# Electric Frequency Drives

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**Abstract**

This article shows the main functioning of frequency drives and the basic calculations. This overview is made while studying electrical drives [4] and should be seen as notes taken during this study.

This article will caption the main topics of frequency drives. It is a continuation of the work done to show mechanical engineers the analogy of the electrical quantities [2].

Frequency drives are more and more used in industry to power drive trains, which makes the basic understanding vital for mechanical engineers to design the drive train. This article aims at giving more insight and is made as notes when studying electrical systems.

## 1 Basics of switch mode power converters

For drives where the power supply frequency is not the desired motor frequency, an Power Processing Unit (PPU) is required to amplify the control signal and supply the desired voltages and currents of the appropriate form and frequency. The basics of the PPU is shown in Figure 1.

The power source, or utility, has a certain AC frequency and it might be single-phase or three-phase power source. The diode rectifier converts the AC current to a DC current, but does not have any control capabilities and thus cannot control the output DC. The capacitor $V_d$ acts as a filter and reduces ripples in the DC voltage. This rectifier efficiency can be as high as 99%.

The switch-mode converter translates the DC power supply to the required input to the motor. This can be in the form of an adjustable-amplitude DC or sinusoidal AC to the motor by amplifying the signal from the controller. The switch-mode converter must be able to reverse the power flow as well. To obtain the required signal transistors are used as switches and are either fully on or off. The transistors act as bi-positional switches as shown in Figure 2. The efficiency of the complete PPU can exceed 95% and even 98% in very large power ratings. When the frequency of the motor is above 60Hz [1], the motor will need to draw more current to keep the correct speed[1]. For smaller speeds the current is not required to increase. The real gain of using a Variable Frequency Drive (VFD) is when the load is not always at 100%, as the power consumption decreases a lot compared to the full power part. This does however not mean that the electric drive should be chosen too large, as the motor itself becomes less efficient, as the power factor as per Equation (55) in [2] will decrease due to an increasing reactive power.

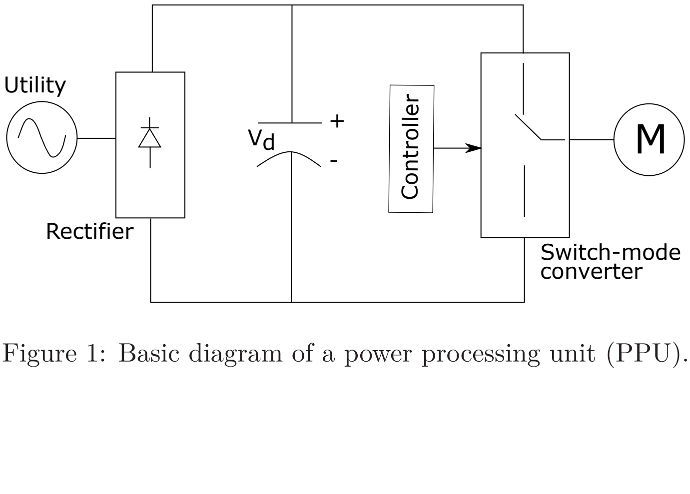


Figure 1: Basic diagram of a power processing unit (PPU).

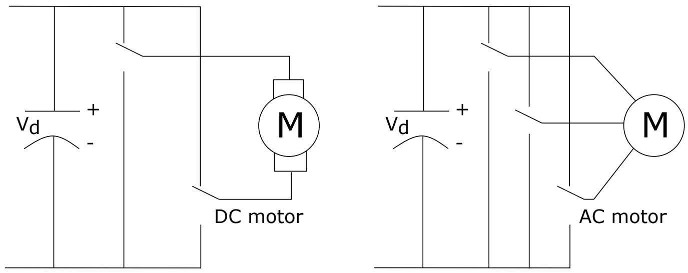


Figure 2: Basic diagram of a switch-mode (PPU) for a switch-mode converter for a DC (left) and AC motor (right).

### 1.1 Analysis of switch-mode converters

The shifting of the bi-positional switches, which are actually two transistors and are itself explained later, cannot result in instantaneous voltage changes due to $V_d$. On the other hand, the current through the windings cannot change instantaneously either. This means that by switching the transistors it is possible to control the current, as the on-off control of the transistors does not have an instantaneous effect.

[1]This is proven by combining the mechanical power in Equation (3) and Equation (49) in [2]. Keep in Equation (3) the torque equal while increasing the rotational speed, shows an increase in power. The power is drawn from the product of current and voltage, and as the voltage stays equal, it must be the current that is increased.

### 1.1.1 Pulse-Width Modulation (PWM)

For simplicity, only one pole, which is one bi-positional switch and spool, is considered. This is shown in Figure 3. The controller is also shown in more detail. The signal $v_{c,A}$ is the reference signal and is input to the controller. The signal $v_{tri}$ is an internal reference signal with a certain period time, as shown on top of Figure 4. When $v_{c,A} > v_{tri}$ the control output is 1 and $v_{AN}(t) = V_d$, but when $v_{c,A} \leq v_{tri}$ the output is 0 and $v_{AN}(t) = 0$, as shown in the middle graph in Figure 4. This means that the voltage over the port can be expressed as:

$$v_{AN} = q_A(t)\, V_d \tag{1}$$

The control signal is dependent on the controller input $v_{c,A}$, which means that the lower the control voltage $v_{c,A}$, the less time of the period the voltage is equal to $V_d$, meaning the average voltage over the period time becomes less.

The inductance at the output of the pole makes sure that the output current to the motor remains more smooth than the voltage change due to the switching. This is shown in Figure 5. The top graph shows the command signal, as shown in Figure 4 as well. The ideal current is a constant current. The drawn current from the utility $i_{dA}$ is again shaped as the control signal, and can be expressed as follows:

$$i_{dA} = q_A(t)\, i_A \tag{2}$$

Due to the inductance the delivered current is more smooth, as show in the bottom graph of Figure 5.

The controller will be discussed later, but it is common to keep $T_s$ (and thus $f_s$) and $\hat{V}_{tri}$ constant. Using the on-off switches and controlling the time of the control signal is called Pulse-Width Modulation (PWM) and influences the average port current and voltage.

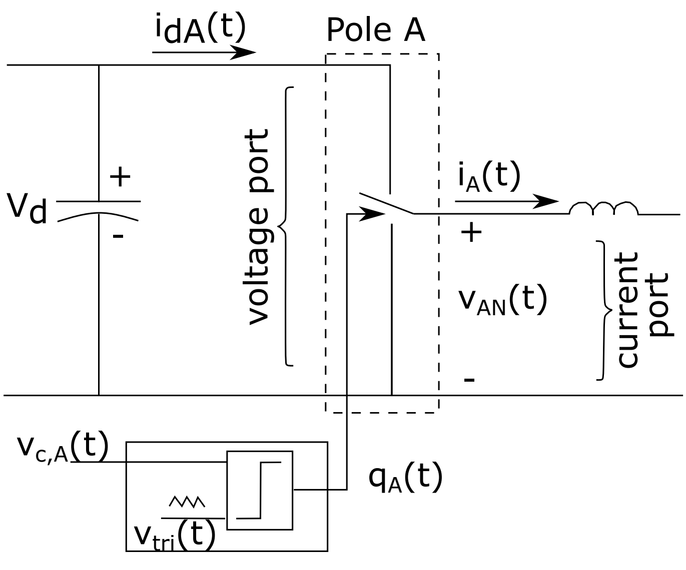

Figure 3: Simplification of pole A, for explanation purposes, including the controller and pole in more detail.

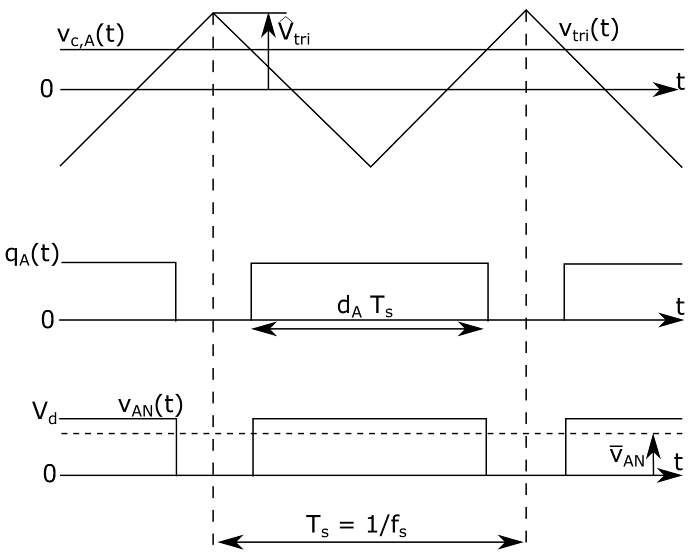

Figure 4: Construction of the control signal.

### 1.1.2 Average representation of the pole

To further study the pole, the duty-ratio $d_A$ is defined:

$$d_A = \frac{dT_s}{T_s} \tag{3}$$

where $dT_s$ is the time in [s] within a time period that the control signal $q_A$ is 1, as defined in Figure 5, and $T_s$ is the time period in [s].

When assuming the supplied voltage $V_d$ is constant, the average port voltage $\bar{v}_{AN}$ can be calculated as:

$$\bar{v}_{AN} = \frac{1}{T_s} \int_{T_s} v_{AN}(t)\, dt = \frac{1}{T_s} \left( \int_0^{d_A T_s} V_d\, d\tau + \int_{d_A T_s}^{T_s} 0 d\tau \right) = d_A\, V_d \tag{4}$$

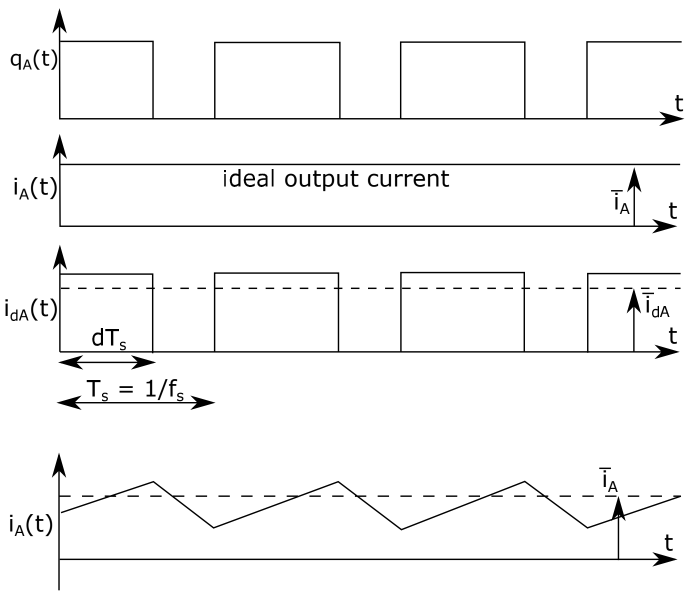

Figure 5: The real current as result of the PWM.

Now the average voltage is known, but dependency on $v_{c,A}$, which influences $d_A$, is not yet known. Important to know is that:

$$if\ v_{c,A} = \hat{V}_{tri} \Longrightarrow d_A = 1 \Longrightarrow \bar{v}_{AN} = V_d \tag{5}$$

$$if\ v_{c,A} = -\hat{V}_{tri} \Longrightarrow d_A = 0 \Longrightarrow \bar{v}_{AN} = 0 \tag{6}$$

This means that during half of a time period the reference signal 'travels' $2\hat{V}_{tri}$. The formula for the straight line going up is $V_{tri}(t) = -\hat{V}_{tri} + 2\,\hat{V}_{tri}\,\frac{t}{T_s}$. The time $dT_s$ that $V_{tri}(t)$ is below $v_{c,A}$ (and thus where the voltage is equal to $v_{c,A}$ and time to $dT_s$) is then $\frac{dT_s}{T_s} = \frac{v_{c,A}\,\hat{V}_{tri}}{2\,\hat{V}_{tri}}$, which leads to:

$$d_A = \frac{1}{2} + \frac{v_{c,A}}{2\,\hat{V}_{tri}} \tag{7}$$

$$\bar{v}_{AN} = \frac{V_d}{2} + \frac{V_d}{2\,\hat{V}_{tri}}\,v_{c,A} \tag{8}$$

This shows that the average output of the pole has a static offset ($V_d/2$) and an amplification of the control signal $v_{c,A}$ by:

$$k_{pole} = \frac{V_d}{2\,\hat{V}_{tri}} \tag{9}$$

Up till now the control signal $v_{c,A}$ is considered constant. This is however not the case in most situations, meaning that the control signal becomes time dependent $v_{c,A}(t)$ and as a result the $q_A(t)$ and the duty ratio $d_A(t)$. This means that Equation 4 becomes:

$$\bar{v}_{AN}(t) = d_A(t)\,V_d \tag{10}$$

Using a similar calculation, the current can be derived:

$$\bar{i}_{dA}(t) = d_A(t)\,\bar{i}_A(t) \tag{11}$$

The ripple in $i_A$ should be kept as small as possible, as it would otherwise result in excessive power losses and torque pulsations. Therefore, the frequency of the controller should be kept much higher than the frequency at which the motor needs to be controlled (when using a sinusoidal or at least regular pattern for $V_{c,A}$).

By using the average current and electrical potential, an ideal transformer is made. This ideal transformer can be used to focus on the quantities of primary interest. However, it should always be noted that these averages are not exactly true and that the quantities are pulsating in reality. However, to get a proper working, the triangular frequency (= carrier frequency of $V_{tri}$) should be, as a rule of thumb, at least be 10 times higher than the the output frequency and of the $V_{c,A}$. Typical is a carrier frequency of 4[kHz], but lowering the carrier frequency reduces the heat generation in the bi-polar switches.

## 1.2 Converter pole as a two-quandrant converter

In Figure 3 the voltage $V_d$ and $v_{AN}$ cannot reverse, but the currents $i_A$ and $i_{dA}$ can reverse. This is defined as a *two-quadrant converter*. To achieve a four-quadrant converter, where voltage as well as current can reverse, requires multiple poles and is already shown in Figure 2.

In this section, the two quadrant pole is further studied, which means that only the current can be reversed. In Figure 6 the familiar pole is shown with added capacitor $E_A$ and a resistance $R_A$ in series with the already familiar inductance $L_A$. With a constant $v_{c,A}$ there will be a steady state, meaning that the output voltage and $E_A$ do not change with time. The average quantities are then:

$$I_A = \frac{V_{AN} - E_A}{R_A} = \frac{d_A\,V_d - E_A}{R_A} \tag{12}$$

Note that $V_d$ is always the power source, hence $V_d \geq E_A$. This means that by controlling $d_A$ the current can be made positive or negative (i.e. determine the direction of the current).

### 1.2.1 Buck mode

A positive current $I_A$, meaning $V_{AN} > E_A$, means that the power flow direction is defined as positive. This is called the 'buck' mode, as the input voltage $V_d$ is 'bucked' by the converter to produce a lower voltage.

### 1.2.2 Boost mode

By adjjusting the duty-ratio $d_A$ such that $V_{AN} < E_A$, the direction of $I_A$ is reversed and the average power flows from $E_A$ to $V_{AN}$, thus implying a 'boost' mode of operation. Equation 12 is still valid in boost mode.

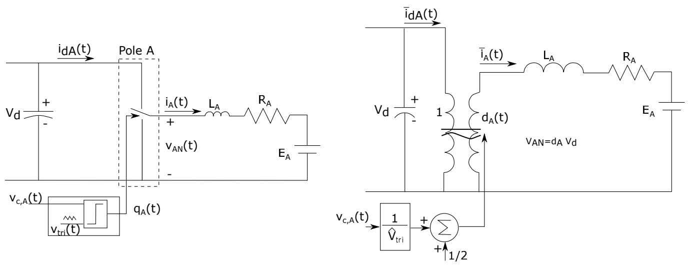


Figure 6: On the left a two-quadrant converter circuit, on the right the average representation of an ideal transformer of the two-quadrant converter.

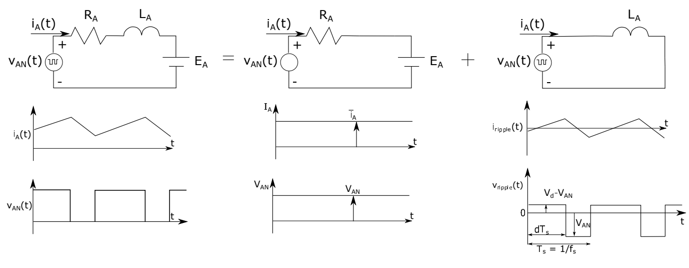


Figure 7: The superposition of the ripple effect on the current and voltage.

Table 1: Switching logic between buck and boost switch.

| $q_A$ | $q_A^+$ | $q_A^-$ |
|---|---|---|
| 1 | 1 | 0 |
| 0 | 0 | 1 |

#### 1.2.3 Ripple calculation

Up till now the average is calculated. It is however also important to know more about the ripple behaviour around the average quantities. Assuming that the carrier frequency, and thus the ripple frequency, is much larger than the output frequency, the changes in current and voltage are small. This means that with small changes, the influence of the resistance $R_A$ can be neglected. This means that the circuit can be simplified using superposition, dividing the circuit over the average values (with $R_A$ and $E_A$) and the ripple effect ($L_A$). See also Figure 7.

This means that the electric potential can be calculated by:

$$v_{AN}(t) = V_{AN} + v_{ripple}(t) \tag{13}$$

Similarly, the current can be calculated:

$$i_A(t) = I_A + i_{ripple}(t) \tag{14}$$

Equation 22 in [2] shows the relation for the inductance over the spool, which is the component with the largest influence on the ripple. It shows that the relation between the difference is current with a relation to the inductance and the electric potential over the spool. Therefore, the current peak-to-peak value, and thus the largest difference in current, is:

$$\Delta i_A = \frac{V_d - V_{AN}}{L_a} dT_s = \frac{V_d - V_{AN}}{L_a} d_A\, T_s \tag{15}$$

### 1.3 Implementation of bi-positional switches

The assumed switches are actually constructed of two transistor-diode combinations, as shown in Figure 8 (without the gate-drive circuitry). One transistor-diode combination is used for buck mode, the other for boost mode. This means that the controls for boost mode $q_A^-$ are the inverse with respect to the buck $q_A^+$ mode of operation (meaning $q_A^- = 1 - q_A^+$). This is also shown in Table 1. When switching, a (tiny) blanking time is introduced between the switching of the two transistors to prevent large currents through the transistors, which would be the result when both transistors are connected at the same time. The switching time of the transistors is in the order of magnitude of $\mu s$.

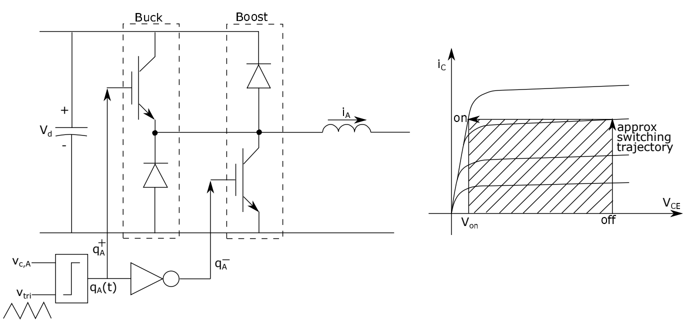


Figure 8: A simplified transistor-diode combination to create a switch.

The transistors are not perfect, meaning that they will dissipate power during switching and when active. The switching frequencies can vary from 2kHz for large motors to 50kHz for small motors. The most dissipated power is during switching. The graph on the right of Figure 8 shows the switching trajectory, meaning that from off to on first the current will increase and afterwards the voltage will decrease. The reverse is visa versa. It also shows the various values for different voltages over the transistor $V_{CE}$, meaning that for a lower voltage the power dissipation will be smaller. As the switching time is small, the power dissipation also results in a small amount of energy being converted to heat. Once the transistor is on, there is still a small electric potential over the transistor, but as these voltages are typically ∼1V, the power loss is small.

### 1.4 Switch-mode converters for DC and AC motors

In this section the knowledge of the previous sections for one pole is used for DC motors (two poles) and AC motors (three poles).

#### 1.4.1 DC motor, four quadrant capability

The main schematic for the DC motor is shown in Figure 9. The two poles are clearly shown. The control signal $q_B(t)$ is inversed compared to control signal $q_A(t)$, but are compared to the same triangular waveform. This means that the duty-ratios are:

$$d_A = \frac{1}{2} + \frac{v_c(t)}{2\,\hat{V}_{tri}} \tag{16}$$

$$d_B = \frac{1}{2} - \frac{v_c(t)}{2\,\hat{V}_{tri}} \tag{17}$$

This means that the average electric potential at the poles are (as shown in Figure 9 (b)):

$$\bar{v}_{AN}(t) = \frac{V_d}{2} + \frac{V_d}{2\,\hat{V}_{tri}} v_c(t) \tag{18}$$

$$\bar{v}_{BN}(t) = \frac{V_d}{2} - \frac{V_d}{2\,\hat{V}_{tri}} v_c(t) \tag{19}$$

(20)

The voltage over the motor is then:

$$\bar{v}_o(t) = \bar{v}_{AN}(t) - \bar{v}_{BN}(t) = \left(\frac{V_d}{\hat{V}_{tri}}\right) v_c(t) \tag{21}$$

The term $\left(\frac{V_d}{\hat{V}_{tri}}\right) = k_{PWM}$ can be replaced and $k_{PWM}$ is the constant gain of the converter.

The duty-ratio for the motor is then calculated using (see also Figure 9 (c)):

$$d(t) = d_A(t) - d_B(t) = \frac{v_c(t)}{\hat{V}_{tri}} \tag{22}$$

Note that duty-ratios $d_A$ and $d_B$ are limited to a number between 0 and 1 by their definition. However, the motor duty factor $d(t)$ can range from -1 to +1. This means that the dc-dc converter for the DC motor can control the electric potential to the positive and negative, meaning the current can also flow either way. This means that the converter has a four-quadrant capability and can drive forward and backwards, in driving as well as regenerative braking mode.

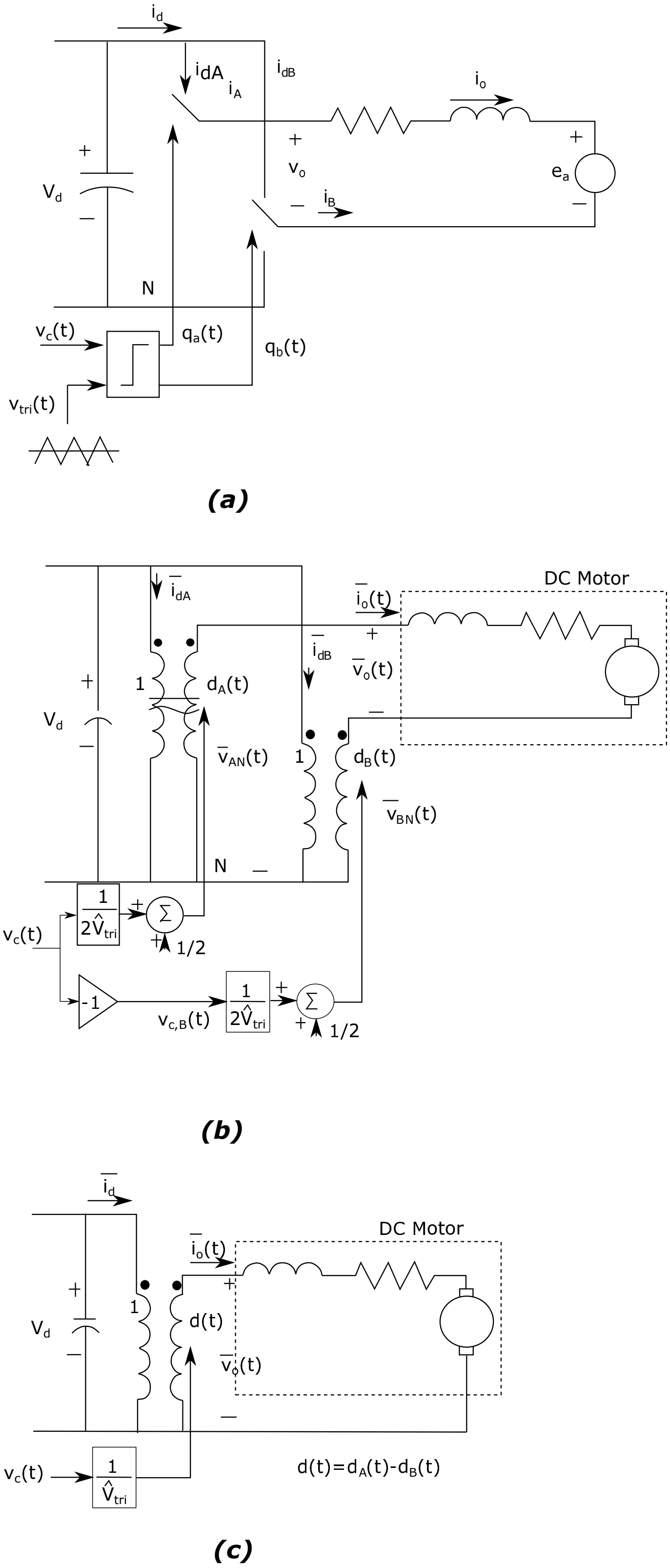


Figure 9: (a) The switching converter for a DC motor and the average representation (b) and (c).

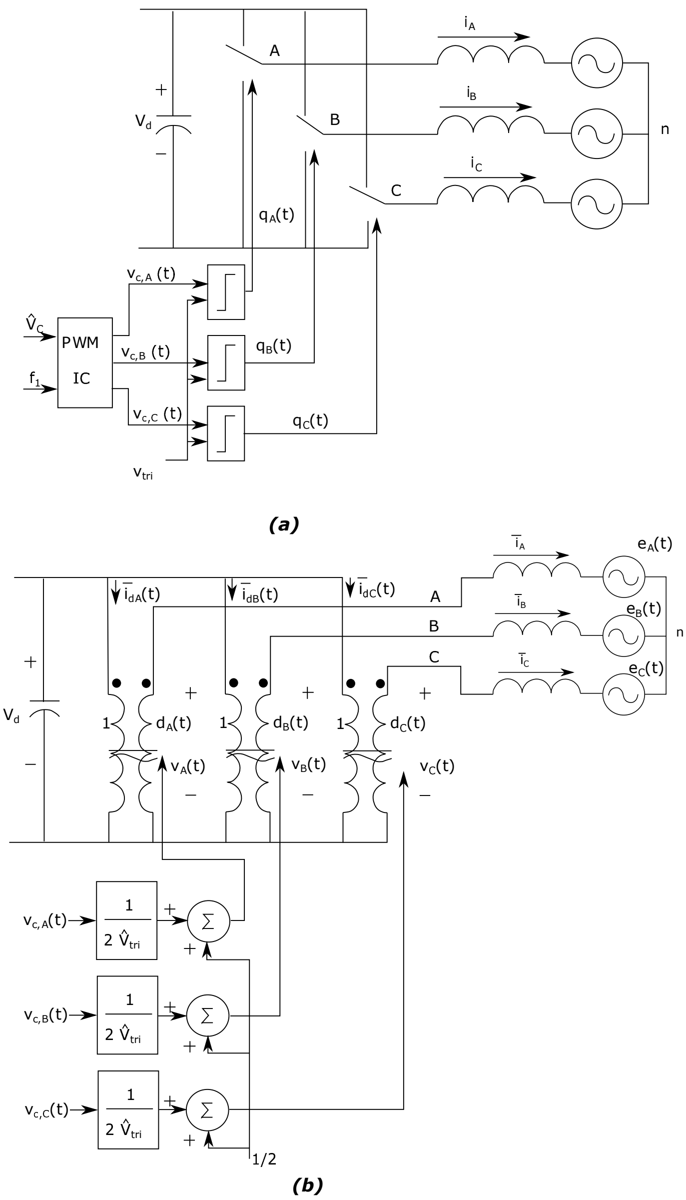


Figure 10: (a) The switching converter for a AC motor and the average representation (b).

### 1.4.2 Converters for three phase AC motors

The converter for AC motors works slightly different. The input of the converter is the amplitude $\hat{V}_c$ and frequency $f_1$ and is supplied by a feedback controller, based on current speed and setpoints given to the feedback controller, but will be shown later. The controller itself is not discussed further here. These inputs are fed to the Pulse-Width Modulation Intergrated Circuits (PWM-IC) to generate three control voltages:

$$v_{c,A}(t) = \hat{V}_c \, sin(\omega_1 \, t) \tag{23}$$

$$v_{c,B}(t) = \hat{V}_c \, sin(\omega_1 \, t - 120°) \tag{24}$$

$$v_{c,C}(t) = \hat{V}_c \, sin(\omega_1 \, t - 240°) \tag{25}$$

These three control voltages are then used to compare to the triangular waveform to get the switching functions $q_A(t)$, $q_B(t)$ and $q_C(t)$ with the following duty-ratios:

$$d_A(t) = \frac{1}{2} + \frac{\hat{V}_c}{2 \, \hat{V}_{tri}} \, sin(\omega_1 \, t) \tag{26}$$

$$d_B(t) = \frac{1}{2} + \frac{\hat{V}_c}{2 \, \hat{V}_{tri}} \, sin(\omega_1 \, t - 120°) \tag{27}$$

$$d_C(t) = \frac{1}{2} + \frac{\hat{V}_c}{2 \, \hat{V}_{tri}} \, sin(\omega_1 \, t - 240°) \tag{28}$$

When averaging is applied to the control voltages, the following is found:

$$\bar{v}_{c,A}(t) = \frac{V_d}{2} + \frac{V_d \, \hat{V}_c}{2 \, \hat{V}_{tri}} \, sin(\omega_1 \, t) \tag{29}$$

$$\bar{v}_{c,B}(t) = \frac{V_d}{2} + \frac{V_d \, \hat{V}_c}{2 \, \hat{V}_{tri}} \, sin(\omega_1 \, t - 120°) \tag{30}$$

$$\bar{v}_{c,C}(t) = \frac{V_d}{2} + \frac{V_d \, \hat{V}_c}{2 \, \hat{V}_{tri}} \, sin(\omega_1 \, t - 240°) \tag{31}$$

Two important notes to make here are that the DC offsets $\frac{V_d}{2}$ will cancel each other in the line-to-line voltages, and that the A-pole phase is chosen to be at 0°. In fact, the phase change can be at any angle by changing the $t = 0$ point, but it is important that the phases have a phase difference of 120°.

When equilibrium is reached, the average potential at 'load-neutral' point $n$ is the same as $V_d/2$, as this is the average voltage of all ports. Therefore, in this equilibrium position the average voltages from the phase to the neutral load point are:

$$\bar{v}_{An}(t) = \left( \frac{V_d}{2 \, \hat{V}_{tri}} \right) \hat{V}_c \, sin(\omega_1 \, t) = k_{pole} \, v_{c,A}(t) \tag{32}$$

$$\bar{v}_{Bn}(t) = \left( \frac{V_d}{2 \, \hat{V}_{tri}} \right) \hat{V}_c \, sin(\omega_1 \, t - 120°) = k_{pole} \, v_{c,B}(t) \tag{33}$$

$$\bar{v}_{Cn}(t) = \left( \frac{V_d}{2 \, \hat{V}_{tri}} \right) \hat{V}_c \, sin(\omega_1 \, t - 240°) = k_{pole} \, v_{c,C}(t) \tag{34}$$

where $k_{pole}$ is as described in Equation 9 and is the gain by which each pole amplifies the control voltage.

This shows that the converter for AC motors will generate the three-phase sinusoidal voltages of the desired frequency and amplitude.

## 1.5 Power semiconductor devices

The main drivers of the success of the frequency drives, are the switch-mode power converters, which rely n diodes and transistors as controllable switches that require only a small voltage as control voltage. The switches are characterised by the following quantities:

1. ***Voltage rating*** is the maximum electric potential applied to the device in 'off' state without damage;
2. ***Current rating*** is the maximum current (often RMS, average or instantaneous current) allowable in the device (allowing more would cause excessive heating and leads to failures);
3. ***Switching speeds*** are the speeds in which the device can switch from 'on' to 'off' and vice versa. The smaller the switching time, the lower the switching losses are. Furthermore, small switching times allow for operation at higher frequencies;
4. ***On-state voltage*** is the voltage drop accross the switch when it is in the 'on' position and while conducting a current. The lower the on-state voltage, the lower the power losses during the on-state.

This list of quantities shows that there are quite some differences between components.

***Power device ratings*** can vary between several $kV$ (up to $9kV$) for the electric potential and current ratings up to several $kA$ (up to $5kA$). These components can be combined in series or parrallel to satisfy any voltage and current ratings. The switching speed is however decreasing with the current and voltage ratings, ranging from a fraction of a milisecond to a few miliseconds. The on-state voltage is however usually in the range of 1-3 $kV$.

***Power diodes*** are available in the range up to $9kV$ and currents up to $5kA$. The on-state voltage drop is usually in the order of $1V$. Note that the fast-switching is used in switch-mode converters. However, the diode rectification of line-frequency AC can be accomplished by slower switching diodes, which have a slightly lower on-state voltage drop.

***Controllable switches*** are available in several forms:

- Bipolar-Junction Transistors (BJTs);
- Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs);
- Gate Turn Off (GTO) thyristors;
- Insulated-Gate Bipolar Transistor (IGBTs).

Of these types, the MOSFETs are primarily used at low power levels and IGBTs in power ranges extending to $MW$ levels. therefore, these two are further explained in the following paragraphs.

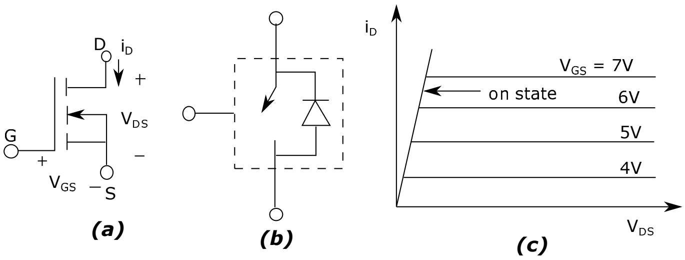


Figure 11: (a) and (b) The circuit symbol of MOSFETs and (c) the MOSFET characteristics.

### 1.5.1 MOSFETs

The MOSFETs are commonly used in voltages up to $200V$ and switching frequencies up to and above $50kHz$. The main benifit of MOSFETs are the low on-state losses, fast switching speeds and their ease of control. The circuit symbol is shown in Figure 11. It has three terminals: Drain $D$, Source $S$ and gate $G$. The main current flow between drain and source. When completely off, as depicted in Figure 11 (b), it approximates an open switch when the electric potential between gate and source is zero. To get the MOSFETs to the on-position, the gate-source voltage of typically 10-15$V$ must be applied continuously.

Important to note is that the MOSFETs in general cannot block negative voltages, so a reversed polarity should be prevented by the circuit.

### 1.5.2 IGBTs

IGBTs combine the ease of control of MOSFETs with low on-state losses with high voltage ratings. The switching frequencies are up to $30kHz$. Therefore, theses IGBTs are used often in the $kW$ to $MW$ range.

The circuit of the IGBTs is shown in Figure 12 (a), while the characteristic is shown in (b). The control is similar to the MOSFETs with the gate that requires only a small amount of energy to switch the device. Just to give an idea of the on-state power losses, the electric potential in the on-state of an $1200V$ IGBTs is approximately $2V$. Similar to the MOSFETs, the IGBTs cannot block negative voltages.

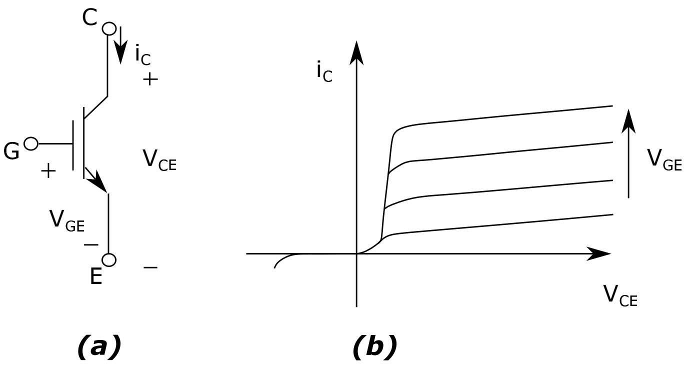


Figure 12: (a) The circuit symbol of IGBTs and (b) the IGBTs characteristics.

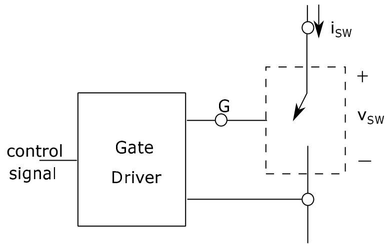


Figure 13: Block diagram of a gate-driver circuit.

The switch times of IGBTs are in the order of 1 microsecond, meaning a switching frequency if $1kHz$ is possible, for ratings of $3.3kV$ and $1200A$. The voltage ratings can become as high as $5kV$, although it might mean lower switching frequencies.

### 1.5.3 Smart power modules including gate drivers

To translate the control signal to the gate voltage of the power semiconductor switch, a gate-driver circuitry is required. An example is shown in Figure 13. The 'Smart power' modules, or Power Integrated Modules (PIM), combine multiple switch and diodes along with the required gate-drive circuitry. Often these modules also include fault protection and diagnostics, making the design of the converters much simpler.

## 2 Current Source Inverter

Inverters are used to convert DC to AC power. The Pulse-Width Modulation (PWM) as shown before keeps the DC voltage the same, while varying the current taken from the supply. The Current Source Inverter (CSI) (also called Current Fed Inverter) makes the current from the source constant, and varies the DC voltage at the output to obtain the constant current.

In Figure 14 a) a schematic is shown. The voltage $V_d$ here is the DC bus, and this voltage is not constant. In series with the DC bus is an inductor $L_d$, and is a storage for current to keep the source current equal while supplying current when needed. The thryristors, capacitors and diodes then control the AC current to the motor phases. For a given speed, the torque is controlled by varying the DC current $I_d$ by varying the voltage $V_d$.

When connected to an AC power supply, the CSI requires a fully controlled rectifier in order to control $V_d$, as shown in Figure 14 b).

When connected to a DC power supply, a chopper is installed between the DC supply and $V_d$ in order to control $V_d$ as shown in Figure 14 c). A chopper converts fixed DC input to a variable DC output, which is required here.

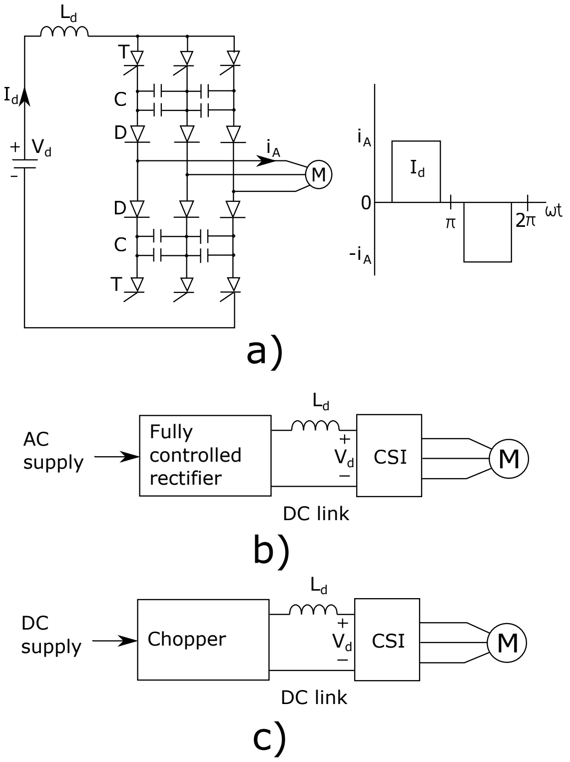


Figure 14: a) Schematic view of an Current Source Inverter (CSI). b) Connection of CSI to an AC supply. c) Connection of CSI to a DC supply.

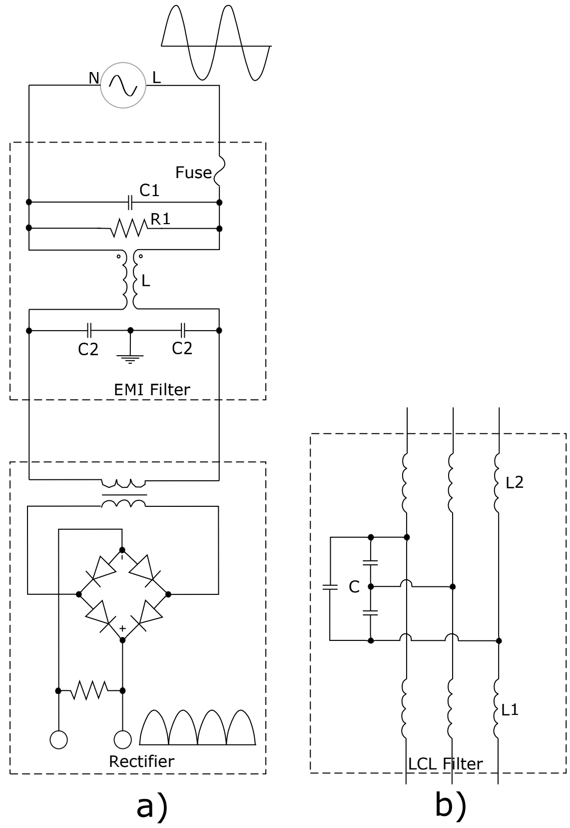


Figure 15: a) Schematic view of an EMI filter at the supply (before rectifier). b) An example of an LCL filter for three phase systems.

# 3 Practical notes

In this section, some practical notes are added to variable frequency drives that need to be considered during the design phase.

## 3.1 Filters for Variable Frequency Drives

In general two types of filters are applied to Variable Frequency Drives (VFD): One filter to filter the AC supply and one filter to smoothen the PPU output signal.

### 3.1.1 Supply EMI filter

In the supply to the PPU, just before the rectifier[2], a filter is used to prevent in-rush currents, guarantee the harmonics and to filter high frequency Electro-Magnetic disturbances from the power source. This filter is an Electro-Magnetic Interference (EMI) filter, and an example of the schematics is shown in Figure 15 a) for a single phase and b) a simplified version for a three phase supply. The VFD uses high frequency switching, which in turn can cause radio frequency noise as well as low frequency harmonic noise that can effect other systems connected to the power supply line. Typical frequency bands where these filters work are from 150kHz to 30MHz.

Looking at Figure 15 a) the capacitor $C1$ attenuates spikes in the supply. The resistor $R1$ is a high value resistor, typically $1M\Omega$ and is installed to discharge the capacitor once the supply is suddenly removed. Inductor $L$ in the supply as well as neutral line acts as a current compensated choke and is wrapped around a core. This is done so that the current through the windings cancel out the magnetic field. Disturbances in supply and neutral line due to switching in the PPU see this $L$ as a high impedance, choking the current rush. Capacitors $C2$ divert noise current to the ground.

In Figure 15 b) a three phases variant is shown. The inductors here have the same function as the inductors in Figure 15 a). The drawn capacitors are the noise capacitors similar to the function of $C2$ in Figure 15 a). The resonance frequency of the filter needs to be placed correctly for the filter to work. The LCL is in basics a third order low pass filter. A too low resonance frequency means that too much will be filtered, and may even mean that an extra resonance is present in the system, making the system less stable. A too high frequency means that the filter does not filter the signal properly. Note that if multiple VFD are not acting simultaneously (switching simultaneously), each PPU of the VFD needs a separate LCL filter, as otherwise the harmonics are not properly filtered.

[2]For more info about the rectifier, see [3]

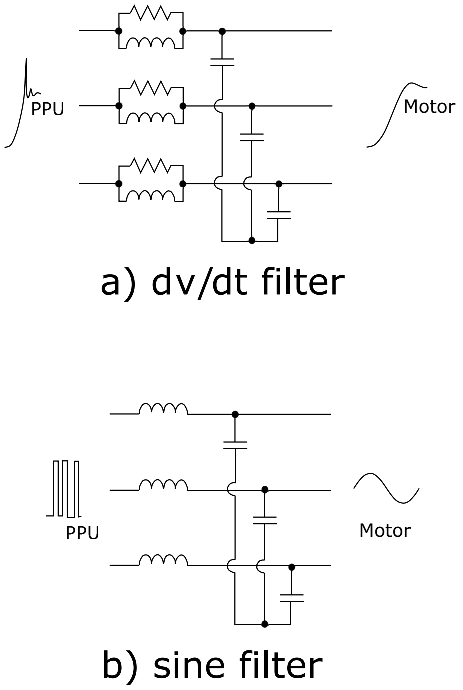


Figure 16: a) Schematic of an dv/dt filter. b) Schematic of a sine filter.

#### 3.1.2 PPU Output dv/dt and sinus filters

As the Power Processing Unit (PPU) usually uses pulse-width modulation (PWM) at high switching frequencies (normally up to 30kHz), filters are used to convert this high frequency switching to a more sinusoidal signal. Output chokes (basically inductors) are usually only used up to 100Hz, so for the higher frequency VFD sinusoidal filters are used. In general there are two types: dv/dt filters and sinus filters, see Figure 16 for the schematics.

**dv/dt filters** The dv/dt filter is a filter that can filter switching frequencies up to several kHz. The voltage peaks are flattened, but will not be completely gone, as shown at the motor side in Figure 16 a). This means that voltage pulses will still be present. To fulfil the motor standards, this filter can only be used for short cable lengths.

**Sine filters** The sine filter can filter frequencies up to several tens of kHz. The output is much more a sine wave, even if the input are voltage pulses. With this type of filter the compliance with motor standards is normally guaranteed.

### 3.2 Shielding of the cable between PPU and motor

The cable between the Power Processing Unit (PPU) and the motor is not a normal cable. This is due to the high currents that create magnetic fields around the conductor (cable), see also [3] for further reading. High currents are also created due to the pulse-width modulation (PWM) high switching frequency, as the voltage difference over the cable switches quickly from 0[V] to maximum, creating high currents. The main components are:

- Outer jacket;
- Shield (with possibly a second shield) to act as a cage of Faraday;
- 3x conductors, one for each phase, each with insulation;
- 3x ground cable to cancel magnetic field by inducting a voltage.

#### 3.2.1 Outer jacket

The outer jacket is for isolation purposes, normally made of PVC. Colour is normally different from other cables to make these recognizable.

#### 3.2.2 Shield

The outer shield is normally either foil or braided.

Foil shielding is normally made of a thin layer of copper or aluminum with polyester backing to increase durability. The foil shielding is light weight, offers a 100% coverage of the area and works up to high Radio Frequency Interferences (RFI). Foil shielding is however fragile and is not very flexible, so for dynamic applications or bending of the wire this is not advised.

A braided shield is made of tightly woven tin or copper wires and is the most traditional method of shielding. Advantages of the braided shield is that it is strong (not fragile) and flexible. It works best in the low to medium Electo-Magnetic Interference (EMI) frequencies. The disadvantages are that it is more bulky (larger cable diameter), heavier, more expensive and timeconsuming to manufacture, is less easy to terminate (e.g. connector at the end of cable) and the main disadvantage is that it does not give a 100%

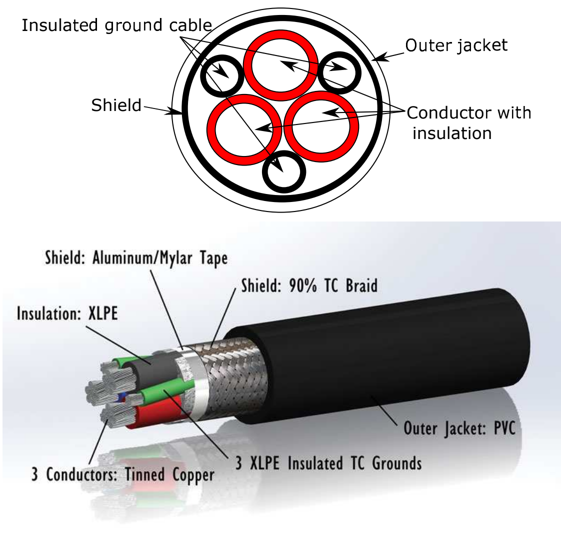


Figure 17: Schematic view of the VFD motor cable (top) and a practical example of a cable (bottom)

coverage. There are braided shields available that cover 70% to 95% of the area. This is dependent on how the shield is woven. This value is also mentioned in the data sheets of the wires.

Some (larger) cables also combine an outer braided shield with a foil shield.

The shield is normally connected to earth at one side of the cable. This is not done at both sides, to prevent that the shield is used to equalise different ground levels and to prevent too high currents in the shield, as it is designed as magnetic shield only.

### 3.2.3 Conductors

The three conductors carry the current to the motor. These conductors are normally of tinned copper and have insulation.

### 3.2.4 Ground cables

The three ground cables are between the conductors, to allow for an induced voltage in the grounded cable due to the (changing) magnetic fields of the conductors. By inducing the voltage as per Faraday's law (see [3]) the magnetic field is decreased. By connecting these cables to ground, the induced voltage will create a small current to ground. Grounding is normally done at the motor as well as drive side, contrary to the shield, which is normally grounded on one side. This is due to the thicker cable when compared to the shield. The ground cables are normally smaller than the conductor cables, as the current through these is much smaller.

## References


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[4] Ned Mohan. *Electric Drives*. MNPERE, 2003.