MAKING MODERN LIVING POSSIBLE

Output Filters Design Guide

VLT® AutomationDrive FC 300
VLT® AQUA Drive FC 200
VLT® HVAC Drive FC 100

THE REAL DRIVE

3 Introduction to Output Filters

3.1 Why use Output Filters

This chapter describes why and when to use Output Filters with Danfoss frequency converters. It is divided into 4 sections:

- Protection of Motor Insulation
- Reduction of Motor Acoustic Noise
- Reduction of High Frequency Electromagnetic Noise in Motor Cable
- Bearing currents and shaft voltage

3.2 Protection of Motor Insulation

3.2.1 The Output Voltage

The output voltage of the frequency converter is a series of trapezoidal pulses with a variable width (pulse width modulation) characterized by a pulse rise-time t_r.

When a transistor in the inverter switches, the voltage across the motor terminal increases by a dU/dt ratio that depends on:

- the motor cable (type, cross-section, length, screened or unscreened, inductance and capacitance)
- the high frequency surge impendance of the motor

Because of the impedance mismatch between the cable characteristic impedance and the motor surge impedance a wave reflection occurs, causing a ringing voltage overshoot at the motor terminals - see *Illustration 3.1*. The motor surge impedance decreases with the increase of motor size resulting in reduced mismatch with the cable impedance. The lower reflection coefficient (Γ) reduces the wave reflection and thereby the voltage overshoot. Typical values are given in *Table 3.1*.
In the case of parallel cables the cable characteristic impedance is reduced, resulting in a higher reflection coefficient higher overshoot. For more information please see IEC 61800-8.

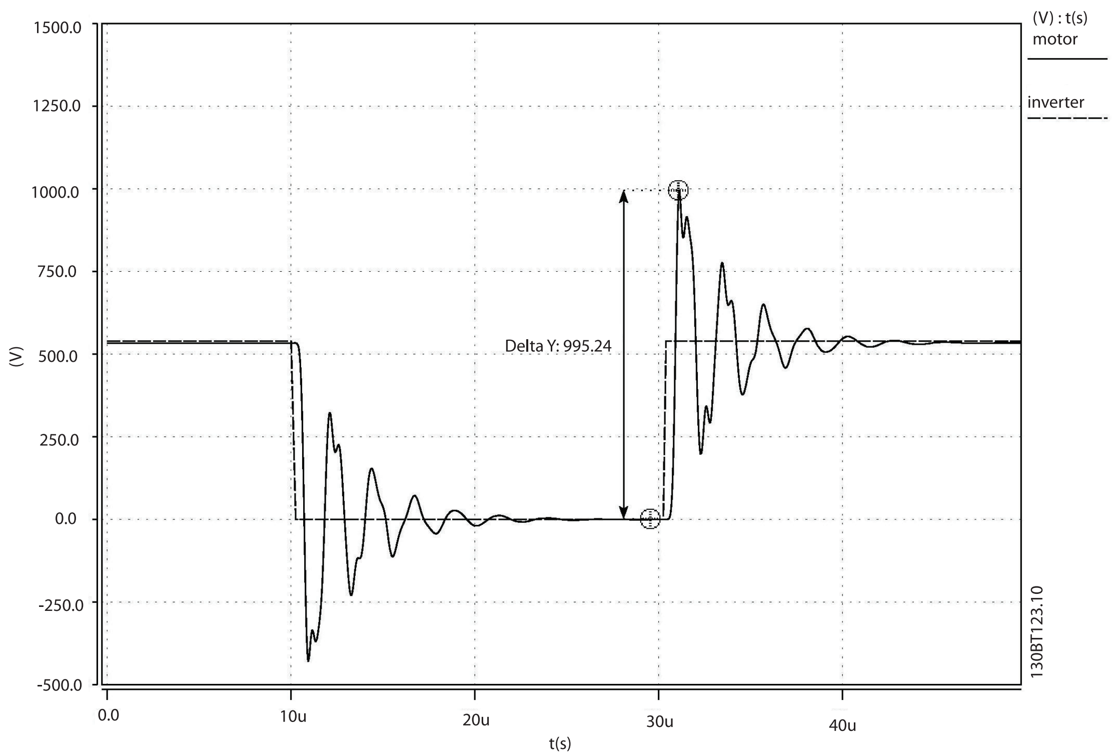


Illustration 3.1 Example of Converter Output Voltage (dotted line) and Motor Terminal Voltage After 200m of Cable (solid line)

Typical values for the rise time and peak voltage U_{PEAK} are measured on the motor terminals between two phases.

Two different definitions for the risetime t_r are used in practice. The international IEC standards define the rise-time as the time between 10% to 90% of the peak voltage U_{peak}. The US National Electrical Manufacturers Association (NEMA) defines the rise-time as the time between 10% and 90% of the final, settled voltage, that is equal to the DC link voltage U_{DC}. See *Illustration 3.2* and *Illustration 3.3*.

To obtain approximate values for cable lengths and voltages not mentioned below, use the following rules of thumb:

1. Rise time increases with cable length.
2. U_{PEAK} = DC link voltage x (1+Γ); Γ represents the reflection coefficient and typical values can be found in table below
   (DC link voltage = Mains voltage x 1.35).
3. dU/dt = $\frac{0.8 \times U_{PEAK}}{t_r}$ (IEC)

   dU/dt = $\frac{0.8 \times U_{DC}}{t_r(NEMA)}$ (NEMA)

(For dU/dt, rise time, U_{peak} values at different cable lengths please consult the drive Design Guide)

Motor power [kW]	Zm [Ω]	Γ
<3.7	2000 - 5000	0.95
90	800	0.82
355	400	0.6

Table 3.1 Typical Values for Reflection Coefficients (IEC 61800-8).

The IEC and NEMA Definitions of Risetime t_r

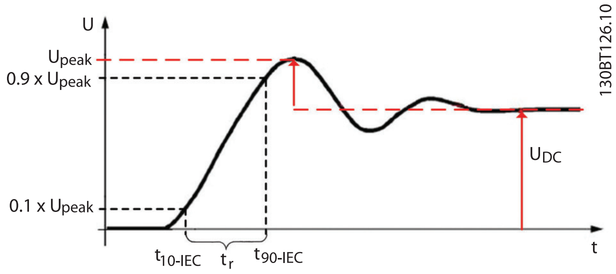


Illustration 3.2 IEC

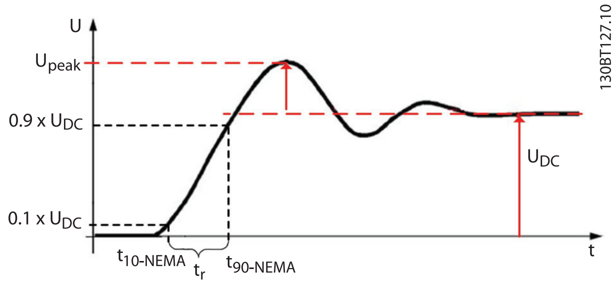


Illustration 3.3 NEMA

Various standards and technical specifications present limits of the admissible U_{peak} and t_r for different motor types. Some of the most used limit lines are shown in *Illustration 3.4*

- IEC 60034-17 – limit line for general purpose motors when fed by frequency converters, 500V motors.
- IEC 60034-25 – limit for converter rated motors: curve A is for 500V motors and curve B is for 690V motors.
- NEMA MG1 – Definite purpose Inverter Fed Motors.

If, in your application, the resulting U_{peak} and t_r exceed the limits that apply for the motor used, an output filter should be used for protecting the motor insulation.

3.5 What are Bearing Currents and Shaft Voltages?

Fast switching transistors in the frequency converter combined with an inherent common-mode voltage (voltage between phases and ground) generate high-frequency bearing currents and shaft voltages. While bearing currents and shaft voltages can also occur in direct-on-line motors, these phenomena are accentuated when the motor is fed from a frequency converter. The majority of bearing damages in motors fed by frequency converters are because of vibrations, misalignment, excessive axial or radial loading, improper lubrication, impurities in the grease. In some cases, bearing damages are caused by bearing currents and shaft voltages. The mechanism that causes bearing currents and shaft voltages is quite intricate and beyond the scope of this Design Guide. Basically, two main mechanisms can be identified:

- Capacitive coupling: the voltage across the bearing is generated by parasitic capacitances in the motor.
- Inductive coupling: caused by circulating currents in the motor.

The grease film of a running bearing behaves like isolation. The voltage across the bearing can cause a breakdown of the grease film and produce a small electric discharge (a spark) between the bearing balls and the running track. This discharge produces a microscopic melting of the bearing ball and running track metal and in time it causes the premature wear-out of the bearing. This mechanism is called *Electrical Discharge Machining* or EDM.

3.5.1 Mitigation of Premature Bearing Wear-Out

There are a number of measures that can be taken for preventing premature wearing and damage of the bearings (not all of them are applicable in all cases – combinations can be used). These measures aim either to provide a low-impedance return path to the high-frequency currents or to electrically isolate the motor shaft for preventing currents through the bearings. Besides, there are also mechanical related measures.

Measures to provide a low-impedance return path

- Follow EMC installation rules strictly. A good high-frequency return path should be provided between motor and frequency converter, for example by using shielded cables.
- Make sure that the motor is properly grounded and the grounding has a low-impedance for high-frequency currents.
- Provide a good high-frequency ground connection between motor chassis and load.
- Use shaft grounding brushes.

Measures that isolate the motor shaft from the load

- Use isolated bearings (or at least one isolated bearing at the non-driving end NDE).
- Prevent shaft ground current by using isolated couplings.

Mechanical measures

- Make sure that the motor and load are properly aligned.
- Make sure the loading of the bearing (axial and radial) is within the specifications.
- Check the vibration level in the bearing.
- Check the grease in the bearing and make sure the bearing is correctly lubricated for the given operating conditions.

One of the mitigation measures is to use filters. This can be used in combination with other measures, such as those presented above. High-frequency common-mode (HF-CM) filters (core kits) are specially designed for reducing bearing stress. Sine-wave filters also have a good effect. dU/dt filters have less effect and it is recommended to use them in combination with HF-CM cores.

4 Selection of Output Filters

4.1 How to Select the Correct Output Filter

An output filter is selected based on the nominal motor current. All filters are rated for 160% overload for 1 minute, every 10 minutes.

4.1.1 Product Overview

To simplify the Filter Selection *Table 4.1* shows which Sine-wave filter to use with a specific frequency converter. This is based on the 160% overload for 1 minute every 10 minutes and is to be considered guideline.

Mains supply 3 x 240 to 500V							
Rated filter current at 50Hz	Minimum switching frequency [kHz]	Maximum output frequency [Hz] With derating	Code number IP20	Code number IP00	Frequency converter size		
					200-240V	380-440V	441-500V
2.5	5	120	130B2439	130B2404	PK25 - PK37	PK37 - PK75	PK37 - PK75
4.5	5	120	130B2441	130B2406	PK55	P1K1 - P1K5	P1K1 - P1K5
8	5	120	130B2443	130B2408	PK75 - P1K5	P2K2 - P3K0	P2K2 - P3K0
10	5	120	130B2444	130B2409		P4K0	P4K0
17	5	120	130B2446	130B2411	P2K2 - P4K0	P5K5 - P7K5	P5K5 - P7K5
24	4	100	130B2447	130B2412	P5K5	P11K	P11K
38	4	100	130B2448	130B2413	P7K5	P15K - P18K	P15K - P18K
48	4	100	130B2307	130B2281	P11K	P22K	P22K
62	3	100	130B2308	130B2282	P15K	P30K	P30K
75	3	100	130B2309	130B2283	P18K	P37K	P37K
115	3	100	130B3181	130B3179	P22K - P30K	P45K - P55K	P55K - P75K
180	3	100	130B3183	130B3182	P37K - P45K	P75K - P90K	P90K - P110
260	3	100	130B3185	130B3184		P110 - P132	P132
410	3	100	130B3187	130B3186		P160 - P200	P160 - P200
510	3	100	130B3189	130B3188		P250	P250
660	2	70	130B3192	130B3191		P315 - P355	P315 - P355
800	2	70	130B3194	130B3193		P400	P400 - P450
1020	2	70	2 x 130B3189	2 x 130B3188		P450 - P500	P500 - P560
1320	2	70	2 x 130B3192	2 x 130B3191		P560 - P630	P630 - P710
1530	2	70	3 x 130B3189	3 x 130B3188		P710 - P800	P800
1980	2	70	3 x 130B9192	3 x 130B3191			P1M0

Table 4.1 Filter Selection

4.3 Electrical Data - Sine-wave Filters

Code Number	IP00 IP20 (IP23)[2]	Filter Current Rating @ 50Hz	 @ 60Hz	 @ 100Hz	Switching Frequency	VLT Power and Current Ratings @ 200-240V		 @ 380-440V		 @ 441-500V		Filter Losses @ 200-240V	 @ 380-440V	 @ 441-500V	L-value	C_Y-Value[1]
		A	A	A	kHz	kW	A	kW	A	kW	A	W	W	W	mH	µF
130B2404 130B2439	IP00 IP20	2.5	2.5	2*	5	0.25 0.37	1.8 2.4	0.37 0.55 0.75	1.3 1.8 2.4	0.37 0.55 0.75	1.1 1.6 2.1	50 60	45 50 60	45 50 60	29	1
130B2406 130B2441	IP00 IP20	4.5	4	3.5*	5	0.55	3.5	1.1 1.5	3 4.1	1.1 1.5	3 3.4	65	60 70	60 65	13	2.2
130B2408 130B2443	IP00 IP20	8	7.5	5*	5	0.75 1.1 1.5	4.6 6.6 7.5	2.2 3	5.6 7.2	2.2 3	4.8 6.3	65 75 80	70 80	70 80	6.9	4.7
130B2409 130B2444	IP00 IP20	10	9.5	7.5*	5			4	10	4	8.2		95	90	5.2	6.8
130B2411 130B2446	IP00 IP20	17	156	13	5	2.2 3 3.7	10.6 12.5 16.7	5.5 7.5	13 16	5.5 7.5	11 14.5	90 100 125	110 125	100 115	3.1	10
130B2412 130B2447	IP00 IP20	24	23	18	4	5.5	24.2	11	24	11	21	150	150	150	2.4	10
130B2413 130B2448	IP00 IP20	38	36	28.5	4	7.5	30.8	15 18.5	32 37.5	15 18.5	27 34	160	170 180	160 170	1.6	10
130B2281 130B2307	IP00 IP20	48	45.5	36	4	11	46.2	22	44	22	40	270	270	260	1.1	14.7
130B2282 130B2308	IP00 IP20	62	59	46.5	3	15	59.4	30	61	30	52	300	310	280	0.85	30
130B2283 130B2309	IP00 IP20	75	71	56	3	18.5	74.8	37	73	37	65	350	350	330	0.75	30
130B3179 130B3181	IP00 IP23	115	109	86	3	22 30	88 115	45 55	90 106	55 75	80 105		470		0.51	15
130B3182 130B3183	IP00 IP23	180	170	135	3	37 45	143 170	75 90	147 177	90 110	130 160		650		0.33	25
130B3184 130B3185	IP00 IP23	260	246	195	3			110 132	212 260	132 160	190 240		850		0.34	25

*) 120Hz
[1]Equivalent STAR-connection value
[2]IP23 - All floor mounted filters

Table 4.4 Sine-wave Filter 3x380-500 V IP00/IP20/IP23

4.4 Sine-Wave Filters

Technical Specifications	
Voltage rating	3 x 200-500V and 500-690V AC
Nominal current @ 50Hz	up to 800A (500V) and 660A (690V). F frame current ratings are achieved by filter paralleling, one filter per inverter module.
Motor frequency derating	
50Hz	Inominal
60Hz	0.94 x Inominal
100Hz	0.75 x Inominal
Minimum switching frequency	nominal switching frequency of the respective FC 102, 202 or 302 x 0.80
Maximum switching frequency	8kHz
Overload capacity	160% for 60 seconds, every 10 minutes.
Enclosure degree	IP00, IP20 for wall-mounted, IP23 for floor mounted.
Ambient temperature	-10° to +45°C
Storage temperature	-25° to +60°C
Transport temperature	-25° to +70°C
Maximum ambient temperature (with derating)	55°C
Maximum altitude without derating	1000m
Maximum altitude with derating	4000m
Derating with altitude	5%/1000m
MTBF	1481842 h
FIT	1.5 106/h
Tolerance of the inductance	± 10%
Degree of pollution EN 61800-5-1	II
Overvoltage category EN 61800-5-1	III
Environmental Conditions Load	3K3
Environmental Conditions Storage	1K3
Environmental Conditions Transport	2K3
Noise level	< frequency converter
Approvals	CE (EN 61558, VDE 0570), RoHS, cULus file E219022 (pending)

The voltage drop across the inductor can be calculated using this formula:

$$ud = 2 \times \pi \times f_m \times L \times I$$

f_m = output frequency
L = filter inductions
I = current

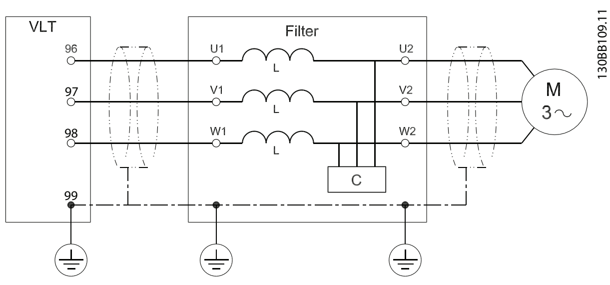
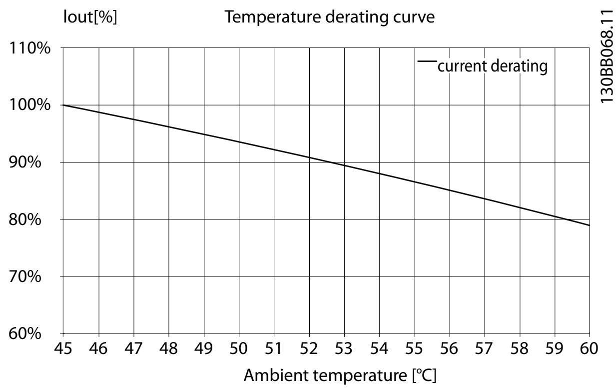


Illustration 4.1 Filter Diagram



4.4.1 dU/dt Filters

Technical Specifications	
Voltage rating	3 x 200-690V
Nominal current @ 50Hz	up to 880A. F frame current ratings are achieved by filter paralleling, one filter per inverter module.
Motor frequency derating	
50Hz	Inominal
60Hz	0.94 x Inominal
100Hz	0.75 x Inominal
Minimum switching frequency	no limit
Maximum switching frequency	nominal switching frequency of the respective FC 102, 202 or 302
Overload capacity	160% for 60 seconds, every 10 minutes.
Enclosure degree	IP00, IP 20 for wall-mounted, IP23 for floor mounted. IP21/NEMA 1 available for wall-mounted using separate kits.
Ambient temperature	-10° to +45°C
Storage temperature	-25° to +60°C
Transport temperature	-25° to +70°C
Maximum ambient temperature (with derating) Maximum altitude without derating	55°C
Maximum altitude without derating	1000m
Maximum altitude with derating	4000m
Derating with altitude	5%/1000m
MTBF	1481842 h
FIT	1.5 10^6 / h
Tolerance of the inductance	± 10%
Degree of pollution EN 61800-5-1	II
Overvoltage category EN 61800-5-1	III
Environmental Conditions Load	3K3
Environmental Conditions Storage	1K3
Environmental Conditions Transport	2K3
Noise level	< frequency converter
Approvals	CE (EN61558, VDE 0570), RoHS, cULus file E219022 (pending)

4.4.2 Sine-Wave Foot Print Filter

Technical Specification

Voltage rating	3 x 200-500V AC
Nominal current I¬N @ 50Hz	10 – 17A
Motor frequency	0-60Hz without derating. 100/120Hz with derating (see derating curves below)
Ambient temperature	-25° to 45°C side by side mount, without derating (see derating curves below)
Min. switching frequency	f_{min} 5kHz
Max. switching frequency	f_{max} 16kHz
Overload capacity	160% for 60 sec. every 10 minutes.
Enclosure degree	IP20
Approval	CE, RoHS

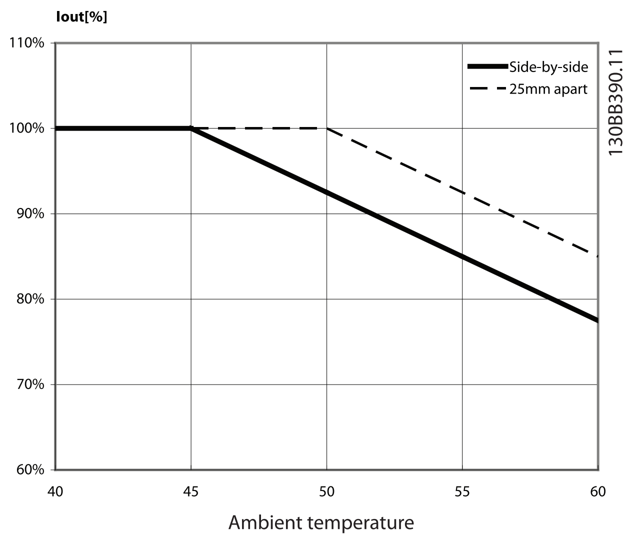


Illustration 4.2 Temperature Derating

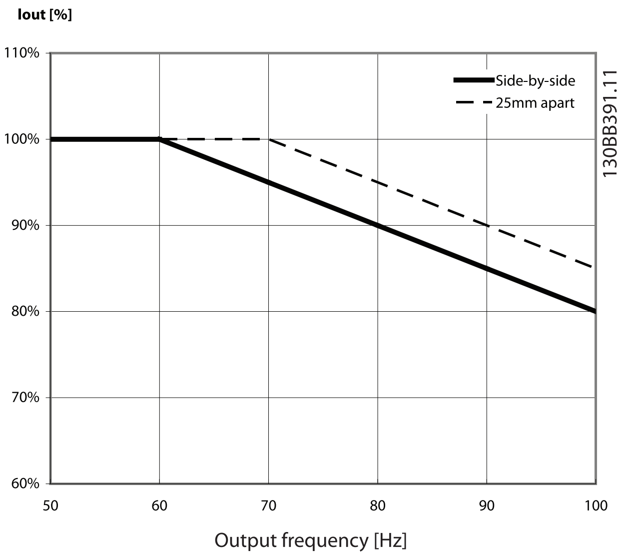


Illustration 4.3 Output Frequency Derating

Code number	Enslosure	Measurements / Dimensions									Weight	Mounting direction	Max. wire cross section		Terminal screw torque	L-shaped terminal kit[1)]
		A (height	a	B (width)	b	C (depth)	c	d	e	f	kg	Wall/Floor	mm²	AWG	Nm/ft-lb	Part no.
130B2404	IP00	200	190	75	60	205	7	8	4.5	5	2.5	wall	4	24 - 10	0.6/0.44	N/A
130B2439	IP20										3.3					
130B2406	IP00	200	190	75	60	205	7	8	4.5	5	3.3	wall	4	24 - 10	0.6/0.44	N/A
130B2441	IP20										4.2					
130B2408	IP00	268	257	90	70	205	8	11	6.5	6.5	4.6	wall	4	24 - 10	0.6/0.44	N/A
130B2443	IP20					206					5.8					
130B2409	IP00	268	257	90	70	205	8	11	6.5	6.5	6.1	wall	4	24 - 10	0.6/0.44	N/A
130B2444	IP20										7.1					
130B2411	IP00	268	257	130	90	205	8	11	6.5	6.5	7.8	wall	4	24 - 10	0.6/0.44	N/A
130B2446	IP20										9.1					
130B2412	IP00	330	312	150	120	260	12	19	9	9	14.4	wall	16	20 - 4	2/1.5	N/A
130B2447	IP20										16.9					
130B2413	IP00	430	412	150	120	260	12	19	9	9	17.7	wall	16	20 - 4	2/1.5	N/A
130B2448	IP20					259					19.9					
130B2281	IP00	530	500	170	125	258	12	19	9	20	34	wall	50	6 - 1/0	8/5.9	N/A
130B2307	IP20					260					39					
130B2282	IP00	610	580	170	125	260	12	19	9	20	36	wall	50	6 - 1/0	8/5.9	N/A
130B2308	IP20										41					
130B2283	IP00	610	580	170	135	260	12	19	9	20	50	wall	50	6 - 1/0	15/11.1	N/A
130B2309	IP20										54					
130B3179	IP00	520	-	470	400	334	175		13	26	95	floor			2.0-6.0	N/A
130B3181	IP23	918	898	904	779	792	661		11	22	205					
130B3182	IP00	580	-	470	400	311	150		13	26	127	floor				N/A
130B3183	IP23	918	898	904	779	792	661		11	22	237					
130B3184	IP00	520	-	500	450	350	200		13	26	197	floor				130B3137
130B3185	IP23	918	898	904	779	792	661		11	22	307					
130B3186	IP00	520	-	500	450	400	250		13	26	260	floor				130B3138
130B3187	IP23	918	898	904	779	792	661		11	22	370					
130B3188	IP00	520	-	500	450	400	250		13	26	265	floor				130B3138
130B3189	IP23	1161	1141	1260	1099	991	860		11	22	425					
130B3191	IP00	620	-	620	575	583	250		13	26	410	floor				130B3139
130B3192	IP23	1161	1141	1260	1099	991	860		11	22	570					

[1)] For floor mounted filters, an optional terminal connection kit is available for the ease of installation. Please see the L-shaped terminal kit sketches. The kit is not included in the filter delivery and should be ordered separately.

Table 5.2 500V Sine-wave Filter - Physical dimensions

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