POWERFACTORY

PowerFactory 2021

Technical Reference

MV Load

ElmLodmv, TypDistrf

PF2021

POWER SYSTEM SOLUTIONS

MADE IN GERMANY

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Contents

1 General Description

The Medium-Voltage Load represents an aggregation of general loads and static generation. Optionally, they can be connected through a MV-LV transformer. In this case, the specification and measurement of electric quantities is done on the MV side of the transformer.

Representations of the MV load model (with and without distribution transformer) are provided in Figure 1.1.

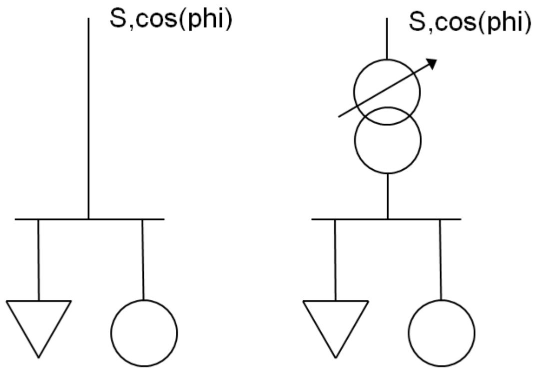

Figure 1.1: *PowerFactory* MV load model.

Note: The MV load element in *PowerFactory* may be used in conjunction with the *Distribution Transformer 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, in addition with the MV-LV transformer. The terms 'element' and 'type' used throughout this document refer to these *PowerFactory* objects.

2 Zero Sequence Representation

The zero sequence representation depends on whether the zero sequence impedance is specified on the *Basic Data* page of the *Distribution Transformer Type*, as shown in Figure 2.1. To specify a zero sequence impedance, check the *iZzero* flag.

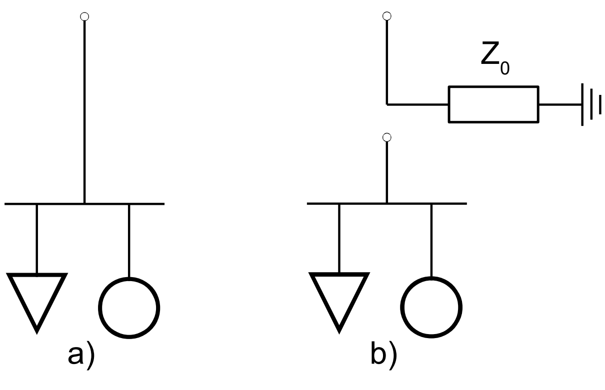

Figure 2.1: Zero sequence model of MV load: a) Z_0 not specified, b) Z_0 specified

3 Load-Flow Analysis

The Load Flow tab available in the MV 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:

- P,cosphi: Enter active power and power factor for the load and for the generation parts
- S,cosphi: Enter apparent power and power factor for the load and for the generation parts
- E,cosphi: Enter yearly energy consumption, power factor, and consumption profile for the load part, and active power and power factor for the generation part

For load flow analysis, it suffices to only specify the electrical consumption and generation of the MV load on the MV side.

Other data characterizing a MV load, such as the number of phases, are defined in the distribution transformer type. If no Type is specified on the Basic Data tab of the MV load element, a technology configuration is assumed based on the technology of the bus to which the load is connected.

3.1 Voltage dependency

On the *Load Flow* page in the *Distribution Transformer Type*, it is possible to specify the voltage dependency of the MV load.

Note: This dependency is only taken into account if the flag *Consider Voltage Dependency of Loads* in the *Load Flow Calculation* command dialog is selected.

Voltage dependency of MV loads can be specified as *Composite (ZIP)* model or *exponent* model.

For the *Composite (ZIP)* model, coefficient aP specifies the part of total active power load which is constant power, coefficient bP specifies the part of total active power load which is constant current and coefficient $cP = 1 - aP - bP$ specifies the part of total active power load which is constant impedance. For the *Composite (ZIP)* the voltage dependency of loads is given in (1) and (2). The subscript '0' indicates the *Operating Point* values as defined on the Load Flow page of the MV load element dialog.

$$P = P_0 \left(aP + bP \cdot \left(\frac{v}{v_0} \right) + cP \cdot \left(\frac{v}{v_0} \right)^2 \right) \tag{1}$$

$$Q = Q_0 \left(aQ + bQ \cdot \left(\frac{v}{v_0} \right) + cQ \cdot \left(\frac{v}{v_0} \right)^2 \right) \tag{2}$$

where v is the busbar voltage (p.u.).

For the *Exponent* model, coefficients eP and eQ specify the voltage dependency of the load according to (3) and (4):

$$P = P_0 \cdot \left(\frac{v}{v_0}\right)^{eP} \tag{3}$$

$$Q = Q_0 \cdot \left(\frac{v}{v_0}\right)^{eQ} \tag{4}$$

If the flag *Consider Voltage Dependency of Loads* in the *Load Flow Calculation* command dialog is not selected, a MV load is always considered to be constant power load in a load flow calculation.

3.2 Balanced Calculations

Figure 3.1 shows the load model used for balanced load flow analysis.

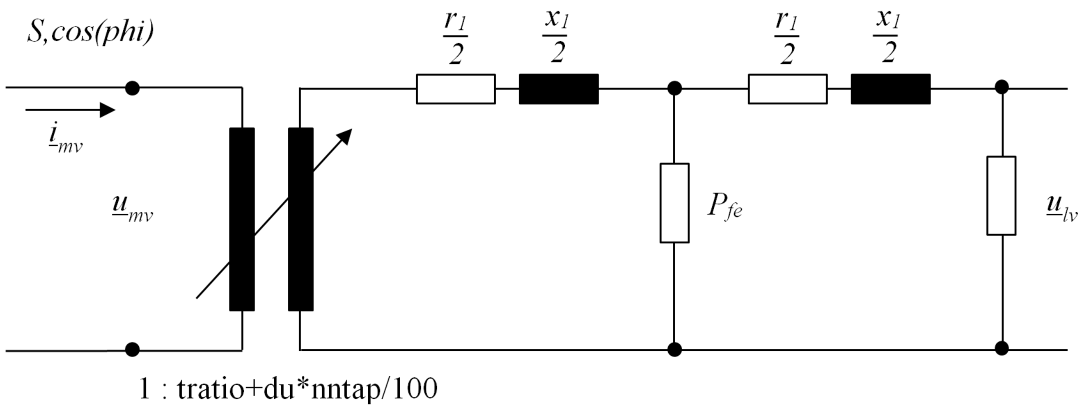

Figure 3.1: Load model used for balanced load-flow analysis

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.

The total active power of the MV load is the substraction of the generation active power (P_{gen}) from the consumption active power (P_{load}):

$$P_{total} = P_{load} - P_{gen}$$

With

$$P_{load} = slini * coslini * scale0 * zonescale * scLoadFac$$
$$P_{gen} = sgini * cosgini * gscale * scGenFac$$

Where

- $slini$ is the specified load apparent power
- $coslini$ is the specified load power factor
- $scale0$ is the load scaling factor
- $zonescale$ is the zone scaling factor, if available
- $scLoadFac$ is the load scaling factor of the load flow analysis command
- $sgini$ is the specified generation apparent power
- $coslini$ is the specified generation power factor
- $gscale$ is the generation scaling factor
- $scGenFac$ is the generation scaling factor of the load flow analysis command

The corresponding reactive power is calculated:

$$Q_{total} = Q_{load} - Q_{gen}$$

With

$$Q_{load} = \begin{cases} slini \cdot \sqrt{1 - coslini^2} \cdot scale0 \cdot zonescale \cdot scLoadFac, & \text{if load is inductive} \\ -slini \cdot \sqrt{1 - coslini^2} \cdot scale0 \cdot zonescale \cdot scLoadFac, & \text{if load is capacitive.} \end{cases}$$

$$Q_{gen} = \begin{cases} sgini \cdot \sqrt{1 - cosgini^2} \cdot gscale \cdot scGenFac, & \text{if generation is inductive} \\ -sgini \cdot \sqrt{1 - cosgini^2} \cdot gscale \cdot scGenFac, & \text{if generation is capacitive.} \end{cases}$$

Where

- $slini$ is the specified load apparent power
- $coslini$ is the specified load power factor
- $scale0$ is the load scaling factor
- $zonescale$ is the zone scaling factor, if available
- $scLoadFac$ is the load scaling factor of the load flow analysis command
- $sgini$ is the specified generation apparent power
- $coslini$ is the specified generation power factor
- $gscale$ is the generation scaling factor
- $scGenFac$ is the generation scaling factor of the load flow analysis command

3.2.1 Calculation Quantities

Depending on the tap position of the transformer defined in the load flow, the actual voltage on the LV side is calculated as follows:

$$
\begin{aligned}
\underline{z}_{trf} &= r_1 + \jmath x_1 \\
\underline{i}_{mv'} &= \frac{\underline{i}_{mv}}{1 + \dfrac{dutap}{100} \cdot (nntap - nnenutral)} \\
\underline{u}_{mv'} &= \underline{u}_{mv} \cdot \left(1 + \frac{dutap}{100} \cdot (nntap - nneutral)\right) \\
\underline{i}_{Pfe} &= \begin{cases} \dfrac{P_{fe}}{1000 \cdot S_{nom}} \cdot \left(\underline{u}_{mv'} - \underline{i}_{mv'} \cdot \dfrac{\underline{z}_{trf}}{2}\right) \\ 0, \text{ if } |\underline{i}_{Pfe}| > |\underline{i}_{mv'}| \end{cases} \\
\underline{i}_{lv'} &= \underline{i}_{mv'} - \underline{i}_{Pfe} \\
\underline{u}_{lv} &= tratio \cdot \left|\underline{u}_{mv'} - \frac{\underline{z}_{trf}}{2} \cdot (\underline{i}_{mv'} + \underline{i}_{lv'})\right|
\end{aligned}
$$

Where

- r_1 is the positive-sequence resistance of the transformer in p.u.
- x_1 is the positive-sequence reactance of the transformer in p.u.
- $\underline{z}_{trf}$ is the transformer impedance in p.u.
- $\underline{i}_{mv}$ is the current on the MV side in p.u.
- $dutap$ is the additional voltage per tap in %
- $nntap$ is the actual tap position
- $nnenutral$ is the neutral tap position
- $\underline{u}_{mv}$ is the voltage on the MV side in p.u.
- $\underline{i}_{Pfe}$ is the current due to iron losses
- P_{fe} is the no load losses magnetizing impedance in kW
- S_{nom} is the rated power in MW
- $tratio$ is the transformer ratio
- $\underline{u}_{lv}$ is the calculated voltage on the LV side in p.u.

The iron losses, $Gmload$, are calculated as:

$$
Gmload = \Re\left\{\underline{i}^{*}_{Pfe} \cdot \left(\underline{u}_{mv'} - \underline{i}_{mv'} \cdot \frac{\underline{z}_{trf}}{2}\right) \cdot 1000\right\} \text{ in kW}
$$

And the total losses are calculated as:

$$
Losses = \frac{\underline{z}_{trf}}{2} \cdot \left(|\underline{i}_{mv'}|^2 - |\underline{i}_{lv'}|^2\right) + \frac{Gmload}{1000} \text{ in MW/Mvar}
$$

3.2.2 MV Load Elements with E, cos(phi) mode

If the medium-voltage load element is specified as *E, cos(phi)*, the variables used for calculation are shown in Table 3.1.

Table 3.1: Parameters for input mode ”E, cos(phi)”

Parameter Name	Description	Obtained from
coslini	Power factor	Element
elini	Yearly Energy	Element
pProfile	Consumption Profile	Element

A standard load profile specifies daily power values (in W) in minutes or hours intervals for different days (Saturday, Sunday, and Weekdays) and for different seasons of the year (Summer, Winter and Rest). These values are already normalized, such that when these values are aggregated to a yearly-scale, the total energy consumed for the whole year is exactly 1000 kWh/a.

In *PowerFactory*, the *Consumption Profile* can point to a Season Profile or to a Time Characteristic. The total energy consumed for the whole year in kWh/a can be specified by the user through the *Yearly Energy* field.

The current active and reactive power values are calculated by:

$$P = p(t_i) * \frac{elini}{\sum p(t_i)} \tag{5}$$

$$Q = \sqrt{\frac{P}{coslini} \cdot \frac{P}{coslini} - P \cdot P} \tag{6}$$

Where

- $p(t_i)$ is the value of consumption profile at time t_i.
- $\sum p(t_i)$ is the integral of the season profile or time characteristic for the whole year. In this case, it is irrelevant whether the characteristic is marked as absolute or relative, since it is normalized by equation 5.

3.3 Unbalanced Calculations

The total per-phase active power of the MV load is the substraction of the generation active power per phase from the consumption active power per phase:

$$P_r = P_{loadr} - P_{genr}$$
$$P_s = P_{loads} - P_{gens}$$
$$P_t = P_{loadt} - P_{gent}$$

With

$$
\begin{aligned}
P_{loadr} &= slinir * coslinir * scale0 * zonescale * scLoadFac \\
P_{loads} &= slinis * coslinis * scale0 * zonescale * scLoadFac \\
P_{loadt} &= slinit * coslinit * scale0 * zonescale * scLoadFac \\
P_{genr} &= sginir * cosginir * gscale * scGenFac \\
P_{gens} &= sginis * cosginis * gscale * scGenFac \\
P_{gent} &= sginit * cosginit * gscale * scGenFac
\end{aligned}
$$

Where

- $slinir$, $slinis$, and $slinit$ are the specified load apparent power per phase
- $coslinir$, $coslinis$, and $coslinit$ are the specified load power factor per phase
- $scale0$ is the load scaling factor
- $zonescale$ is the zone scaling factor, if available
- $scLoadFac$ is the load scaling factor of the load flow analysis command
- $sginir$, $sginis$, and $sginit$ are the specified generation apparent power per phase
- $coslinir$, $coslinis$, and $coslinit$ are the specified generation power factor per phase
- $gscale$ is the generation scaling factor
- $scGenFac$ is the generation scaling factor of the load flow analysis command

The corresponding total per-phase reactive power values are calculated as follows:

$$
\begin{aligned}
Q_r &= Q_{loadr} - Q_{genr} \\
Q_s &= Q_{loads} - Q_{gens} \\
Q_t &= Q_{loadt} - Q_{gent}
\end{aligned}
$$

With

$$
Q_{loadr} = \begin{cases} slinir \cdot \sqrt{1 - coslinir^2} \cdot scale0 \cdot zonescale \cdot scLoadFac, & \text{if load is inductive} \\ -slinir \cdot \sqrt{1 - coslinir^2} \cdot scale0 \cdot zonescale \cdot scLoadFac, & \text{if load is capacitive.} \end{cases}
$$

$$
Q_{loads} = \begin{cases} slinis \cdot \sqrt{1 - coslinis^2} \cdot scale0 \cdot zonescale \cdot scLoadFac, & \text{if load is inductive} \\ -slinis \cdot \sqrt{1 - coslinis^2} \cdot scale0 \cdot zonescale \cdot scLoadFac, & \text{if load is capacitive.} \end{cases}
$$

$$
Q_{loadt} = \begin{cases} slinit \cdot \sqrt{1 - coslinit^2} \cdot scale0 \cdot zonescale \cdot scLoadFac, & \text{if load is inductive} \\ -slinit \cdot \sqrt{1 - coslinit^2} \cdot scale0 \cdot zonescale \cdot scLoadFac, & \text{if load is capacitive.} \end{cases}
$$

$$
Q_{genr} = \begin{cases} sginir \cdot \sqrt{1 - cosginir^2} \cdot gscale \cdot scGenFac, & \text{if generation is inductive} \\ -sginir \cdot \sqrt{1 - cosginir^2} \cdot gscale \cdot scGenFac, & \text{if generation is capacitive.} \end{cases}
$$

$$
Q_{gens} = \begin{cases} sginis \cdot \sqrt{1 - cosginis^2} \cdot gscale \cdot scGenFac, & \text{if generation is inductive} \\ -sginis \cdot \sqrt{1 - cosginis^2} \cdot gscale \cdot scGenFac, & \text{if generation is capacitive.} \end{cases}
$$

$$
Q_{gent} = \begin{cases} sginit \cdot \sqrt{1 - cosginit^2} \cdot gscale \cdot scGenFac, & \text{if generation is inductive} \\ -sginit \cdot \sqrt{1 - cosginit^2} \cdot gscale \cdot scGenFac, & \text{if generation is capacitive.} \end{cases}
$$

Where

- $slinir$, $slinis$, and $slinit$ are the specified load apparent power values per phase
- $coslinir$, $coslinis$, and $coslinit$ are the specified load power factors per phase
- $scale0$ is the load scaling factor
- $zonescale$ is the zone scaling factor, if available
- $scLoadFac$ is the load scaling factor of the load flow analysis command
- $sginir$, $sginis$, and $sginit$ are the specified generation apparent power values per phase
- $coslinir$, $coslinis$, and $coslinit$ are the specified generation power factors per phase
- $gscale$ is the generation scaling factor
- $scGenFac$ is the generation scaling factor of the load flow analysis command

3.3.1 3PH-D

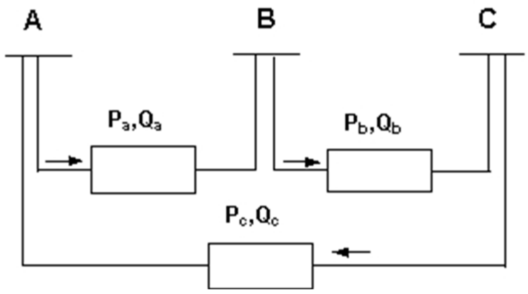

Figure 3.2: Load model used for unbalanced 3-phase Delta connection

The voltages for this model are calculated as follows:

$$u_r = u_a - u_b$$
$$u_s = u_b - u_c$$
$$u_t = u_c - u_a$$

3.3.2 3PH PH-E

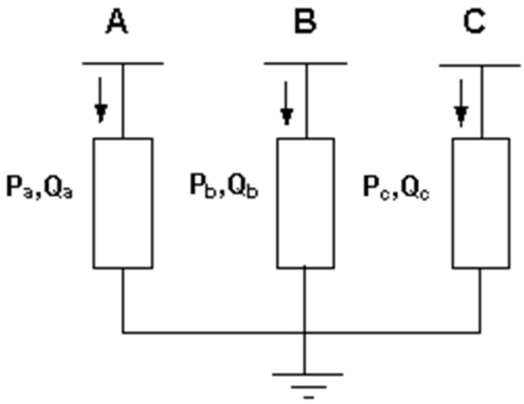

Figure 3.3: Load model used for unbalanced 3-phase PH-E connection

The voltages for this model are calculated as follows:

$$u_r = u_a$$
$$u_s = u_b$$
$$u_t = u_c$$

If the load has a distribution transformer type assigned with specified zero sequence impedance, then the voltages are:

$$u_r = u_a - u_0$$
$$u_s = u_b - u_0$$
$$u_t = u_c - u_0$$

3.3.3 3PH-'YN'

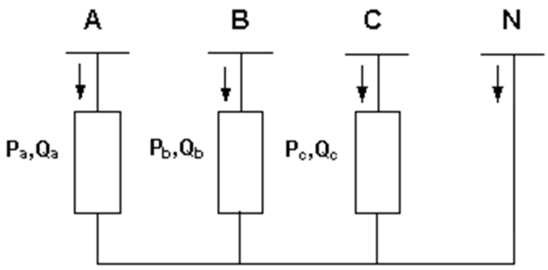

Figure 3.4: Load model used for unbalanced 3-phase YN connection

The voltages for this model are calculated as follows:

$$u_r = u_a - u_n$$
$$u_s = u_b - u_n$$
$$u_t = u_c - u_n$$

If the load has a distribution transformer type assigned with specified zero sequence impedance, then the voltages are:

$$u_r = u_a - u_n - u_0$$
$$u_s = u_b - u_n - u_0$$
$$u_t = u_c - u_n - u_0$$

3.3.4 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 3.5 and Figure 3.6.

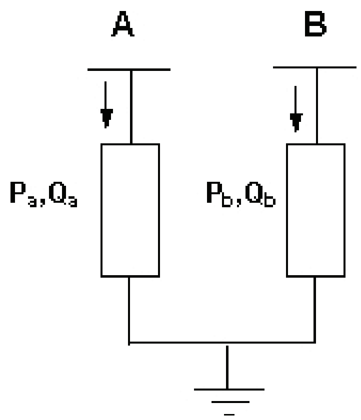

Figure 3.5: 2-phase, Technology 2PH PH-E load model

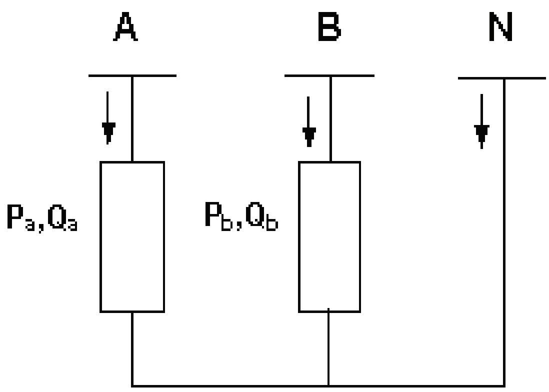

Figure 3.6: 2-phase, Technology 2PH-'YN' load model

3.3.5 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 3.7).

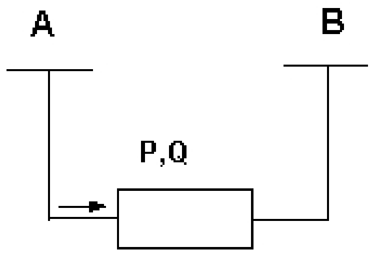

Figure 3.7: 1-phase, Technology 1PH PH-PH load model

The 1PH PH-N load model can be used for a load connected between one phase and the neutral phase (see Figure 3.8).

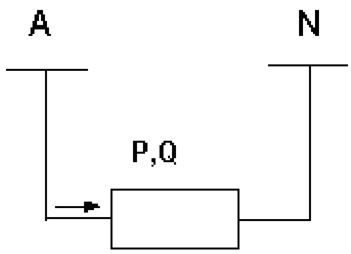

Figure 3.8: 1-phase, Technology 1PH PH-N load model

The 1PH PH-E load model can be used for a load connected between one phase and earth (see Figure 3.9).

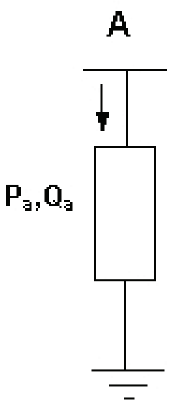

Figure 3.9: 1-phase, Technology 1PH PH-E load model

3.3.6 Calculation Quantities

Depending on the tap position of the transformer defined in the load flow, the actual voltage on the LV side is calculated as follows:

$$
\begin{aligned}
\underline{z}_{trf} &= r_1 + \jmath x_1 \\
\underline{i}_{r(mv)'} &= \frac{\underline{i}_{r(mv)}}{1 + \frac{dutap}{100} \cdot (nntap - nnenutral)} \\
\underline{i}_{s(mv)'} &= \frac{\underline{i}_{s(mv)}}{1 + \frac{dutap}{100} \cdot (nntap - nnenutral)} \\
\underline{i}_{t(mv)'} &= \frac{\underline{i}_{t(mv)}}{1 + \frac{dutap}{100} \cdot (nntap - nnenutral)} \\
\underline{u}_{r(mv)'} &= \underline{u}_{r(mv)} \cdot \left(1 + \frac{dutap}{100} \cdot (nntap - nneutral)\right) \\
\underline{u}_{s(mv)'} &= \underline{u}_{s(mv)} \cdot \left(1 + \frac{dutap}{100} \cdot (nntap - nneutral)\right) \\
\underline{u}_{t(mv)'} &= \underline{u}_{t(mv)} \cdot \left(1 + \frac{dutap}{100} \cdot (nntap - nneutral)\right) \\
\begin{bmatrix} \underline{i}_{0'} \\ \underline{i}_{1'} \\ \underline{i}_{2'} \end{bmatrix} &= \mathbf{A}^{-1} \begin{bmatrix} \underline{i}_{r(mv)'} \\ \underline{i}_{s(mv)'} \\ \underline{i}_{t(mv)'} \end{bmatrix} \\
\begin{bmatrix} \underline{u}_{0'} \\ \underline{u}_{1'} \\ \underline{u}_{2'} \end{bmatrix} &= \mathbf{A}^{-1} \begin{bmatrix} \underline{u}_{r(mv)'} \\ \underline{u}_{s(mv)'} \\ \underline{u}_{t(mv)'} \end{bmatrix} \\
\underline{i}_{1(Pfe)} &= \begin{cases} \frac{P_{fe}}{1000 \cdot S_{nom}} \cdot \left(\underline{u}_{1'} - \underline{i}_{1'} \cdot \frac{\underline{z}_{trf}}{2}\right) \\ 0, \text{ if } |\underline{i}_{1(Pfe)}| > |\underline{i}_{1'}| \end{cases} \\
\underline{i}_{2(Pfe)} &= \begin{cases} \frac{P_{fe}}{1000 \cdot S_{nom}} \cdot \left(\underline{u}_{2'} - \underline{i}_{2'} \cdot \frac{\underline{z}_{trf}}{2}\right) \\ 0, \text{ if } |\underline{i}_{2(Pfe)}| > |\underline{i}_{2'}| \end{cases} \\
\underline{i}_{1(lv)'} &= \underline{i}_{1(mv)'} - \underline{i}_{1(Pfe)} \\
\underline{i}_{2(lv)'} &= \underline{i}_{2(mv)'} - \underline{i}_{2(Pfe)} \\
\underline{u}_{1(lv)} &= tratio \cdot \left|\underline{u}_{1(mv)'} - \frac{\underline{z}_{trf}}{2} \cdot (\underline{i}_{1(mv)'} + \underline{i}_{1(lv)'})\right| \\
\underline{u}_{2(lv)} &= tratio \cdot \left|\underline{u}_{2(mv)'} - \frac{\underline{z}_{trf}}{2} \cdot (\underline{i}_{2(mv)'} + \underline{i}_{2(lv)'})\right| \\
\underline{u}_{0(lv)} &= 0 \\
\begin{bmatrix} \underline{u}_{lv:a} \\ \underline{u}_{lv:b} \\ \underline{u}_{lv:c} \end{bmatrix} &= \left|\mathbf{A} \begin{bmatrix} \underline{u}_{0(lv)} \\ \underline{u}_{1(lv)} \\ \underline{u}_{2(lv)} \end{bmatrix}\right| \text{ in p.u.}
\end{aligned}
$$

Where

- r_1 is the positive-sequence resistance of the transformer in p.u.
- x_1 is the positive-sequence reactance of the transformer in p.u.

- $\underline{z}_{trf}$ is the transformer impedance in p.u.
- $\underline{i}_{r(mv)}$, $\underline{i}_{s(mv)}$, and $\underline{i}_{t(mv)}$ are the phase currents on the MV side in p.u.
- $dutap$ is the additional voltage per tap in %
- $nntap$ is the actual tap position
- $nnenutral$ is the neutral tap position
- $\underline{u}_{r(mv)}$, $\underline{u}_{s(mv)}$, and $\underline{u}_{t(mv)}$ are the phase voltages on the MV side in p.u.
- $\underline{i}_{1(Pfe)}$ and $\underline{i}_{2(Pfe)}$ are the positive and negative sequence currents due to iron losses
- P_{fe} is the no load losses magnetizing impedance in kW
- S_{nom} is the rated power in MW
- $tratio$ is the transformer ratio
- $\underline{u}_{lv:a}$, $\underline{u}_{lv:b}$, and $\underline{u}_{lv:c}$ are the calculated phase voltages on the LV side in p.u.

The iron losses, $Gmload$, are calculated as:

$$Gmload = \Re\Big\{\Big[\underline{i}^*_{1(Pfe)} \cdot \Big(\underline{u}_{1(mv)'} - \underline{i}_{1(mv)'} \cdot \frac{\underline{z}_{trf}}{2}\Big) + \underline{i}^*_{2(Pfe)} \cdot \Big(\underline{u}_{2(mv)'} - \underline{i}_{2(mv)'} \cdot \frac{\underline{z}_{trf}}{2}\Big)\Big] \cdot 1000\Big\} \text{ in kW}$$

And the total losses are calculated as:

$$Losses = \frac{\underline{z}_{trf}}{2} \cdot \Big[\Big(|\underline{i}_{1(mv)'}|^2 - |\underline{i}_{1(lv)'}|^2\Big) + \Big(|\underline{i}_{2(mv)'}|^2 - |\underline{i}_{2(lv)'}|^2\Big)\Big] + \frac{Gmload}{1000} \text{ in MW/Mvar}$$

4 Short-Circuit

4.1 Complete

4.1.1 Short-Circuit Contribution

The MV Load model for the ”complete” short-circuit calculation is the following:

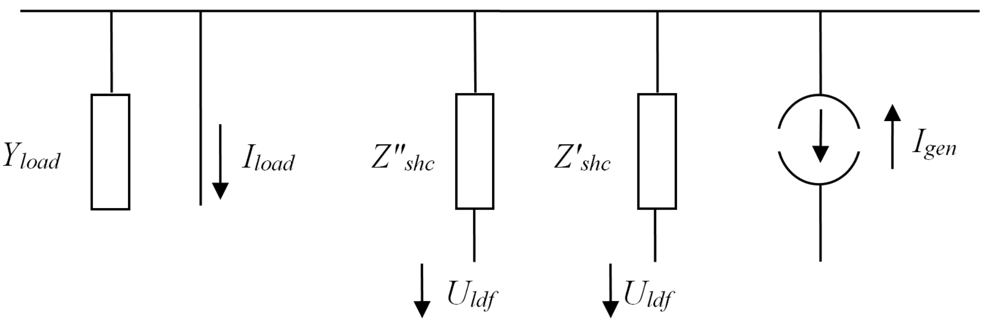

Figure 4.1: Load model used for complete short-circuit

Where

- Y_{load} is the load admittance for ”Impedance” load type
- I_{load} is the load current for ”Current” load type
- I_{gen} is the generation current for ”Impedance” load type
- Z''_{shc} is the sub-transient short-circuit contribution (load + generation)
- Z'_{shc} is the transient short-circuit contribution (load + generation)
- U_{ldf} is the voltage value calculated with load-flow analysis

The total sub-transient short-circuit contribution is:

$$I''_{shc} = U'' \cdot I_{load} + I_{load} - I_{gen} + \frac{U'' - U_{ldf}}{Z''_{shc}}$$

Where U'' is the sub-transient short-circuit voltage.

The total transient short-circuit contribution is:

$$I'_{shc} = U' \cdot I_{load} + I_{load} - I_{gen} + \frac{U' - U_{ldf}}{Z'_{shc}}$$

Where U' is the transient short-circuit voltage.

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

The Subtransient Short-Circuit Contribution Impedance

$$Z''_{shc} = \frac{1}{S''_{k,l} \cdot S_{l,ini} \cdot cosphi_{l,ini} \cdot scale \cdot zonescale + S''_{k,g} \cdot S_{g,ini} \cdot cosphi_{g,ini} \cdot zonescale + Skss_{fix}}$$

$$\Im\{Z''_{shc}\} = \frac{Z''_{shc}}{\sqrt{1 + (R/X)^2}}$$

$$\Re\{Z''_{shc}\} = R/X \cdot \Im\{Z''_{shc}\}$$

Where

- Z''_{shc} is the subtransient short-circuit contribution
- $S''_{k,l}$ is the subtransient short-circuit level for load in MVA/MW
- $S''_{k,g}$ is the subtransient short-circuit level for generation in MVA/MW
- $Skss_{fix}$ is the fixed subtransient short-circuit level in MVA

- $S_{l,ini}$ is the load apparent power operating point
- $cosphi_{l,ini}$ is the load power factor
- $S_{g,ini}$ is the generation apparent power operating point
- $cosphi_{g,ini}$ is the generation power factor
- $scale$ is the scaling factor
- $zonescale$ is the zone scaling factor
- R/X is the R to X" ratio

The Transient Short-Circuit Contribution Impedance

$$Z'_{shc} = \frac{1}{S'_{k,l} \cdot S_{l,ini} \cdot cosphi_{l,ini} \cdot scale \cdot zonescale + S'_{k,g} \cdot S_{g,ini} \cdot cosphi_{g,ini} \cdot zonescale + Sks_{fix}}$$
$$\Im\{Z'_{shc}\} = \frac{R}{X} \cdot \frac{Z'_{shc}}{\sqrt{1+(R/X)^2}}$$
$$\Re\{Z'_{shc}\} = \sqrt{(Z'_{shc})^2 - (\Re\{Z'_{shc}\})^2}$$

Where

- Z'_{shc} is the transient short-circuit contribution
- $S'_{k,l}$ is the transient short-circuit level for load in MVA/MW
- $S'_{k,g}$ is the transient short-circuit level for generation in MVA/MW
- Sks_{fix} is the fixed transient short-circuit level in MVA
- $S_{l,ini}$ is the load apparent power operating point
- $cosphi_{l,ini}$ is the load power factor
- $S_{g,ini}$ is the generation apparent power operating point
- $cosphi_{g,ini}$ is the generation power factor
- $scale$ is the scaling factor
- $zonescale$ is the zone scaling factor
- R/X is the R to X" ratio

"Impedance" Load Type

The load admittance is calculated as follows:

$$Y_{load} = \left(\frac{I_{ldf}}{U_{ldf}}\right)^2 - \frac{S_{gini}}{(U_{ldf})^2}$$

The load current is set to zero:

$$I_{load} = 0$$

and

$$I_{gen} = \frac{S_{gini}}{U_{ldf}} \text{ when } S_{gini} > 0$$

"Current Source" Load Type

The load current is calculated as follows:

$$I_{load} + I_{gen} = I_{ldf}$$

The load admittance is set to zero

$$Y_{load} = 0$$

5 RMS Simulation

5.1 Balanced RMS Simulation

5.1.1 Load, No Generation

If no generation is available, the load is modelled as a constant admittance.

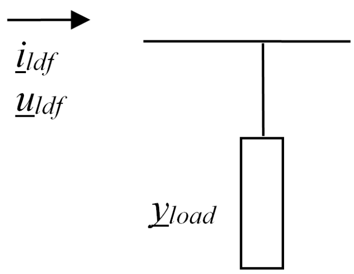

Figure 5.1: RMS-Simulation model with load and no generation

The initialization for this model is thus:

$$\underline{y}_{load} = \frac{\underline{i}_{ldf}}{\underline{u}_{ldf}}$$

And the equation for this model is:

$$\underline{i}_{rms} = \underline{y}_{load} \cdot \underline{u}_{rms}$$

5.1.2 Load with Generation

If generation is available, the load part is modelled as a constant admittance, while the generation part is modelled as a current source, with a magnitude of current injection (i_{gen}) and the angle with respect to the load-flow voltage ($phiui_{gen}$).

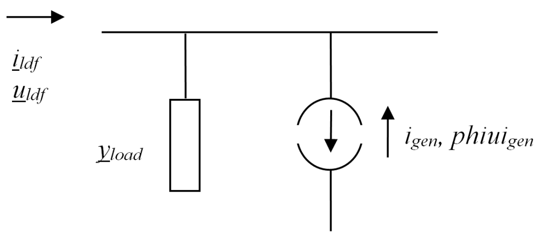

Figure 5.2: RMS-Simulation model with load and generation

The initialization equations for this model are thus:

$$\begin{aligned} \underline{y}_{load} &= \frac{\underline{i}_{ldf}}{\underline{u}_{ldf}} \\ i_{gen} &= \left| -\underline{i}_{ldf} + \underline{y}_{load} \cdot \underline{u}_{ldf} \right| \\ phiui_{gen} &= angle(\underline{u}_{ldf}) - angle(\underline{i}_{gen}) \end{aligned}$$

The equation of the model is:

$$\underline{i}^{*}_{rms} \cdot \underline{u}_{rms} = (\underline{y}_{load} \cdot \underline{u}_{rms})^{*} - |\underline{u}_{rms}| \cdot i_{gen} \cdot (cos(phiui_{gen}) + \jmath sin(phiui_{gen}))$$

5.2 Unbalanced RMS Simulation

5.2.1 Load, No Generation

If no generation is available, the load is modelled as a constant admittance. The initialization for this model is thus:

$$\underline{y}_{r,load} = \frac{\underline{i}_{r,ldf}}{\underline{u}_{r,ldf}}$$
$$\underline{y}_{s,load} = \frac{\underline{i}_{s,ldf}}{\underline{u}_{s,ldf}}$$
$$\underline{y}_{t,load} = \frac{\underline{i}_{t,ldf}}{\underline{u}_{t,ldf}}$$

And the equations for this model are:

$$\underline{i}_{r,rms} = \underline{y}_{r,load} \cdot \underline{u}_{r,rms}$$
$$\underline{i}_{s,rms} = \underline{y}_{s,load} \cdot \underline{u}_{s,rms}$$
$$\underline{i}_{t,rms} = \underline{y}_{t,load} \cdot \underline{u}_{t,rms}$$

5.2.2 Load with Generation

Initialization:

$$\underline{y}_{r,load} = \frac{\underline{i}_{r,ldf}}{\underline{u}_{r,ldf}} - \frac{\underline{s}_{r,gen}}{\underline{u}_{r,ldf}^2}$$
$$\underline{y}_{s,load} = \frac{\underline{i}_{s,ldf}}{\underline{u}_{s,ldf}} - \frac{\underline{s}_{s,gen}}{\underline{u}_{s,ldf}^2}$$
$$\underline{y}_{t,load} = \frac{\underline{i}_{t,ldf}}{\underline{u}_{t,ldf}} - \frac{\underline{s}_{t,gen}}{\underline{u}_{t,ldf}^2}$$
$$i_{r,gen} = \left|-\underline{i}_{r,ldf} + \underline{y}_{r,load} \cdot \underline{u}_{r,ldf}\right|$$
$$i_{s,gen} = \left|-\underline{i}_{s,ldf} + \underline{y}_{s,load} \cdot \underline{u}_{s,ldf}\right|$$
$$i_{t,gen} = \left|-\underline{i}_{t,ldf} + \underline{y}_{t,load} \cdot \underline{u}_{t,ldf}\right|$$
$$phiui_{r,gen} = angle(\underline{u}_{r,ldf}) - angle(\underline{i}_{r,gen})$$
$$phiui_{s,gen} = angle(\underline{u}_{s,ldf}) - angle(\underline{i}_{s,gen})$$
$$phiui_{t,gen} = angle(\underline{u}_{t,ldf}) - angle(\underline{i}_{t,gen})$$

Equations:

$$\underline{i}_{r,rms} = (\underline{y}_{r,load} \cdot \underline{u}_{r,rms}) - |\underline{i}_{r,gen}| \cdot \big(cos(angle(\underline{u}_{r,rms}) - phiui_{r,gen}) + \jmath sin(angle(\underline{u}_{r,rms}) - phiui_{r,gen})\big)$$
$$\underline{i}_{s,rms} = (\underline{y}_{s,load} \cdot \underline{u}_{s,rms}) - |\underline{i}_{s,gen}| \cdot \big(cos(angle(\underline{u}_{s,rms}) - phiui_{s,gen}) + \jmath sin(angle(\underline{u}_{s,rms}) - phiui_{s,gen})\big)$$
$$\underline{i}_{t,rms} = (\underline{y}_{t,load} \cdot \underline{u}_{t,rms}) - |\underline{i}_{t,gen}| \cdot \big(cos(angle(\underline{u}_{t,rms}) - phiui_{t,gen}) + \jmath sin(angle(\underline{u}_{t,rms}) - phiui_{t,gen})\big)$$

5.2.3 3PH-D

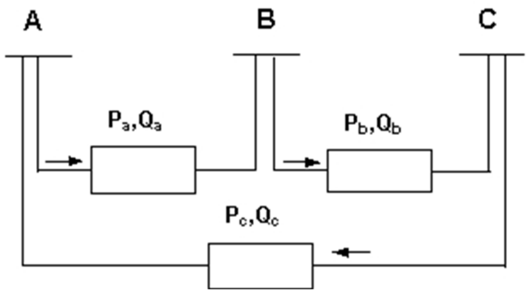

Figure 5.3: Load model used for unbalanced 3-phase Delta connection

The phase voltages for this model are calculated as follows:

$$
\begin{aligned}
u_r &= u_a - u_b \\
u_s &= u_b - u_c \\
u_t &= u_c - u_a
\end{aligned}
$$

The phase currents are calculated as:

$$
\begin{aligned}
i_r &= i_a - i_b \\
i_s &= i_b - i_c \\
i_t &= i_c - i_a
\end{aligned}
$$

5.2.4 3PH PH-E

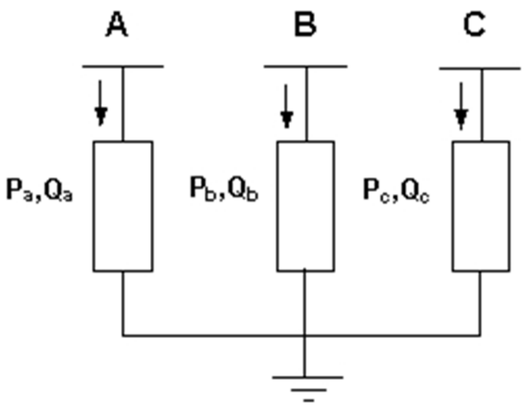

Figure 5.4: Load model used for unbalanced 3-phase PH-E connection

The voltages for this model are calculated as follows:

$$u_r = u_a$$
$$u_s = u_b$$
$$u_t = u_c$$

The phase currents are calculated as:

$$i_r = i_a$$
$$i_s = i_b$$
$$i_t = i_c$$

If the load has a distribution transformer type assigned, then the voltages are:

$$u_r = u_a - u_0$$
$$u_s = u_b - u_0$$
$$u_t = u_c - u_0$$

$$i_r = i_a - i_0$$
$$i_s = i_b - i_0$$
$$i_t = i_c - i_0$$

5.2.5 3PH-'YN'

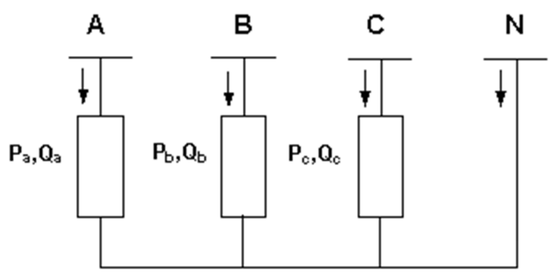

Figure 5.5: Load model used for unbalanced 3-phase YN connection

The voltages for this model are calculated as follows:

$$u_r = u_a - u_n$$
$$u_s = u_b - u_n$$
$$u_t = u_c - u_n$$

$$\begin{aligned} i_r &= i_a \\ i_s &= i_b \\ i_t &= i_c \end{aligned}$$

If the load has a distribution transformer type assigned, then the voltages are:

$$\begin{aligned} u_r &= u_a - u_n - u_0 \\ u_s &= u_b - u_n - u_0 \\ u_t &= u_c - u_n - u_0 \end{aligned}$$

$$\begin{aligned} i_r &= i_a - i_0 \\ i_s &= i_b - i_0 \\ i_t &= i_c - i_0 \end{aligned}$$

6 EMT Simulation

A constant admittance model is used. Generation is ignored.

7 Harmonics

7.1 Impedance Model

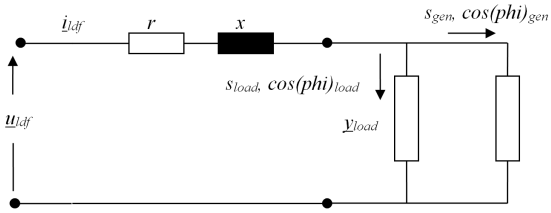

Figure 7.1: Harmonics: Impedance model

The load admittance is calculated from the load flow analysis results:

$$\underline{y}_{load} = \frac{\underline{i}_{ldf}}{\underline{u}_{ldf}} - \frac{s_{gen}}{\underline{u}_{ldf}^2}$$

7.1.1 Purely Inductive

If the imaginary part of $\underline{y}_{load}$ is negative, the load is modelled as an inductive load:

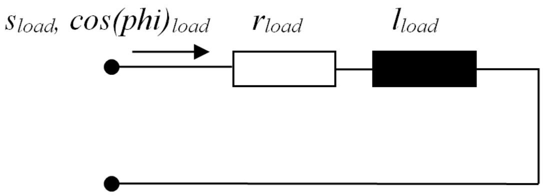

Figure 7.2: Harmonics: Impedance model, Purely Inductive

with:

$$r_{load} = \Re\left\{\frac{1}{\underline{y}_{load}}\right\}$$
$$l_{load} = \frac{\Im\left\{\frac{1}{\underline{y}_{load}}\right\}}{2\pi f_{nom}}$$

7.1.2 Purely Capacitive

If the imaginary part of $\underline{y}_{load}$ is positive, the load is modelled as a capacitive load:

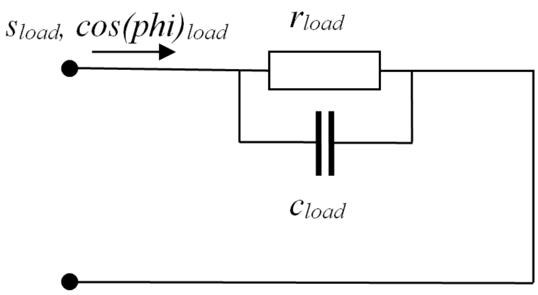

Figure 7.3: Harmonics: Impedance model, Purely Capacitive

with:

$$r_{load} = \Re\left\{\frac{1}{\underline{y}_{load}}\right\}$$
$$c_{load} = \frac{\Im\left\{\underline{y}_{load}\right\}}{2\pi f_{nom}}$$

7.1.3 Mixed Inductive/Capacitive

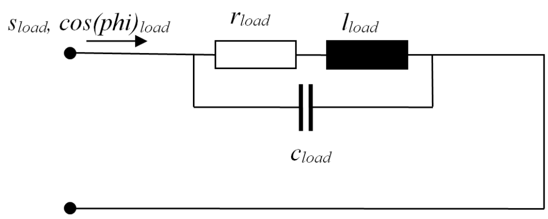

Figure 7.4: Harmonics: Impedance model, Mixed Inductive/Capacitive

with:

$$
\begin{aligned}
c_{load} &= \frac{\Im\left\{\underline{y}_{load}\right\}}{(1-ppgrd)\cdot 2\pi f_{nom}} \\
\underline{z}_{rea} &= \frac{1}{\Re\{\underline{y}_{load}\} - \jmath\dfrac{\Im\{\underline{y}_{load}\}\cdot ppgrd}{1-ppgrd}} \\
r_{load} &= \Re\{\underline{z}_{rea}\} \\
l_{load} &= \frac{\Im\{\underline{z}_{rea}\}}{2pif_{nom}}
\end{aligned}
$$

7.2 Current Source Model

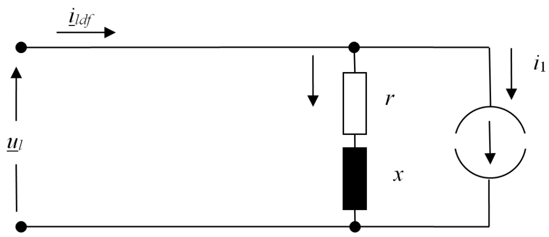

Figure 7.5: Harmonics: Current Source Model

Initialization:

$$\underline{i}_1 = \underline{i}_{ldf} - \underline{u}_{ldf}\cdot \underline{y}_1$$

Equation:

$$\underline{i} = \underline{y}_1 \cdot \underline{u} + \underline{i}_1$$

List of Figures