5. ELECTROMAGNETIC COMPATIBILITY OF ELECTRICAL DRIVES

5.1. Conductivity and radiation disturbances of converters

Semiconductor converters will cause conductivity and radiation disturbances in the supply network and electrical circuits of industrial equipment. A non-controllable rectifier and voltage or impulse inverter consumes energy in the power supply only when the supply voltage is higher than the DC voltage in the output of the converter. For that reason, consumed current is fragmentary and its peak values are high. Current consists of the main harmonic component and higher harmonic components. The current consumed by the frequency converter consists of the 5th, 7th, 11th and 13th harmonic components. Higher harmonic components of the current cause:

- disturbances of supply voltage, caused by the non-sinusoidal form of a converter’s current, and voltage will influence other devices which are fed from the same supply network. Disturbances may be distributed over feeding lines or via the electromagnetic field in the range of radio frequency.

- oscillation processes in the power factor compensation circuits which may cause over-voltage pulses in critical conditions.

Critical operation modes are as follows:

a) at least 10-20 % of installation power of the supply consumed by power electronic converters

b) compensation circuit of the power factor and the feeding transformer makes up an oscillation circuit, the resonance frequency of which is close to the frequency of the 5th or 7th harmonic component of 50 Hz supply voltage (250 or 350 Hz)

c) high power consumers are switched to the power supply

When high power consumers are switched on during the transient process, after the first voltage drop, higher frequency oscillations will follow, which are damped during some half of a wave. If the frequency of free oscillations during commutation process is close to the frequency of any, e.g., 7th, harmonic component, the resonant effect will follow. The problem is the high amplitude of these voltage oscillations. For example, in the power supply with the rated voltage 400 V, the measured peak voltage can exceed 1200 V. It is dangerous to other devices switched to the supply network.

Because of relatively high frequency and fast switching processes, the pulse width modulation (PWM) of a semiconductor converter causes a number of additional problems. On the one hand, fast switching processes make it possible to reduce losses in transistors and to generate PWM modulated sinusoidal voltage. On the other hand, the PWM causes:

- signals with large harmonic spectre and conductivity disturbances in the power network as well as radiation disturbances in radio frequency range.

- magnetic noise in a motor. On PWM operation, the alternating magnetic induction causes the high frequency vibrations in the magnetic core and additional acoustic noise.
Acoustic noise may be reduced by help of modernization of pulse width modulation. For example, the frequency of pulse width modulation may be controlled by such way that the modulation will be asynchronous in relation to the output frequency. To externalize acoustic noise, the frequency of pulse width modulation can be controlled randomly even the output frequency is constant (e.g., the pulse width modulation with random frequency can be used).

Fast switching processes of an inverter cause reflection phenomena of voltage waves in the cable connected between the inverter and the motor. Depending on the switching time of the transistor, propagation speed of the pulse in the cable line and critical length of the cable, the amplitude of the pulse from inverter side can be summarized with the amplitude of the pulse reflected from motor side. For this reason, the peak voltage in the output cable may exceed the DC voltage of the converter two times.

Power and control circuit interaction is caused by electromagnetic radiation and may disturb the operation of the control device. To externalize such kind of disturbances, certain requirements are established in the standards (e.g., the power and control cables must not lay side by side in parallel. Also, when the distance between output power cables of different frequency converters is too small, it may cause mutual interactions between converters. To externalize this, screened cables or filters are used.

To externalize conductivity disturbances in a drive, the choke or filter is used in supply and output lines. These devices are connected between the supply source and the converter and between the inverter and the motor. Mainly reactors and high frequency filters are connected to the supply circuit of the converter. Schemes and construction of filters, reactors and chokes may be different. A reactor in the supply circuit of the converter helps to reduce the charge current of the capacitor and protects the rectifier.

Radiation disturbances can be reduced using screened cables. The additional effect will be achieved by use of output filters. Filters give a maximum effect when they are placed close to the frequency converter. A condition of providing reduction of disturbance is grounding of the converter and filter bodies. As filtrated voltage of the motor is sinusoidal and does not consist of higher harmonics of transient voltages, a screened cable between the filter and the motor is not necessary when the drive is operating outside a residential area.

According to standards EN 50081 and EN 50082 requirements, residential level of electromagnetic compatibility is to be achieved with screening of a drive and use of EMC filters. Additionally, to reduce radiation, the ferrite chokes must be connected to the power cable circuit.

To externalize the harmful influence of frequency converters on devices and people, the converters must satisfy electromagnetic compatibility (EMC) requirements for general purpose variable speed AC drives. These requirements must be followed on mounting as well as on operating of frequency converters. Most of frequency converters are designed such that they could be used in industrial, business and residential area.

The foot-print filters and stand alone filters are used in frequency converters. With foot-print filters, the connections between the filter and the converter are as short as possible.

Supply circuit chokes. In the supply circuit of a frequency converter there are connected chokes, limiting the short circuit current, which must be selected depending on the rated
current of converter. The chokes must smooth the consumed current and limit the short circuit current as well as higher harmonic components of the current. These purposes are achieved by increasing the inductance of the circuit. A choke increases the over-voltage withstand of the frequency converter.

The complex resistance of the choke with the complex resistance of the frequency converter makes the voltage divider for over-voltage pulses and the resulting over-voltage depends on the ratio of resistances. An increase in the over-voltage withstand enables us to improve the protection of a frequency converter by using conventional protection devices, such as varistors, gas discharge devices and capacitors because the choke limits the current of the circuit. For that reason, in higher supply voltage converters chokes are used.

Chokes in a supply circuit must be separately fitted with every frequency converter so that one converter is separated from another.

Supply circuit filters. Fast operation transistors (of an inverter) will cause some problems of electromagnetic compatibility (EMC). High frequency disturbances are distributed by electromagnetic radiation and directly by a supply circuit (conductivity disturbance). With filters connected to the supply circuit, disturbances in the frequency range 0.15-30 MHz must be limited. According to standard EN 55011, devices are classified depending on their installation place and character of high frequency disturbance voltage into two groups: devices which are operating outside a residential area and devices which are intended for operation in a residential area.

Filters of feeding circuits consist of capacitors, which cause a leakage current in a circuit. The value of the leakage current may grow to 200 mA. Capacitive leakage current appears in the load side of the frequency converter (in a cable connected to the converter and motor). Therefore, it is impossible to use leakage current protection relays to protect people. For human protection, a voltage sensitive protection device must be connected between the ground contact of a converter and the ground electrode.

Output filters. Pulse width modulation of the output voltage of the frequency converter, which makes it possible to generate a sinusoidal current, continuous magnetic flux and rotating magnetic field, causes undesirable influences:

- additional noise of the motor
- capacitive currents in the cable
- over-voltage pulses on motor contacts
- high frequency radiation disturbances in the environment

Undesirable influences may be reduced by using output filters. It must be noticed that output filters cause additional voltage, reducing the magnetic field and the motor torque. Therefore, in lifting mechanisms, where short time overloading is essential, output filters are avoided. Then a special module of electromagnetic compatibility or output choke is used. With cables over 50 m, the requirement is that the voltage drop on active resistance must be smaller than 2% of rated voltage. Improvement of electromagnetic compatibility is possible by special EMC modules with a supply circuit filter in the input and ferrite choke in the output.

The output choke is a ferrite core with 3 to 5 loops of the connection cable of the motor and the converter. Output choke reduces the electromagnetic radiation of the cable substantially. There is no additional voltage drop in the output choke.

5.2. Long cables
The important element of the electric drive is the cable between the frequency converter and the motor. By using fast operating IGBT transistors in the inverter, the rise time of voltage pulse is smaller than 0.5 μs and frequencies of harmonic components of impulse voltage are in the range of MHz (Table 5.1). At high frequencies, a cable of 20-30 meters is a long line with distributed parameters.

Table 5.1

<table>
<thead>
<tr>
<th>Component</th>
<th>Turn-on time, μs</th>
<th>Turn-off time, μs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power MOSFETs</td>
<td>0.1 - 0.5</td>
<td>0.3 - 1.0</td>
</tr>
<tr>
<td>IGBTs</td>
<td>0.2 - 1.0</td>
<td>0.7 - 4.0</td>
</tr>
<tr>
<td>Thyristors (SCR)</td>
<td>4 - 10</td>
<td>100 - 300</td>
</tr>
<tr>
<td>GTOs</td>
<td>2 - 5</td>
<td>10 - 25</td>
</tr>
</tbody>
</table>

Long cables can be described with distributed parameters per meter: resistance $R_0$, inductance $L_0$, capacitance $C_0$, insulation conductance $G_0$ or with the characteristic impedance $Z_C$.

$$Z_C = \sqrt{\frac{R + j\omega L_0}{G + j\omega C_0}} \approx \frac{L_0}{\sqrt{C_0}}.$$  \hspace{1cm} (5.1)

The propagation factor $k_p$

$$k_p = \sqrt{\frac{(R + j\omega L_0)(G + j\omega C_0)}{}}.$$  \hspace{1cm} (5.2)

The typical value of $Z_C$ is from 30 to 80 Ω. The pulse or the sine wave propagates through the cable at a finite speed, which is the function of the relative dielectric permeability $\varepsilon_r$ ($\mu_0 = 4\pi \cdot 10^{-7}$ H/m; $\varepsilon_0 = 8.86 \cdot 10^{-12}$ F/m).

$$v = \frac{1}{\sqrt{L_0 C_0}} = \frac{1}{\sqrt{\mu_0 \varepsilon_0 \varepsilon_r}}.$$  \hspace{1cm} (5.3)

For the cable, the relative permeability $\varepsilon_r$ is from 3 to 8 and the speed $v = 120...180$ m/μs. Therefore, modelling of pulse propagation in cable lines depends on the length of the cable. For short cables, the model consists of the cable equivalent circuit with lumped parameters. For long cables, the equivalent circuit of the transmission line and the distributed parameters must be used. If the cable length exceeds the critical length $l_{cr}$ ($l > l_{cr}$), then the second type models must be used.

$$l_{cr} = \frac{v \cdot t_r}{2},$$  \hspace{1cm} (5.4)

where $t_r$ is the rise-time of the pulse. In this case, the pulse, which travels along a cable line will be reflected at the end of the cable (from the motor terminals) after the time interval $t_r/2$ and the reflected pulse returns to the inverter after the time interval $t_r$. Then, the second
reflection occurs and the reflected pulse voltage is added to the initial pulse voltage. With ideal reflection, the total voltage maximum is two times higher than the peak voltage of the initial pulse. The real reflection factor at the motor $k_{refm}$ is

$$k_{refm} = \frac{Z_m - Z_c}{Z_m + Z_c},$$  (5.5)

where $Z_m$ is the impedance of the motor, the function of the full inductance $L_m$ of the motor and capacitance $C_m$ of the stator winding.

$$Z_m = \sqrt{\frac{L_m}{C_m}}. \quad (5.6)$$

The typical value of $Z_m$ is from 100 to 1000 Ω. The higher value of $Z_m$, the smaller the motor is.

For example, on the supply voltage 380 V, DC voltage of the converter is 540 V and over-voltage pulse of up to 1080 V.

Over-voltages may be result from the resonance of the LC circuit, whereas capacitance is the winding capacitance in relation to the ground. Over-voltage pulse is dangerous to a motor. Because of this, induction motors with suitable insulation or reactors and filters must be used (Fig. 6.1).

![Diagram of Frequency converter, Choke, Motor, Supply voltage, Output filter, Motor](image)

Figure 5.1 Use of over voltage limiting chokes and output filters
With induction motors fed on a frequency converter, the requirement is that overvoltages must not overcome the maximum values intended for motor insulation. The maximum value of the pulse voltage $U_{m}$ depending on the rise-time, is determined by IEC and motor standards. The breakdown voltage of insulation $U_{br}$ depends on the frequency, dielectrical conductivity, dielectrical losses $\tan \delta$ and proportional coefficient.

$$U_{bd} = K \sqrt{\frac{1}{f \cdot \varepsilon \cdot \tan \delta}}$$

(5.7)

Pulses with a short rise-time decrease the breakdown voltage of insulation because the breakdown voltage is reduced with an increase in the frequency.

### 5.3 Recommendations for converter installation

Electromagnetic compatibility (EMC) for the machinery controlled by the inverter can be achieved by the following guidelines:

1. Check the filter and inverter rating labels to ensure that the part numbers are correct.
2. Ensure the best possible grounding of the filter.
3. Both the filter and the inverter have to be securely mounted.
4. Connect the incoming mains supply to the filter terminals marked “Line”; connect any ground cables to the ground stud provided. Connect the filter terminals marked “Load” to the main supply of the inverter using short lengths of an appropriate gauge cable.
5. Connect the motor and fit the output ferrite provided with the filter as close to the inverter as possible. Armoured or screened cable should be used with the three-phase conductors only passing twice through the output choke. The ground conductor should be securely grounded at both inverter and motor ends. The screen should be connected to the enclosure body.
6. It is important that the lead length from the filter to the inverter and unscreened length of motor output cable be kept as short as possible and that the incoming mains and outgoing motor cables be kept well separated.
References