New Output Filter Concept for Power Drive Systems

Author: Stefan Melly, Product Marketing, August 2002

The use of modern drives brings up numerous questions concerning the reliability and operational safety of complete systems. The new «Sinus Plus» output filter concept from Schaffner contributes a lot to the fact that most of the problems related to frequency converters can be solved.

1. Initial situation

Modern frequency converters for regulating the rotational speed of AC motors are today an integral part of both the industrial and residential environments. There have been detailed reports about the advantages of regulated and unregulated drives in all possible forms of the relevant literature. This article will, instead, discuss the interference-causing potential of frequency converters - something that cannot be neglected - and the corresponding solutions to counter it.

Both the limits as well as interference-suppression measures for electromagnetic compatibility (EMC), and since January 2001, also for harmonics, are completely subject to international standardization. However, if the entire problem is viewed not from the perspective of the standards, but from the perspective of the reliability and operational safety of the entire system, it is found that the safety is in no way guaranteed, owing to the conditions prevailing at the output of the frequency converter.

At present, there are trends to be observed in the frequency inverter market, which could have tremendous effects on the reliability of entire drive systems as well as on the measures to be taken to guarantee it:

- Miniaturization, both in the case of frequency converters as well as of motors; often accompanied by savings in costs of the insulation strength of motor windings
- Retrofit of frequency converter drives in existing systems with old motors and unshielded cables
- Trends towards high-rotational speed machines with low mass (e.g. HF-spindles)
- Innovative low-speed motor technologies with a high number of poles (e.g. tool beds with torque-motors in machine-tool engineering applications)

2. Problems at the frequency converter output

The most important problem cases in the context of the output signal of modern frequency inverters (e.g. pulse-width modulation) are explained below.

2.1 dv/dt – Voltage potential jumps in relation to the time:

In order to keep the losses in the frequency converter or servo low, the aim is to keep the switching times of the power semiconductors as short as possible. The result of this is that with the newest generation of IGBT's, rise times of - sometimes - more than 12kV/µs can be measured, whereas – depending on the motor – a dv/dt of <1000V/µs is considered as permissible (VDE0530: 500 – 1000V/µs).

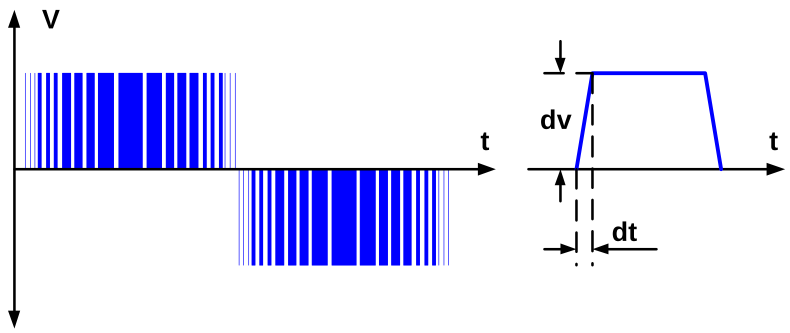


Fig. 1: PWM-Signal and single pulse at the inverter output

In the case of short motor cables up to about 20m, these rise times - owing to the small line impedance - act fully on the insulation of the motor windings. Depending on the structure of the motor coils, wires that carry the full voltage are situated immediately in parallel and next to each other. Since even very short parallel-laid wires have a capacitive action, the permanent potential jumps result in pole reversal losses across the winding insulation. Now, if the enamel insulation is impure even to a very minor extent, this results in the so-called hot-spots, and hence, sooner or later, to a destruction of the winding insulation.
In any case, this dv/dt-stress load leads to premature aging and hence to a reduction in the life of the motor.

2.2 Voltage overshoots and voltage peaks:
Due to the structure of the windings, a motor acts in the equivalent circuit diagram – owing to the fast voltage pulses of the switching frequency – like a capacitor and not, as is the case of normal 50Hz applications, as an inductance. With every additional meter of motor cable, more wire inductance is added to this structure. This inductance acts like a choke according to the energy storage principle. If chokes are subject to voltage pulses, voltage peaks occur every time switching on or off takes place. The higher the energy content (inductance) of the choke, the higher do these voltage peaks become. I.e. the longer the motor cable, the higher the maximum voltage amplitudes. These amplitudes can, in turn, reach values that cause a stress situation in the winding insulation of the connected motor.

Owing to the cable impedance, the dv/dt stress – in the case of longer motor cables – is reduced to less problematical values. On the basis of the line theory, however, peak values of 1600V or more can occur due to cable reflections, which can have very steep dv/dt values. According to VDE0530, peak values of <1000V are permissible.

Despite the reduced dv/dt owing to the cable impedance, this does not result in any significant stress relief for the motor, since now, the increased voltage amplitudes represent the dominant stress factor.

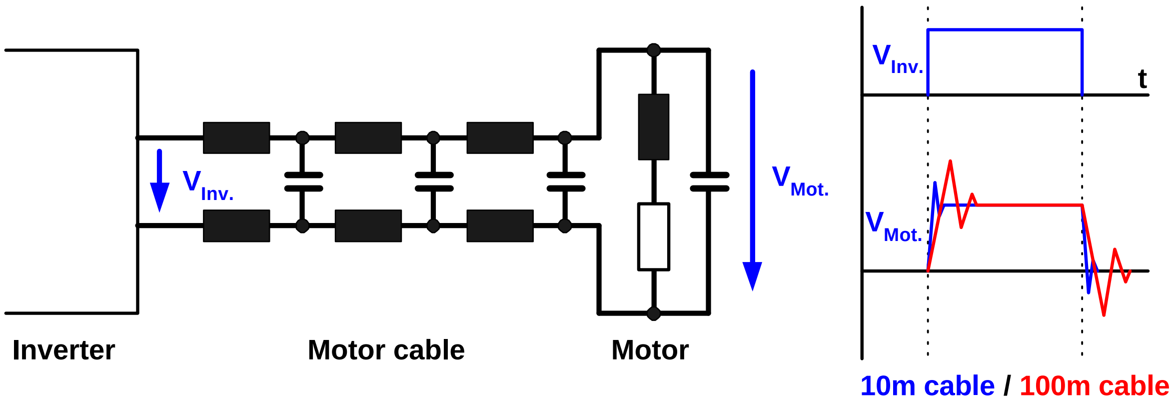


Fig. 2: Simplified equivalent circuit diagram (only 2 phases are shown) and theoretical single pulse at 10m and at 100m motor cable length

2.3 Additional losses in the motor:
Apart from the problem with the winding insulation, owing to the steep switching edges, another phenomenon occurs: harmonics of the output signal. By applying Fourier analysis, it can be mathematically proven that the harmonic spectrum of the motor currents becomes wider with the steepness of the pulses; i.e. the harmonic content increases. The current ripple (PWM + harmonics) results in additional magnetic losses in the motor. The life of the motor is sensitively shortened owing to the permanently increased operating temperature.

2.4 Cable shields and parasitic earth currents:
From the standpoint of EMI suppression, shielded motor cables are required to avoid back-coupling of radiated interference to the mains cable in the frequency range from about 1 - 30MHz. This measure of the EMC can, however, only be considered to be efficient, if the ends of the cable shield of the motor cable are put in contact with the ground of the motor and the frequency converter if possible at HF low-impedance and over as large an area as possible. This ensures that the interference currents can mostly flow back to the source by the shortest route.
Frequency converters normally work in grounded networks and do not have any potential separation. The geometric expansion of both, the frequency converter, motor and this shielded motor cable therefore form parasitic capacitance's of the electrically conducting components with respect to the ground potential. If the available DC voltage is chopped in the frequency converter, then, during the potential jumps of the voltage, considerable pulse currents flow across the parasitic capacitance's to the earth. The level of the interference currents on the cable shield depends on the dv/dt as well as the value of the parasitic capacitance's ($I = C * dv/dt$). With a motor cable length of about 100m, peak values of the pulse currents of 20 Amperes and more are not unusual, regardless of the power rating class of the drive.
The harmonic spectrum of these currents can reach a range of several MHz. The shield of the motor cable offers, owing to the existing braiding, a very large surface area and a sufficient cross-section to carry these currents. As a result, the impedance of the shield across a broad frequency range is of a very low-impedance nature. Losses owing to skin effect are limited to a minimum owing to the large surface area. However, inadequate ground connections of the cable shield (the so-called **«**Pig-Tails**»**), on the other hand, are highly resistive for the frequency range under consideration and often nullify the desired shielding effect.
If there are parallel-laid control cables or electronic components in the vicinity of the motor cables, pulsed HF currents flow across their geometric expansion and the resultant parasitic capacitance's, which in turn could have an impermissible influence on neighboring equipment through capacitive coupling.

If neighboring components are located in the immediate vicinity of the motor cable, the conductor loops and the high di/dt values of the shield currents additionally result in a magnetic coupling, which can also result in impermissible influencing.

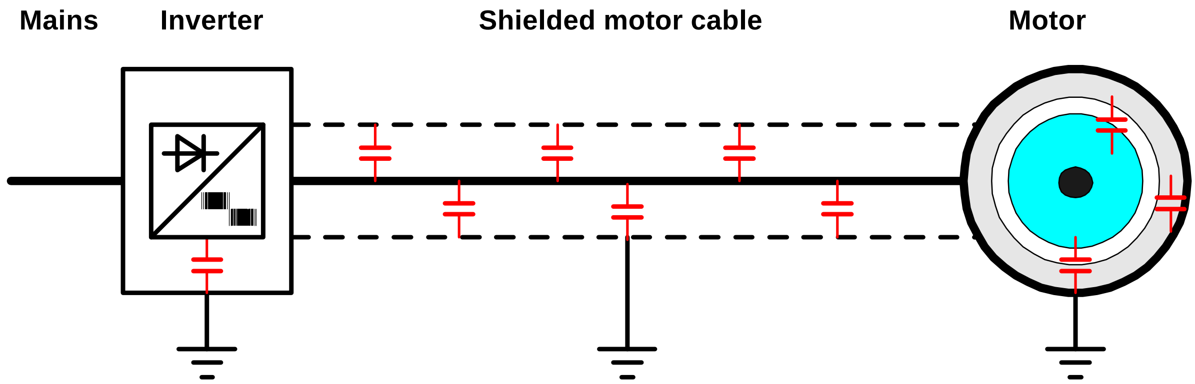


Fig. 3: Some of the most important parasitic capacitance's in a drive system

The currents flowing across the shield must be supplied by the frequency converter additionally. They are not dependent on the rating of the drive, but only on the geometric expansion of the structure. With small power ratings, the result of this, especially in case of long motor cables, can be that a frequency converter of the next higher rating has to be used, which is able to supply both, the currents required by the load, as well as the parasitic currents via the earthing.

The operation of several motors, which are connected in parallel on one frequency converter, is problematical. The parallel connection of several shielded cables results in a relatively high total capacitance and hence to the correspondingly high shield currents. The parallel connection of several drives, however, brings even more problems with it. Parasitic currents across the motor and the entire system can considerably affect the reliability of the whole system.

2.5 Bearing damage:

Basically, a distinction has to be made between two different physical occurrences:

- the *shaft voltage* (or rotor voltage) is an inductive voltage that is induced in the motor shaft owing to the differences in the flux densities of the stator and rotor. Above all, it is influenced by the length of the motor. As long as the lubricant film in the bearing is intact, the voltage builds up till finally, a compensating current flows towards the earth. In this case, the path of least resistance is through the motor bearings. This bearing current (**I_1**), over a long period of time, usually results in drying of the bearings and thus failure of the motor. To a certain degree, it is possible to counter this phenomenon by using ceramic bearings.

- the *bearing voltage* is an asymmetric (common mode) voltage, which occurs because of capacitive coupling between the motor housing, the stator and the rotor (**C_1, C_2, C_3**) and results in dv/dt- and electrostatic discharge currents ($I_{dv/dt}$ and I_{EDM}) across the bearing (**$C_{Bearing}$, $U_{Bearing}$**). To be more accurate, this bearing voltage results in two different currents: in the first minutes of operation, as long as the lubricant in the bearing is cold, currents in the range from 5 - 200mA ($I_{dv/dt}$) flow through **$C_{Bearing}$** because of the dv/dt. These rather negligible currents generally do not result in any bearing damage. When the lubricant film has got heated up after a little while, peak currents of 5 - 10A and more can be measured (I_{EDM}). These flashovers leave behind small pits on the surface of the bearing. The running of the bearing becomes increasingly rougher because of the damaged surface and the life thus gets considerably shortened. Typically, the bearing voltage is between 10 and 30V. But since it is directly dependent on the mains supply voltage, bearing damage increases over-proportional with higher supply voltages.

In the case of unshielded motor cables, the cable capacitance (**C_{Cable}**) and hence the current (**I_{Cable}**) is relatively small. The parasitic capacitance's in the inside of the motor dominate. In the ideal case, the parasitic currents flow through the motor housing to the ground (**I_{C1}**). However, if the grounding of the motor is inadequate, an additional impedance results (**Imp.**), which limits the current (**I_{C1}**). As a result of the additional impedance, the potentials at **C_2, C_3** and **$C_{Bearing}$** increase sharply. The values of the bearing currents also increase massively, and flow fully through the bearings to the earth (**$I_{Bearing}$**); in that case, the life expectancy of the ball bearings, and hence of the entire motor is reduced to a few hours.

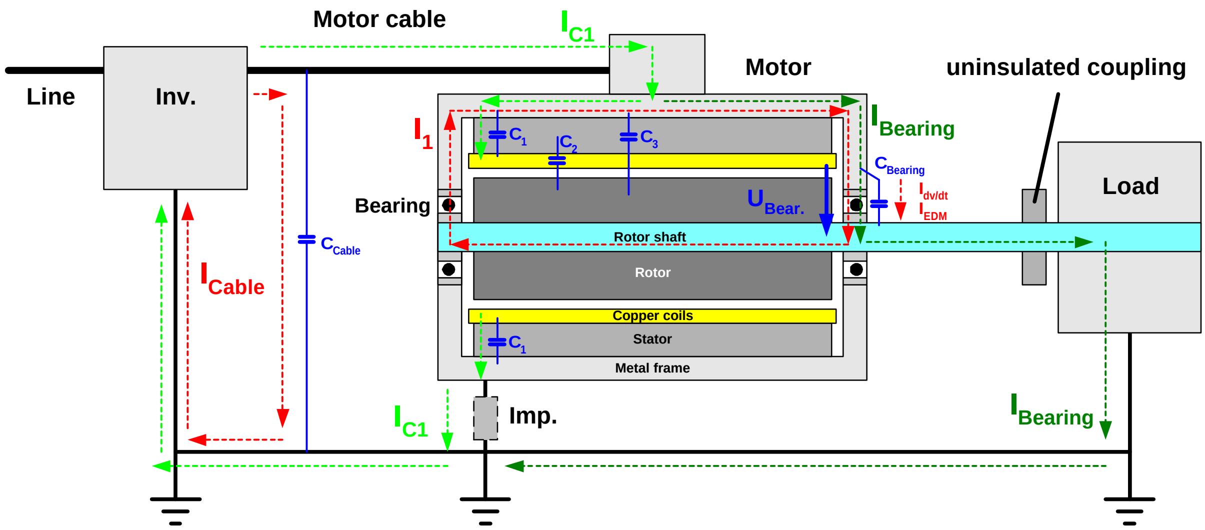


Fig. 4: Longitudinal section through a motor, parasitic capacitance's and bearing currents

2.6 Acoustic noise levels:

As compared to the previously described problem cases, the whistling noises – caused by the switching frequency – of the motor would appear to be negligible. However, in applications related to heating, air-conditioning and ventilation technology, in which the noise is distributed more intensely in the entire building through air ducts or heating pipes, this point has to be taken into account.

3. Possible solutions

In general, because of reasons of cost, time and space, an attempt is first made to manage without additional components. However, often, the consequential costs that can result from motor or system failures are out of all proportion to the far lower initial costs of preventive interference suppression measures.

If the decision goes in favor of components for increasing the reliability and operational safety, the following types have established themselves in the market:

- dv/dt chokes and filters (low inductance, hardly any reduction in the control dynamic)
- Motor chokes (increased inductance, better signal smoothing, but cannot be universally used in the case of controlled drives)
- Sinusoidal output filters (high L and C for optimizing the output signal, cannot be used universally either *)

3.1 Traditional symmetric sinusoidal output filters – FN5020:

By traditional symmetric sinusoidal output filters, one means LC-low passes filters, which convert the PWM-signal of the frequency converter between the phases into a smooth sinusoidal curve. The residual ripple of the signal can be adjusted exactly by using the values of the L and C. An optimum cost-benefit ratio is often reached at a ripple voltage of 3 - 5%.

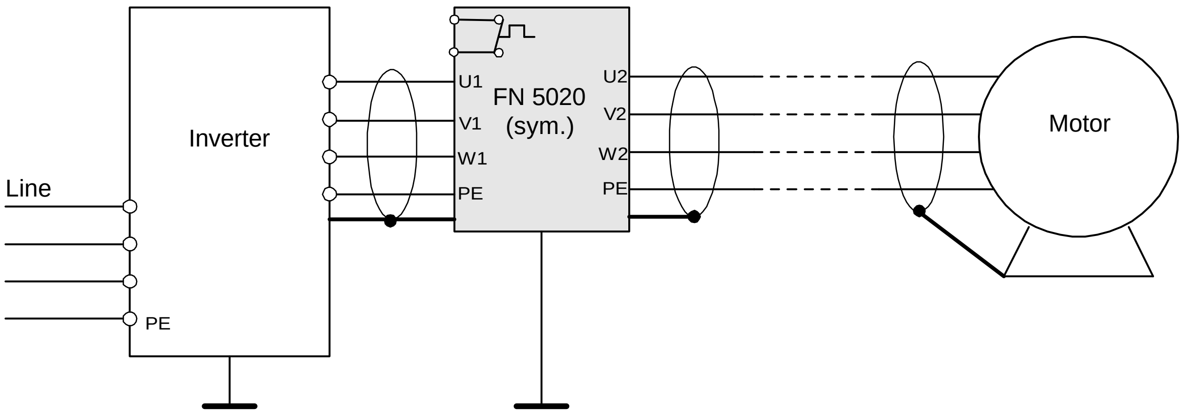


Fig. 5: Block schematic of a drive with symmetric sinusoidal filter at the frequency converter output

Symmetric sinusoidal output filters, which are connected directly to the converter output, have, above all, the following advantages:

- Complete protection of the motor from dv/dt and over-voltages
- Reduction of the additional magnetic losses and eddy current losses in the motor
- Reduction of the additional losses of the frequency converter owing to lower pulse currents to earth
- Reduction of the acoustic noise of the motor
- Reduction of the interference potential, coming from shielded motor cables
- Increasing the reliability and operational safety of the overall system

For a large number of applications, this can be considered to be the ideal solution. A large number of problems is solved efficiently and in a cost-effective manner with the symmetric sinusoidal signal.

(Remark: it must be noted here, that the use of sinusoidal filters is suitable for servo drives with synchronous or torque motors only to a limited extent because of the time function element (idle time), and the concomitant reduction in the control dynamic, since a 100% reproducibility of the sequences has the highest priority. Alternatively, dv/dt-filters and chokes can be provided).*

In some cases, additional measures are necessary. Symmetric sinusoidal filters, despite all their advantages, are not able to improve certain problem cases, since despite the filter, there is still a pulsed signal to earth. These problems are:

- Bearing damage
- Parasitic earth currents
- Necessity of shielded motor cables
- Limited maximum possible motor cable length

3.2 «Sinus Plus» – FN5020 & additional module FN5030:

Sinus Plus is a highly developed modular sinusoidal filter concept from Schaffner, which is unique in the market today. Consisting of a traditional symmetric and an additional asymmetric sinusoidal filter module, it can be customized exactly to any requirement. The additional module is capable, using innovative circuits and additional connection to the dc-link, of sending the asymmetric interference's directly to the very place where they have originated.

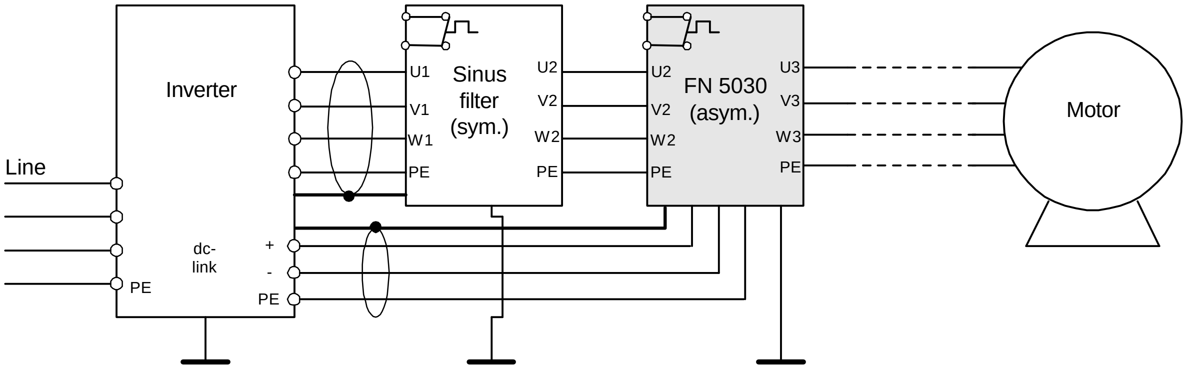


Fig. 6: Block schematic diagram of a drive with sym. and asym. sinusoidal filters at the frequency converter output

This procedure is in keeping with the basic principle of interference suppression techniques: take the necessary measures at the source of the noise, not at the drain.

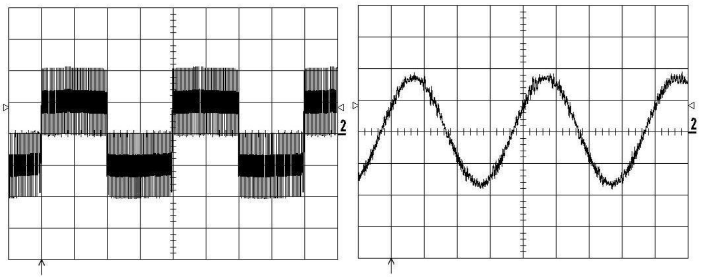
Sinus Plus should always be considered to be a modular system in which the symmetrical filter part (FN5020) can be connected autonomously, but the asymmetric (FN5030), on the other hand, may only be connected together with the symmetric module. Operated in combination, this solution results in the following additional advantages:

- Complete elimination of bearing damage
- The possibility to use unshielded motor cables without any reductions in the immunity
- Practically no more limitations with regard to the maximum cable length
- Almost complete elimination of the pulse currents to earth
- No interference influence of neighboring cables and equipment
- Elimination of the additional losses in the frequency converter
- Reduction in the suppression efforts on the input side. Since frequency converters are operated in ground-referred networks, every measure taken on the output side also influences the behavior on the input side (and vice versa). Owing to the fact that when Sinus Plus is used, hardly any pulsed interference currents flow to the earth, the asymmetric part of the EMC mains input filter can be reduced resulting in total cost savings.

Sinus Plus is designed for motor frequencies up to 600Hz and thus takes into account the trend in the market towards motors with higher rotational speeds.

3.3 Measurement results:

The following measurement results show the step-wise improvement of the signal quality from the output signal of the frequency converter to the signal at the motor, after the sinusoidal output filters. *(Measurement results 7, 8 originate from another measurement setup than that of 9, 10, but are nonetheless suitable for illustration purposes).*

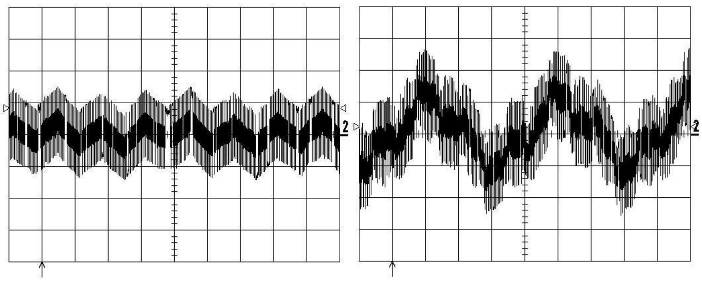


A B

Fig. 7:

Curve A: Inverter output U_{P-P}

Curve B: Signal at the motor after the sym. sinusoidal filter U_{P-P}



A B

Fig. 8:

Curve A: Inverter output U_{P-E}

Curve B: Signal at the motor after the sym. sinusoidal filter U_{P-E}

It can be clearly said that after the symmetric filter module U_{P-P} has a near-mains quality, U_{P-E} however still has potential for improvement.

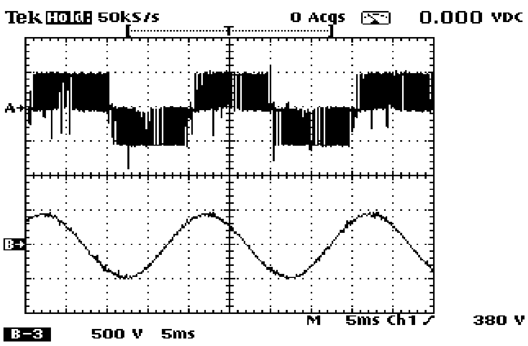


Fig. 9:

Curve A: Inverter output U_{P-P}

Curve B: Signal at the motor, after both sinusoidal filters U_{P-P}

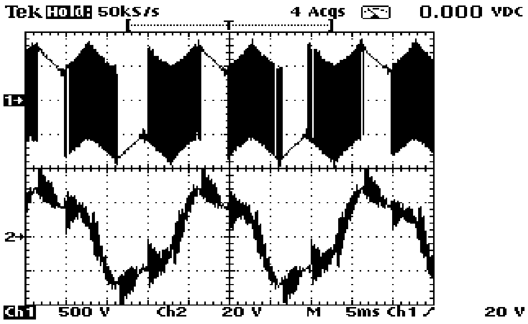


Fig. 10:

Curve 1: Inverter output U_{P-E}

Curve 2: Signal at the motor, after both sinusoidal filters U_{P-E}

Both sine waves (U_{P-P} & U_{P-E}) at the motor can theoretically be optimized further with relatively simple measures. However, the whole issue must also be viewed from an economic perspective. Therefore, in developing this series of filters, the uppermost priority was given to an optimum problem solution with the most economical effort possible.

3.4 Standard solution FN5020 & FN5030:

Sinus Plus consists of the filters FN5020 (sym.) and FN5030 (asym.) and has the following technical specifications:

Operating voltage:	3 x 500VAC / 1000VDC
Rated currents:	25, 55, 75 and 120A
Ambient temperature:	50°C
Temperature range:	-25°C to +100°C
Motor frequency:	up to 600Hz
Switching frequency:	6 - 15kHz
Filter combinations:	FN5020 & FN5030 (other combinations after discussion)
Extras:	Sinusoidal output filters for other current ranges or specifications available on inquiry.

(Further details can be found in the technical data sheet)

3.5 Application examples:

- *Retrofits:* if existing installations have to be upgraded with frequency inverters, the problem to be confronted is that often, neither the motor nor the - usually - unshielded cables are “frequency-converter-capable“. Owing to their location in the system, they cannot be replaced, or can be replaced only with considerable effort and difficulty (e.g. underground pump systems etc.). By using Sinus Plus, it is possible to continue working with the existing unshielded cable without a second thought; in addition, the connected motor is also protected efficiently.
- *Chemical industry:* in the chemical industry, in particular, the use of shielded motor cables is often excluded because of technical safety regulations. Sinus Plus makes operation possible in such cases without the necessity for any major workarounds.
- *Savings potential:* if the fact is taken into consideration that instead of connecting several hundred meters of shielded cable to a drive, unshielded cables can be used, it is possible to achieve cost savings that far exceed the procurement cost of Sinus Plus.
- *Cranes:* often, crane applications have stringent requirements for the flexibility of the cables. Dispensing with the less flexible shielded cables, as a direct result of using Sinus Plus, goes a long way towards satisfying this requirement.

4. Conclusion

By using the Sinus Plus output filter concept of the Schaffner company, the output signal of various frequency inverters is optimized both symmetrically and asymmetrically. Being a modular system, it can be combined optimally according to requirement and application and can thus eliminate all the problems that go with modern frequency converters. Costly failures and down-times of production plants will be a thing of the past, if such failures are attributable to the physical properties of the frequency converter. Efficiency, reliability, operational safety and availability are increased to a great extent. Since the output signal after the two filter modules has a quality close to that of the mains supply, subjects like cable length and cable shielding become insignificant factors, which opens up completely new perspectives with regard to location of deployment and flexibility.
In the meaning of an optimal problem solution, the decision for or against a particular approach must, in any case, be based on a sound technical and economic analysis.

More detailed information, technical data sheets as well as help in every phase of the product life-cycle can be obtained from the local Schaffner subsidiary or from the head office.