POWERFACTORY

PowerFactory 2021

Technical Reference

Harmonic Filter

ElmFilter

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

The following filter topologies are supported in all calculation functions:

- Single-tuned
- High-pass Second order
- High-pass Third order
- High-pass C-type
- Double-tuned type 1
- Double-tuned type 2
- Double-tuned type 3
- Double-tuned type 4

For all filter types it is possible to enter parameter data either as design or layout parameters. Each reactor is modelled as an inductance in series with a resistance.

In load flow calculations and RMS simulations, the harmonic filter is represented with its impedance at nominal frequency. In harmonics calculations it is possible to specify frequency dependency of the filter parameters.

The single-tuned, second-order and C-type high-pass topologies are also available in the Shunt/Filter element *ElmShnt*.

All the internal p.u. voltages and fluxes available as result variables (such as p.u. voltage/flux of an inductor or p.u. voltage of a capacitor) are based on the busbar nominal voltage $U_{bus,nom}$, and not on the filter element rated voltage. All internal p.u. currents available as result variables (such as p.u. current through an inductor or resistor) are based on the following base current:

$$I_{base} = \frac{1MVA}{\sqrt{3} \cdot U_{bus,nom}}$$

In case of single phase filters (technology: 1PH PH-N and 1PH PH-E) the base of p.u. voltages is the corresponding line-ground voltage of the busbar (for system type AC/BI: $U_{bus,nom}/2$).

1.1 Technology

The connection technologies shown in Figures 1.1, 1.2 and 1.3 are available for all the filter types. For the 3PH-'YN', 2PH-'YN' and 1PH-'PH-N' technology, the neutral conductor can be connected either to the neutral of the terminal where the filter is connected or to a separate terminal. For the 3PH-'YN' and 2PH-'YN' technology it is possible to configure the star point as 'connected', i.e. grounded through an internal grounding impedance with resistance *Re* and reactance *Xe*, or if the star point is 'disconnected', i.e isolated star point. Filters with 2PH-'Y' or 1PH PH-PH technology should not be connected to neutral.

The p.u. voltages across inductors, capacitors and parallel resistors available as result variables are referred to the base voltages specified in Table 1.1 depending on the filter technology. These base voltages always refer to the connected terminal and not to the filter rated voltage.

Table 1.1: Base voltages according to filter technology

Technology	Base voltage
3PH-'D'	Terminal Line-Line nominal voltage
3PH-'Y'	Terminal Line-ground nominal voltage
3PH-'YN'	Terminal Line-ground nominal voltage
2PH-'Y'	Terminal Line-ground nominal voltage
2PH-'YN'	Terminal Line-ground nominal voltage
1PH PH-PH	Terminal Line-Line nominal voltage
1PH PH-N	Terminal Line-ground nominal voltage
1PH PH-E	Terminal Line-ground nominal voltage

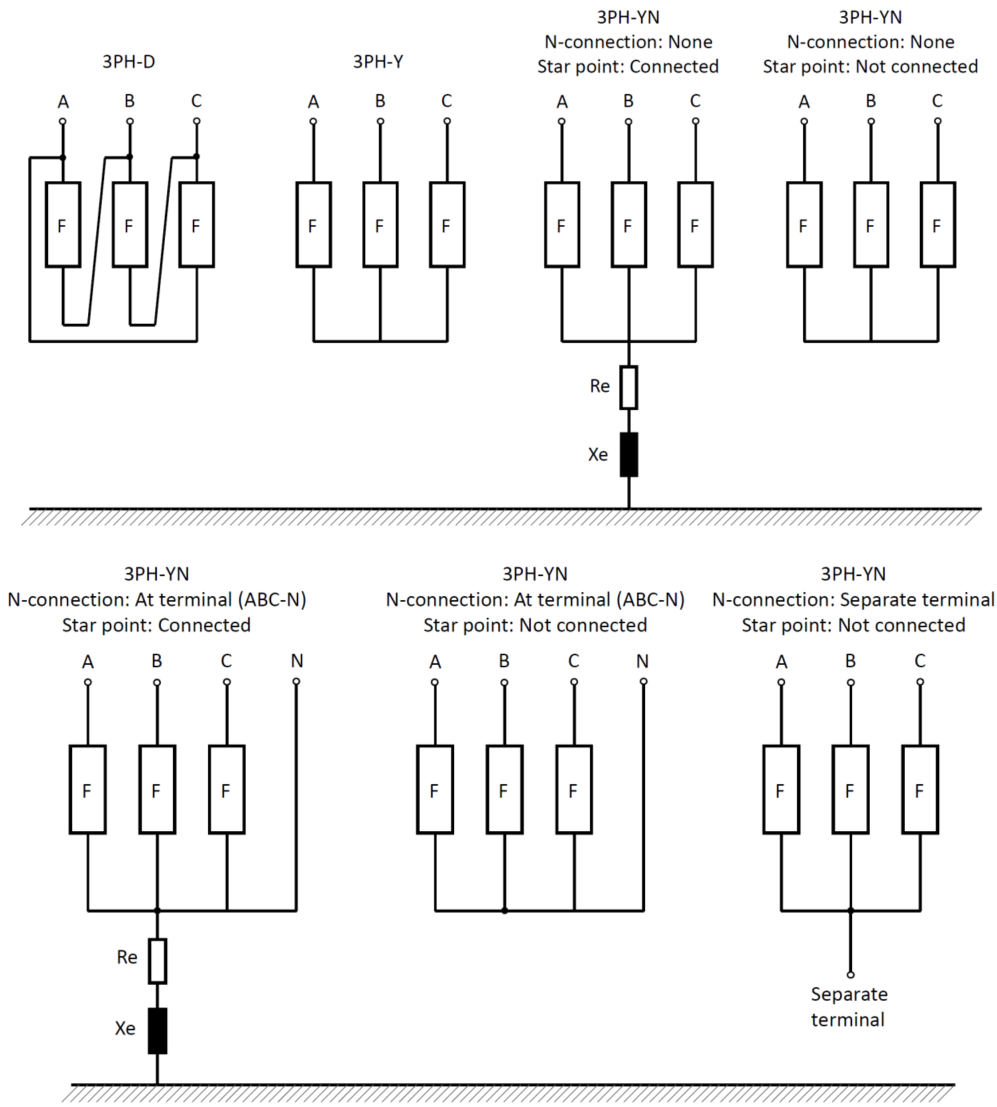

Figure 1.1: 3PH connection technology

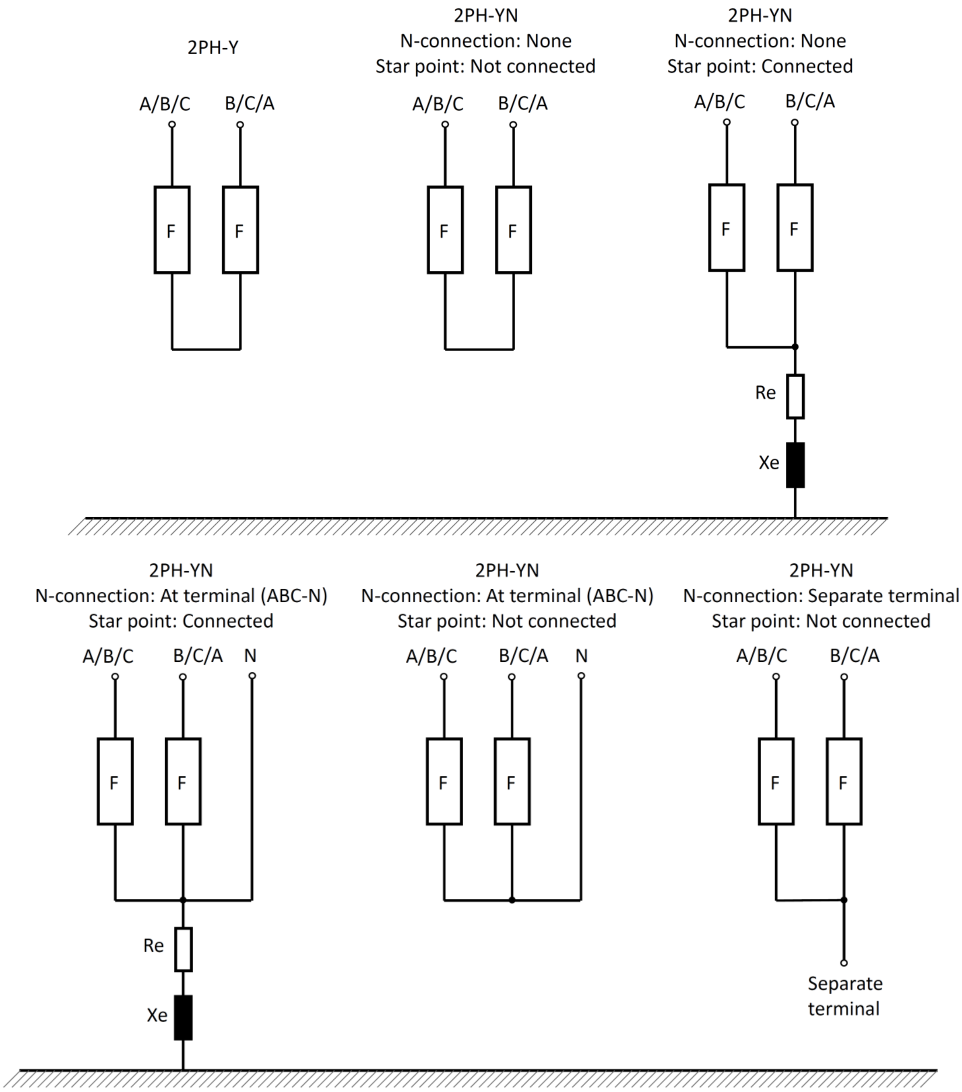

Figure 1.2: 2PH connection technology

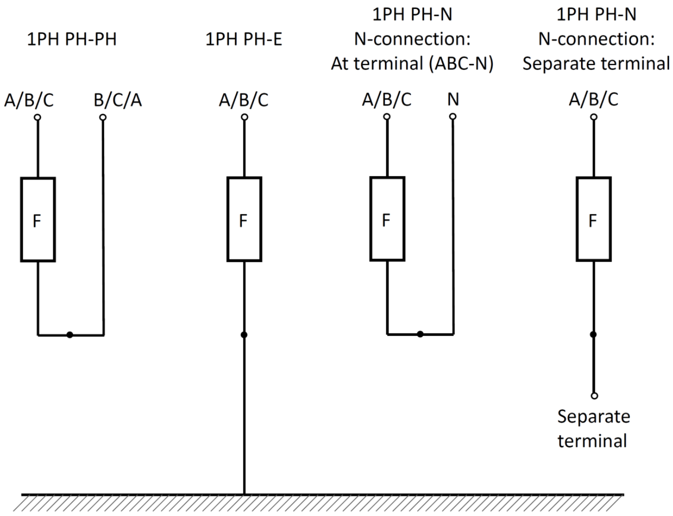

Figure 1.3: 1PH connection technology

1.2 Single-tuned Filter

The basic configuration of the single-tuned filter is shown in Figure 1.4.

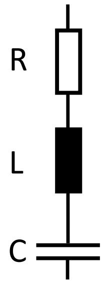

Figure 1.4: Single-tuned filter

Design filter parameters are entered as rated reactive power Q_{tot} at nominal frequency (in Mvar), resonance frequency (in Hz) or tuning order, quality factor.

Layout parameters are entered as inductance L (in mH), capacitance C (in μF) and resistance R (in Ohm).

1.2.1 Common Relations

Resonance Frequency f_{res}

The filter resonance frequency is calculated as:

$$f_{res} = \frac{1}{2 \cdot \pi \cdot \sqrt{L \cdot 10^{-3} \cdot C \cdot 10^{-6}}} \qquad \text{in Hz}$$

L: Inductance in mH
C: Capacitance in μF

Relation between Inductance L, Resonance Frequency f_{res} and Capacitance C

The inductance L can be calculated according to following equation:

$$L = \frac{10^3}{(2 \cdot \pi \cdot f_{res})^2 \cdot C \cdot 10^{-6}} \qquad \text{in mH}$$

C: Capacitance in μF
f_{res}: Resonance Frequency in Hz

Relation between Resonance Frequency and Tuning Order

$$n_{res} = \frac{f_{res}}{f_{nom}}$$

f_{nom}: Nominal frequency in Hz
f_{res}: Resonance frequency in Hz
n_{res}: Tuning order

Quality Factor (QF) Definition

$$QF = \frac{2 \cdot \pi \cdot f_{res} \cdot L \cdot 10^{-3}}{R}$$

Rated Capacitive Power Q_{cap}

Define the susceptance B_{cap} in S as:

$$B_{cap} = 2 \cdot \pi \cdot f_{nom} \cdot C \cdot 10^{-6}$$

where C is in µF.

Depending on the technology, the rated voltage (U_r) and the phase system of the terminal, the rated capacitive power in Mvar can be calculated as:

<u>3PH-'D'</u>

$$Q_{cap} = 3 \cdot B_{cap} \cdot U_r^2$$

<u>3PH-'Y' or 3PH-'YN'</u>

$$Q_{cap} = B_{cap} \cdot U_r^2$$

<u>2PH-'Y'</u>

$$Q_{cap} = \frac{1}{2} \cdot B_{cap} \cdot U_r^2$$

<u>2PH-'YN' with *AC* system type</u>

$$Q_{cap} = 2 \cdot B_{cap} \cdot (U_r/\sqrt{3})^2 = \frac{2}{3} \cdot B_{cap} \cdot U_r^2$$

<u>2PH-'YN' with *AC/BI* system type</u>

$$Q_{cap} = 2 \cdot B_{cap} \cdot (U_r/2)^2 = \frac{1}{2} \cdot B_{cap} \cdot U_r^2$$

<u>1PH PH-PH</u>

$$Q_{cap} = B_{cap} \cdot U_r^2$$

<u>1PH PH-N or 1PH PH-E with *AC* system type</u>

$$Q_{cap} = B_{cap} \cdot (U_r/\sqrt{3})^2 = \frac{1}{3} \cdot B_{cap} \cdot U_r^2$$

<u>1PH PH-N or 1PH PH-E with *AC/BI* system type</u>

$$Q_{cap} = B_{cap} \cdot (U_r/2)^2 = \frac{1}{4} \cdot B_{cap} \cdot U_r^2$$

where

U_r: ‘Rated line-line voltage’ in kV ($U_r = ufltnom$)
Q_{cap}: ‘Rated capacitive reactive power’ in Mvar

Rated Reactive Power Q_{tot}

The relation between rated reactive power and rated capacitive power is:

$$Q_{tot} = Q_{cap} \cdot \left(\frac{n_{res}^2}{n_{res}^2 - 1} \right) = Q_{cap} \cdot \left(\frac{f_{res}^2}{f_{res}^2 - f_{nom}^2} \right) \qquad \text{in Mvar}$$

Q_{tot}: ‘Rated reactive power’ in Mvar
f_{nom}: Nominal frequency in Hz
f_{res}: Resonance frequency in Hz
n_{res}: Tuning order

1.3 High-pass Second order Filter

The basic configuration of the High-pass Second order filter is shown in Figure 1.5.

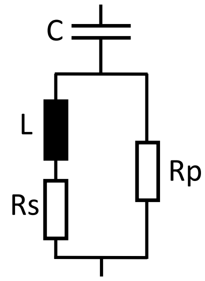

Figure 1.5: High-pass Second order filter

The filter impedance is predominantly resistive at high frequencies and approaches Rp as the frequency increases.

Design filter parameters are entered as rated reactive power Q_{tot} at nominal frequency (in Mvar), resonance frequency (in Hz) or tuning order, quality factor.

Layout parameters are entered as inductance L (in mH), capacitance C (in μF) and resistances Rs and Rp (in Ohm).

The resistance Rs, in series with the inductor, can be entered in the layout parameter frame in Ohm independently of the input option. By default, the series resistance Rs is equal to zero.

The parallel resistance Rp is not considered if it is defined as equal to zero ($Rp = 0$). The branch is then considered open, i.e. the corresponding conductance Gp is equal to zero ($Gp = 0$).

All common relations, with the exception of the quality factor, are similar/equal to those used by the Single-tuned filter, see section 1.2.1.

Differently from the Single-tuned filter, for the high-pass filters the quality factor is defined according to the literature [1] as:

$$QF = \frac{Rp}{2 \cdot \pi \cdot f_{res} \cdot L \cdot 10^{-3}}$$

1.4 High-pass Third order Filter

The basic configuration of the High-pass Third order filter is shown in Figure 1.6.

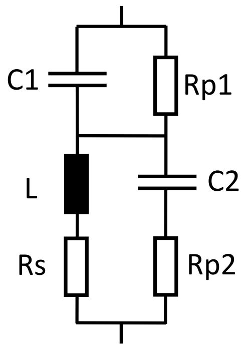

Figure 1.6: High-pass Third order filter

The filter impedance is predominantly resistive at high frequencies and approaches $Rp2$ as the frequency increases. This filter has lower power losses than the High-pass Second order filter at fundamental frequency because of the high impedance due to capacitor $C2$ in series with $Rp2$ [1].

Design filter parameters are entered as rated reactive power Q_{tot} at nominal frequency (in Mvar), resonance frequency (in Hz) or tuning order, quality factor. In this case, layout parameters are calculated assuming $C1$ and $C2$ to be equal.

Layout parameters are entered as inductance L (in mH), capacitances $C1$ and $C2$ (in μF) and resistances Rs, $Rp1$ and $Rp2$ (in Ohm).

The resistances Rs and $Rp1$ can be entered in the layout parameter frame in Ohm independently of the input option. By default, the series resistance Rs is equal to zero. The parallel resistance $Rp1$ is not considered if it is defined as equal to zero ($Rp1 = 0$). The branch is then considered open, i.e. the corresponding conductance $Gp1$ is equal to zero ($Gp1 = 0$).

All common relations are similar/equal to those used by the Single-tuned filter, see section 1.2.1.

The quality factor is defined as:

$$QF = \frac{Rp}{2 \cdot \pi \cdot f_{res} \cdot L \cdot 10^{-3}}$$

1.5 High-pass C-type Filter

The basic configuration of the High-pass C-type filter is shown in Figure 1.7.

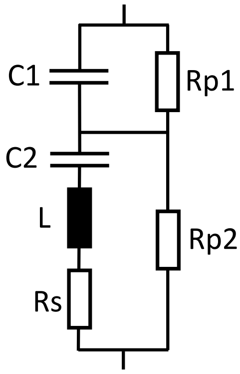

Figure 1.7: High-pass C-type filter

The arm $C2$-L is tuned at fundamental frequency, bypassing the resistor $Rp2$ and thus reducing losses at fundamental frequency as compared to a High-pass Second order filter [1].

Design filter parameters are entered as rated reactive power Q_{tot} at nominal frequency (in Mvar), resonance frequency (in Hz) or tuning order, quality factor.

Layout parameters are entered as inductance L (in mH), capacitance C (in μF) and resistances Rs, $Rp1$ and $Rp2$ (in Ohm).

The resistances Rs and $Rp1$ can be entered in the layout parameter frame in Ohm independently of the input option. By default, the series resistance Rs is equal to zero.

The parallel resistances $Rp1$ and $Rp2$ are not considered if defined as equal to zero (e.g. $Rp1 = 0$). The branch is then considered open, i.e. the corresponding conductance is equal to zero (e.g. $Gp1 = 0$).

All common relations are similar/equal to those used by the Single-tuned filter, see section 1.2.1.

The quality factor is defined as:

$$QF = \frac{Rp}{2 \cdot \pi \cdot f_{res} \cdot L \cdot 10^{-3}}$$

1.6 Double-tuned filter

Four double-tuned filter topologies are available in *PowerFactory*. Filter parameters can be specified as layout or design parameters. The next section describes the relationship between layout and design parameters for a double-tuned filter.

1.6.1 Double-tuned filter parameters

Given the design parameters, the layout parameters $L1$, $L2$, $C1$ and $C2$ of the double-tuned filter are calculated according to [1]. Since near the resonance frequencies the double-tuned filter is practically equivalent to two single-tuned filters in parallel, the double-tuned filter parameters can be calculated if the single-tuned filters parameters are known.

The L and C parameters of each single-tuned filter (of "R-L-C" type) can be determined assuming that the two single-tuned filters share equally the rated reactive power of the double-tuned filter and that each single-tuned filter is tuned to one of the two resonance frequencies of the double-tuned filter. If subscripts a and b refer to the two single-tuned filters, the double-tuned filter parameters are calculated given the single-tuned filter parameters as:

$$C1 = C_a + C_b$$

$$C2 = \frac{C_a \cdot C_b \cdot (C_a + C_b) \cdot (L_a + L_b)^2}{(L_a \cdot C_a - L_b \cdot C_b)^2}$$

$$L1 = \frac{L_a \cdot L_b}{L_a + L_b}$$

$$L2 = \frac{(L_a \cdot C_a - L_b \cdot C_b)^2}{(C_a + C_b)^2 \cdot (L_a + L_b)}$$

The resistances $Rp1$ and $Rp2$ are then calculated, given the inductances $L1$ and $L2$, the mean geometric frequency f_{mean} and the quality factors $QF1$ and $QF2$.

If instead layout parameters are specified for the double-tuned filter, the design parameters are calculated under the assumption that the filter is lossless. The two resonance frequencies of the filter are calculated by solving the equation (obtained by equating the total frequency-dependent filter impedance to zero):

$$\omega^4 \cdot (L1 \cdot L2 \cdot C1 \cdot C2) - \omega^2 \cdot (L2 \cdot C1 + L1 \cdot C1 + L2 \cdot C2) + 1 = 0$$

The nominal reactive power Q_{tot} of the filter is calculated as:

$$Q_{tot} = \frac{U_r^2}{|\underline{Z}|}$$

where

$$\underline{Z} = j \cdot (\omega_{nom} \cdot L1 - \frac{1}{\omega_{nom} \cdot C1}) + \frac{L2/C2}{j \cdot (\omega_{nom} \cdot L2 - \frac{1}{\omega_{nom} \cdot C2})}$$

1.6.2 Double-tuned type 1 Filter

The basic configuration of the Double-tuned type 1 filter is shown in Figure 1.8.

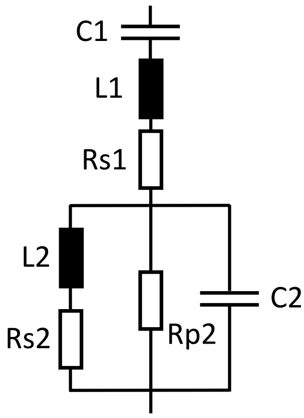

Figure 1.8: Double-tuned type 1 filter

Design filter parameters are entered as rated reactive power Q_{tot} at nominal frequency (in Mvar), filter resonance frequencies (in Hz) or tuning orders, quality factor for parallel branch $L2$-$Rp2$ at mean geometric frequency.

Layout parameters are entered as inductances $L1$ and $L2$ (in mH), capacitances $C1$ and $C2$ (in μF) and resistances $Rp2$, $Rs1$ and $Rs2$ (in Ohm).

The series resistances $Rs1$ and $Rs2$ can be entered in the layout parameter frame in Ohm independently of the input option. By default, the series resistances $Rs1$ and $Rs2$ are equal to zero.

The parallel resistance $Rp2$ is not considered if it is defined as equal to zero ($Rp2 = 0$). The branch is then considered open, i.e. the corresponding conductance is equal to zero ($Gp2 = 0$).

The quality factor is defined according to the following equations:

$$f_{mean} = \sqrt{f_{res1} \cdot f_{res2}}$$

$$QF2 = \frac{Rp2}{2 \cdot \pi \cdot f_{mean} \cdot L2}$$

The layout parameters are calculated given the design parameters according to section 1.6.1.

1.6.3 Double-tuned type 2 Filter

The basic configuration of the Double-tuned type 2 filter is shown in Figure 1.9.

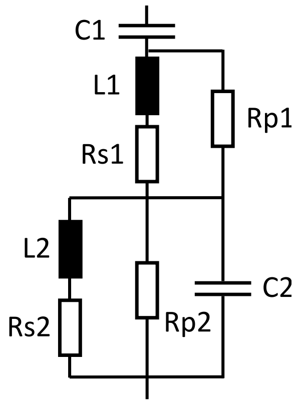

Figure 1.9: Double-tuned fype 2 filter

Design filter parameters are entered as rated reactive power Q_{tot} at nominal frequency (in Mvar), filter resonance frequencies (in Hz) or tuning orders, quality factors for parallel branch $L1$-$Rp1$ and for parallel branch $L2$-$Rp2$ at mean geometric frequency.

Layout parameters are entered as inductances $L1$ and $L2$ (in mH), capacitances $C1$ and $C2$ (in μF) and resistances $Rp1$, $Rp2$, $Rs1$ and $Rs2$ (in Ohm).

The series resistances $Rs1$ and $Rs2$ can be entered in the layout parameter frame in Ohm independently of the input option. By default, the series resistances $Rs1$ and $Rs2$ are equal to zero.

The parallel resistances $Rp1$ and $Rp2$ are not considered if defined as equal to zero ($Rp1 = 0$ or $Rp2 = 0$). The corresponding branch is then considered open, i.e. the corresponding conductances are equal to zero ($Gp1 = 0$ or $Gp2 = 0$).

The quality factors are defined according to the following equations:

$$f_{mean} = \sqrt{f_{res1} \cdot f_{res2}}$$

$$QF1 = \frac{Rp1}{2 \cdot \pi \cdot f_{mean} \cdot L1}$$

$$QF2 = \frac{Rp2}{2 \cdot \pi \cdot f_{mean} \cdot L2}$$

The layout parameters are calculated given the design parameters according to section 1.6.1.

1.6.4 Double-tuned type 3 Filter

The basic configuration of the Double-tuned type 3 filter is shown in Figure 1.10.

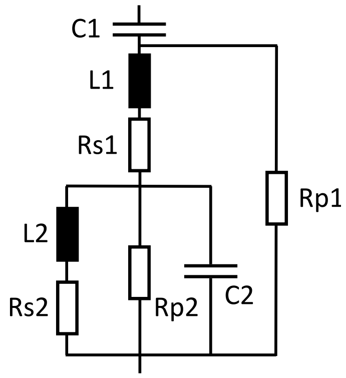

Figure 1.10: Double-tuned type 3 filter

Design filter parameters are entered as rated reactive power Q_{tot} at nominal frequency (in Mvar), filter resonance frequencies (in Hz) or tuning orders, quality factor for parallel branch $L2$-$Rp2$ at mean geometric frequency, resistance $Rp1$ in Ohm.

Layout parameters are entered as inductances $L1$ and $L2$ (in mH), capacitances $C1$ and $C2$ (in μF) and resistances $Rp1$, $Rp2$, $Rs1$ and $Rs2$ (in Ohm).

The series resistances $Rs1$ and $Rs2$ can be entered in the layout parameter frame in Ohm independently of the input option. By default, the series resistances $Rs1$ and $Rs2$ are equal to zero.

The parallel resistances $Rp1$ and $Rp2$ are not considered if defined as equal to zero ($Rp1 = 0$ or $Rp2 = 0$). The corresponding branch is then considered open, i.e. the corresponding conductances are equal to zero ($Gp1 = 0$ or $Gp2 = 0$).

The quality factor for the parallel branch $L2$-$Rp2$ is defined according to the following equations:

$$f_{mean} = \sqrt{f_{res1} \cdot f_{res2}}$$

$$QF2 = \frac{Rp2}{2 \cdot \pi \cdot f_{mean} \cdot L2}$$

The layout parameters are calculated given the design parameters according to section 1.6.1.

1.6.5 Double-tuned type 4 Filter

The basic configuration of the Double-tuned type 4 filter is shown in Figure 1.11.

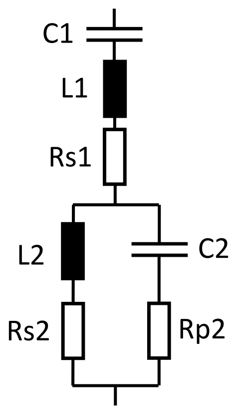

Figure 1.11: Double-tuned type 4 filter

Design filter parameters are entered as rated reactive power Q_{tot} at nominal frequency (in Mvar), filter resonance frequencies (in Hz) or tuning orders, quality factor for parallel branch $L2$-$Rp2$ at mean geometric frequency.

Layout parameters are entered as inductances $L1$ and $L2$ (in mH), capacitances $C1$ and $C2$ (in μF) and resistances $Rp2$, $Rs1$ and $Rs2$ (in Ohm).

The series resistances $Rs1$ and $Rs2$ can be entered in the layout parameter frame in Ohm independently of the input option. By default, the series resistances $Rs1$ and $Rs2$ are equal to zero.

The quality factor for the parallel branch $L2$-$Rp2$ is defined according to the following equations:

$$f_{mean} = \sqrt{f_{res1} \cdot f_{res2}}$$

$$QF2 = \frac{Rp2}{2 \cdot \pi \cdot f_{mean} \cdot L2}$$

The layout parameters are calculated given the design parameters according to section 1.6.1.

2 Load Flow Analysis

2.1 Calculation Quantities

The following calculation quantities are available. The indexes ”1” or ”2” should be added to get the corresponding quantities for components C1, C2, L1, L2, Rp1 and Rp2: For example, Uc is the voltage across capacitor C for a Single-tuned or High-pass Second order filter, while $Uc1$ and $Uc2$ are the corresponding voltages over the capacitors C1 and C2 for a Double-tuned filter. In the same way, $Urlph$ is the voltage (phase value) across inductor L for a Single-tuned or High-pass Second order filter, while $Url1ph$ and $Url2ph$ are the corresponding voltages across the inductors L1 and L2 for a Double-tuned filter. Note: only for the High-pass Third order and C-type filter the variable Uc represents the sum voltage over cacacitors C1 and C2.

2.1.1 Detailed Quantities

The p.u. voltage of the detailed quantities are based either on

- U_{ph-ph}, nominal line-line voltage of the connected busbar
- U_{ph-e}, nominal line-ground voltage of the connected busbar

Balanced load flow

Table 2.1: Detailed quantities for balanced load flow

Quantity	Unit	Description	Comment
uc	$p.u.$	Voltage across Capacitor	Only for High-pass Third order and C-type, total voltage over capacitor C1 and C2. Based on U_{ph-ph} for D-connections or U_{ph-e} for Y/YN-connections
Uc	kV	Voltage across Capacitor	Only for High-pass Third order and C-type, total voltage over capacitor C1 and C2
IL	A	Current through Inductor L	
IC	A	Current through Capacitor C	
IRp	A	Current through Rp	
PRp	kW	Losses in Rp	
PL	kW	Losses in Inductor (Rs)	
url	$p.u.$	Voltage across Inductor (Rs-L)	based on U_{ph-ph} for D-connections or U_{ph-e} for Y/YN-connections
Url	kV	Voltage across Inductor (Rs-L)	

Unbalance load flow

Table 2.2: Detailed quantities for unbalanced load flow

Quantity	Unit	Description	Comment
$ucph$	$p.u.$	Voltage across Capacitor (Phase Value)	Only for High-pass Third order and C-type, total voltage over capacitor C1 and C2. Based on U_{ph-ph} for D-connections or U_{ph-e} for Y/YN-connections
$Ucph$	kV	Voltage across Capacitor (Phase Value)	Only for High-pass Third order and C-type, total voltage over capacitor C1 and C2
$ILph$	A	Current through Inductor L (Phase Value)	
$ICph$	A	Current through Capacitor C (Phase Value)	
$IRpph$	A	Current through Rp (Phase Value)	
$urlph$	$p.u.$	Voltage across Inductor (Phase Value)	based on U_{ph-ph} for D-connections or U_{ph-e} for Y/YN-connections
$Urlph$	kV	Voltage across Inductor (Phase Value)	
uc	$p.u.$	Voltage across Capacitor (max abc)	Max. of all phase, $ucph$ Only for High-pass Third order and C-type, total voltage over capacitor C1 and C2
Uc	kV	Voltage across Capacitor (max abc)	Max. of all phase, $Ucph$ Only for High-pass Third order and C-type, total voltage over capacitor C1 and C2
IL	A	Current through Inductor (max abc)	Max. of all phase, $ILph$
IC	A	Current through Capacitor (max abc)	Max. of all phase, $ICph$
IRp	A	Current through Rp (max abc)	Max. of all phase, $IRpph$
url	$p.u.$	Voltage across Inductor (max abc)	Max. of all phase, url
Url	kV	Voltage across Inductor (max abc)	Max. of all phase, Url
PRp	kW	Losses in Rp	
PL	kW	Losses in Inductor (Rs)	

2.1.2 Losses

The active power flow of a filter, due to its resistances, is equal to the $Ploss$.

Table 2.3: Losses Quantities

Quantity	Unit	Description	Value
$Ploss$	MW	Losses (total)	$= P$
$Qloss$	$Mvar$	Reactive-Losses (total)	$= 0$
$Plossld$	MW	Losses (load)	$= Ploss - Plossnld$
$Qlossld$	$Mvar$	Reactive-Losses (load)	$= Qloss - Qlossnld$
$Plossnld$	MW	Losses (no load)	$= 0$
$Qlossnld$	$Mvar$	Reactive-Losses (no load)	$= 0$

3 Harmonics/Power Quality

3.1 Parameter Frequency Depencency

Frequency-dependent characteristics may be defined for the parameters as listed in the following subsections.

Note: For absolute characteristics, the values defined in the element (not in the characteristic) will be used at the fundamental frequency.

3.1.1 Single-tuned Filter

Frequency-dependent parameters may optionally be defined for the following parameters (parameter names follow in parentheses): R ($rsrea$), L ($lrea$) and C ($ccap$).

3.1.2 High-pass Second order Filter

Frequency-dependent parameters may optionally be defined for the following parameters (parameter names follow in parentheses): Rs ($rsrea$), L ($lrea$), C ($ccap$) and Rp ($rpara$).

3.1.3 High-pass Third order Filter

Frequency-dependent parameters may optionally be defined for the following parameters (parameter names follow in parentheses): Rs ($rsrea$), L ($lrea$), C1 ($c1$), C2 ($c2$), Rp1 ($rp1$) and Rp2 ($rp2$).

3.1.4 High-pass C-type Filter

Frequency-dependent parameters may optionally be defined for the following parameters (parameter names follow in parentheses): Rs ($rsrea$), L ($lrea$), C1 ($c1$), C2 ($c2$), Rp1 ($rp1$) and Rp2 ($rp2$).

3.1.5 Double-tuned type 1 filter

Frequency-dependent parameters may optionally be defined for the following parameters (parameter names follow in parentheses): Rs1 ($rs1$), L1 ($l1$), C1 ($c1$), Rs2 ($rs2$), L2 ($l2$), C2 ($c2$) and Rp2 ($rp2$).

3.1.6 Double-tuned type 2 filter

Frequency-dependent parameters may optionally be defined for the following parameters (parameter names follow in parentheses): Rs1 ($rs1$), L1 ($l1$), Rp1 ($rp1$), C1 ($c1$), Rs2 ($rs2$), L2 ($l2$), C2 ($c2$) and Rp2 ($rp2$).

3.1.7 Double-tuned type 3 filter

Frequency-dependent parameters may optionally be defined for the following parameters (parameter names follow in parentheses): Rs1 ($rs1$), L1 ($l1$), C1 ($c1$), Rs2 ($rs2$), L2 ($l2$) C2 ($c2$), Rp2 ($rp2$) and Rp1 ($rp1$).

3.1.8 Double-tuned type 4 filter

Frequency-dependent parameters may optionally be defined for the following parameters (parameter names follow in parentheses): Rs1 ($rs1$), L1 ($l1$), C1 ($c1$), Rs2 ($rs2$), L2 ($l2$) C2 ($c2$) and Rp2 ($rp2$).

3.2 Result Variables

Different quantities relevant to harmonics calculations are available for each inductor, capacitor and parallel resistor as result variables. As an example, for inductor L the following result variables are defined:

- *url* (p.u.), Voltage across Inductor L (value at the output frequency)
- *ufn_rl* (p.u.), Fundamental Frequency Voltage across Inductor L (Rs-L)
- *uhrms_rl* (p.u.), Harmonic Voltage (rms) across Inductor L (Rs-L)
- *uha_rl* (p.u.), Harmonic Voltage (arith.) across Inductor L (Rs-L)
- *ut_rl* (p.u.), Total Voltage (u_fn+uhrms) across Inductor L (Rs-L)
- *Url* (kV), Voltage across Inductor L (value at the output frequency)
- *Ufn_rl* (kV), Fundamental Frequency Voltage across Inductor L (Rs-L)
- *Uhrms_rl* (kV), Harmonic Voltage (rms) across Inductor L (Rs-L)
- *Uha_rl* (kV), Harmonic Voltage (arith.) across Inductor L (Rs-L)
- *Ut_rl* (kV), Total Voltage (U_fn+Uhrms) across Inductor L (Rs-L)
- *IL* (A), Current through Inductor L (value at the output frequency)
- *Ifn_L* (A), Fundamental Frequency Current through Inductor L (Rs-L)
- *Ihrms_L* (A), Harmonic Current (rms) through Inductor L (Rs-L)
- *Irms_L* (A), RMS Value of Current through Inductor L (Rs-L)
- *PL* (kW), Losses in Inductor (Rs) (value at the output frequency)
- *Pfn_L* (kW), Fundamental Frequency Losses of Inductor (Rs)
- *Ph_L* (kW), Harmonic Losses of Inductor (Rs)
- *Pt_L* (kW), Total Losses of Inductor (Rs)

The *ufn_rl*, *Ufn_rl*, *Pfn_rl* and *Ifn_rl* parameters are the voltage, power and current values at fundamental frequency.

The *url*, *Url*, *PL* and *IL* parameters are the voltage, power and current values at the selected output frequency.

The remaining parameters are calculated as:

$$uhrms\_rl = \sqrt{\sum_{k=2}^{n} {url_k}^2}$$
$$uha\_rl = \sum_{k=2}^{n} url_k$$
$$ut\_rl = ufn\_rl + uhrms\_rl$$

$$Uhrms\_rl = \sqrt{\sum_{k=2}^{n} {Url_k}^2}$$
$$Uha\_rl = \sum_{k=2}^{n} Url_k$$
$$Ut\_rl = Ufn\_rl + Uhrms\_rl$$

$$Ihrms\_L = \sqrt{\sum_{k=2}^{n} {IL_k}^2}$$
$$Irms\_L = \sqrt{Ifn\_L^2 + Ihrms\_L^2}$$

$$Ph\_L = \sum_{k=2}^{n} PL_k$$
$$Pt\_L = Pfn\_L + Ph\_L$$

where n is the total number of harmonics which are being considered and the subscript k refers to the k_{th} harmonic.

4 References

[1] J. Arrillaga, N.R. Watson *Power System Harmonics*, Wiley, 2003.

List of Figures