_cQ} \cdot \left(\frac{f_e}{1}\right)^{kqf} \end{aligned} \tag{30}$$

5.2.1.4 Nonlinear, regulated model

The dynamic, nonlinear regulated load model is represented by the block diagram is presented in Figure 5.5 where $f_e = F_e/F_{nom}$ and $|\underline{u}|$ is the absolute value of the connected voltage.

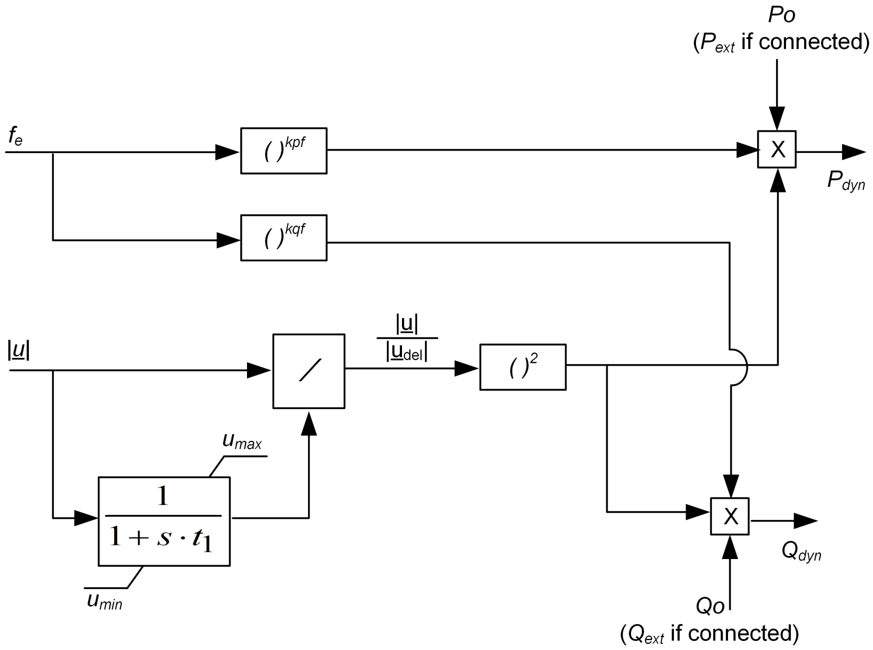

Figure 5.5: Model used to approximate the behaviour of the non-linear dynamic load

This *Nonlinear, regulated model* without explicitly modelled transformer with tap changer can be used to represent a LV tap changer effect on the HV side of the load. The parameter $t1$ in this model represents the transformer dynamics time constant.

The following equation describes the model:

$$
\begin{aligned}
P_{dyn} &= P_0 \cdot \left(\frac{|\underline{u}|}{|\underline{u}_{del}|}\right)^2 \cdot \left(\frac{f_e}{1}\right)^{kpf} \\
Q_{dyn} &= Q_0 \cdot \left(\frac{|\underline{u}|}{|\underline{u}_{del}|}\right)^2 \cdot \left(\frac{f_e}{1}\right)^{kqf}
\end{aligned}
\qquad (31)
$$

where the output of the first order delay block is limited to the minimum u_{min} and maximum u_{max} defined voltage limits.

5.2.2 Voltage range of the models

The behaviour of the dynamic models is different when the voltage gets outside the defined range between u_{min} and u_{max} (parameters $udmin$ and $udmax$) and so short-circuits and other voltage collapses can be withstood.

The *Nonlinear, regulated model* has a quadratic voltage dependency where the delayed voltage is limited within a voltage range. During a voltage collapse (for example due to a short circuit), the quadratic term regulates the load so that there is also a strong reduction of the load which then rises with the time constant $t1$ until the denominator voltage hits the lower limit $udmin$. During the rest of the short-circuit duration, the power remains constant.

For the other dynamic models, the voltage dependency can be freely defined and therefore an additional multiplier is defined so that the load can be adjusted when the voltage is not in the defined range. The power is then adjusted according to the following equations:

$$
\begin{aligned}
P_{dyn} &= k \cdot P_d \\
Q_{dyn} &= k \cdot Q_d
\end{aligned}
\qquad (32)
$$

where:

$$k = \begin{cases} 1 & u_{\min} < u < u_{\max} \\ \dfrac{2 \cdot |u|^2}{u_{\min}^2} & 0 < u < \dfrac{u_{\min}}{2} \\ 1 - 2 \cdot \left(\dfrac{|u| - u_{\min}}{u_{\min}}\right)^2 & \dfrac{u_{\min}}{2} < u < u_{\min} \\ 1 + (|\underline{u}| - u_{\max})^2 & |\underline{u}| > u_{\max} \end{cases} \tag{33}$$

This adjustment can be seen in Figure 5.6.

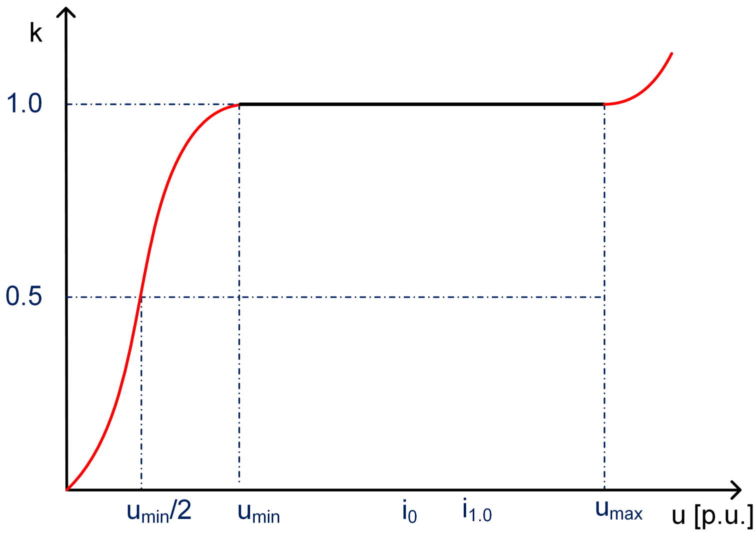

Figure 5.6: Power adjustment

5.3 Consider load transformer option

When the option *Consider Load Transformer* is selected for 3PH PH-E and 3PH-'YN' loads, a zero sequence impedance can be defined for the load transformer which is taken into account for the zero sequence system:

$$\underline{z}0 = \frac{r0 + \jmath x0}{Strat} \tag{34}$$

5.4 Load Events

A value pertaining to a load can be changed throughout the course of an RMS or EMT simulation via the use of load events. The user must specify a load element, and also a point in time in the simulation for the event to occur. The value of the load can then be altered using the load event. There are different ways to change the power of the selected load/s:

- *Step*
  Changes the current value of the power (positive or negative) by the given value (in % of the nominal power of the load) at the time of the event;

- *Ramp*
  Changes the current value of the power by the given value (in % of the nominal power of the load), over the time specified by the Ramp Duration (in seconds). The load ramping starts at the time of the event.

In order for a load-ramp event to be simulated, the *Allow Load-Ramp Event* option in the load element dialogue on the RMS-Simulation tab must be enabled. If only load-step events are to be simulated, the *Allow Load-Ramp Event* option does not need to be enabled. Load events must be defined using the *Load Event* object.

5.5 Use of External Signals

The signal inputs *Pext* and *Qext* of the load element can be used to change the load during dynamic simulation. For 100% static loads, a *PowerFactory* measurement file can be used to directly control the active and reactive power consumption of the load. However, if the load consists of a dynamic and a static part, only the dynamic part can be controlled by external signals. In this case, the static part remains at its initial value (and voltage dependent deviations).

For load types defined as 3-phase and as being 100% *Dynamic* (*RMS-Simulation* page of the load type), the input signals correspond to the active and reactive power. For load types with settings different to these, the input signals may correspond to another variable: for example, for load types defined as single-phase, the signals *Pext* and *Qext* correspond to the admittance.

The single-phase, two-phase and DC-loads are constant impedance load models. No input or output variables exist.

5.5.1 Inputs/Outputs/State Variables of the Dynamic Model

Table 5.1: Input Definition of the RMS-Model

Input Signal	Symbol	Description	Unit
Pext		Active Power Input	MW
Qext		Reactive Power Input	Mvar
fref		Reference frequency (automatically assigned)	p.u.

Table 5.2: State Variables Definition of the RMS-Model

Parameter	Symbol	Description	Unit
xu		Delayed Δu (delay with t1) or $\lvert \underline{u}_{del} \rvert$ in the nonlinear regulated model	p.u.
xf		Delayed Δf (delay with t1), not available in the nonlinear regulated model	p.u.
cosphiu		Cosine of voltage angle	
sinphiu		Sine of voltage angle	

6 EMT Simulation

In EMT simulations all loads are modelled as passive loads where for the load model it can be selected between *Purely Inductive/Capacitive* or *Mixed Inductive/Capacitive*. If the latter is selected, the user can also specify the ratio of capacitive/inductive reactive power as a percentage.

The following equations are used for Y connection:

$$\begin{aligned}
u_a &= Rr \cdot i_{L_a} + Lr \cdot \frac{di_{L_a}}{dt} \\
u_b &= Rs \cdot i_{L_b} + Ls \cdot \frac{di_{L_b}}{dt} \\
u_c &= Rt \cdot i_{L_c} + Lt \cdot \frac{di_{L_c}}{dt} \\
i_a &= i_{L_a} + Cr \cdot \frac{du_a}{dt} \\
i_b &= i_{L_b} + Cs \cdot \frac{du_b}{dt} \\
i_c &= i_{L_c} + Ct \cdot \frac{du_c}{dt}
\end{aligned} \tag{35}$$

The following equations are used for D connection:

$$\begin{aligned}
u_a - u_b &= Rr \cdot i_{L_ab} + Lr \cdot \frac{di_{L_ab}}{dt} \\
u_b - u_c &= Rs \cdot i_{L_bc} + Ls \cdot \frac{di_{L_bc}}{dt} \\
u_c - u_a &= Rt \cdot i_{L_ca} + Lt \cdot \frac{di_{L_ca}}{dt} \\
i_a &= i_{L_ab} + Cr \cdot \left(\frac{du_a}{dt} - \frac{du_b}{dt}\right) - \left(i_{L_ca} + Ct \cdot \left(\frac{du_c}{dt} - \frac{du_a}{dt}\right)\right) \\
i_b &= i_{L_bc} + Cs \cdot \left(\frac{du_b}{dt} - \frac{du_c}{dt}\right) - \left(i_{L_ab} + Cr \cdot \left(\frac{du_a}{dt} - \frac{du_b}{dt}\right)\right) \\
i_c &= i_{L_ca} + Ct \cdot \left(\frac{du_c}{dt} - \frac{du_a}{dt}\right) - \left(i_{L_bc} + Cr \cdot \left(\frac{du_b}{dt} - \frac{du_c}{dt}\right)\right)
\end{aligned} \tag{36}$$

The resistances, inductances and capacitances used above are internal calculation parameters of the model.

Note: The use of negative active power in EMT simulations leads to unstable behaviour, since negative P is interpreted as negative resistance.

6.1 Inputs/Outputs/State Variables of the Dynamic Model

Table 6.1: State Variables Definition of the EMT-Model

Parameter	Symbol	Description	Unit
curLA	i_{L_a} or i_{L_ab}	Inductive current	p.u.
curLB	i_{L_b} or i_{L_bc}	Inductive current	p.u.
curLC	i_{L_c} or i_{L_ca}	Inductive current	p.u.

A References

[1] M. E. de Morais, “Beitrag zur Ermittlung der Frequenz- und Spannungsabhängigkeit von Verbraucherteilnetzen mit einer automatischen Messwerterfassungsanlage,” *Dissertation, Universität Stuttgart*, 1985.

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