Analysis of the limitations on the ability of the three-phase system to drive an electric motor, and possible alternatives for improving the thermal efficiency and power output in particular

Brief explanation of the Achilles heel of the three-phase system

In short, the core problem with the three-phase system is that it only works with analogue sine signals with a fixed phase difference.

The three-phase system only works with pure sine waves because the rotation speed of the motor depends on the frequency of the signal, and a pure sine wave is the only signal that contains only one frequency. Anything other than a pure sine wave will limit the thermal efficiency. This is because non-sine-wave signals, which contain multiple frequencies, will attempt to drive the rotor at multiple speeds simultaneously.

The three-phase system also only works with a phase difference, as this phase difference is used to rotate the magnetic field in the motor, and without a phase difference the motor cannot rotate.

The three-phase system was designed as an analogue system, and the current in the coils must follow an analogue waveform (sine) to work most efficiently. This poses a problem because the electronics are bulkier and more expensive than in a purely digital solution.

The core problems of the three-phase system are responsible for a snowball effect of resulting limitations, the most important of which are discussed below.

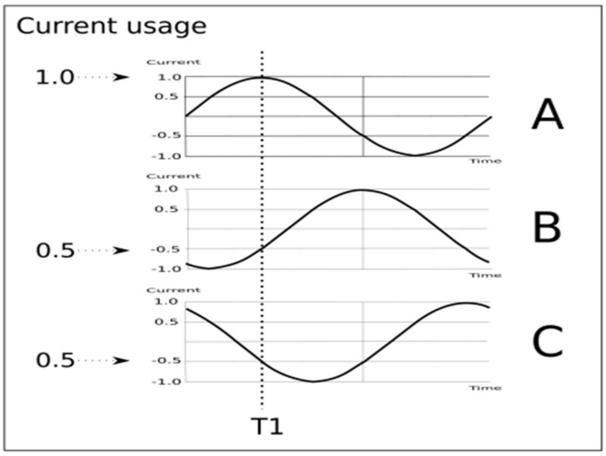
Poor use of the maximum current capacity

When designing an motor and its electronics, efforts are made to optimise the individual parts in relation to each other, so that they are not over- or under-dimensioned in comparison to each other. This is done both to reduce the manufacturing costs and to increase lifespan.

A sinusoidal signal has a relatively high maximum value (PEAK), but a significantly lower average value (AVG). The entire system must therefore be dimensioned to handle the maximum current and voltage dictated by the sinusoidal curve, even though the average values are much lower. This means that the maximum current that the system is designed to handle is only present for a fraction of the time.

Furthermore, the three-phase system is based on three phases with a phase difference. This means that there is no point at which the three phases (A, B and C in Figure 1) have the maximum current simultaneously.

Fig. 1



Estimated current usage

Usage of electric current capacity, at time T1

(1+0,5+0,5) /3 = aprox **67 %** current usage

From Figure 1, it is easy to see that there is no point at which the three phases (A, B, and C) have the maximum current simultaneously. It can also be estimated from the graph that the utilisation of the maximum current capacity at time T1 is approximately 67%. Mathematically, it can be proven that the three-phase system has an average utilisation of the maximum current capacity of 63%. This corresponds to the average value (AVG) of the sinusoidal curve. For an electric motor, there is a direct correlation between the current in the coils, the magnetic field, and the torque and power of the motor. The use of a sinusoidal signal therefore limits the utilisation of the current capacity and hence also the amount of torque and power that the motor can provide.

Suboptimal form factor

The form factor is determined by the ratio between the RMS and AVG values for a waveform. The form factor is extremely important, as it affects the thermal efficiency that can be achieved when a particular waveform is used in an electric motor. In simple terms, the AVG value tells us something about how strong a magnetic field we can achieve in the motor, and the RMS value tells us something about how much heat we generate.

In general, a strong magnetic field is desirable with the least possible heat generation, a situation that corresponds to a form factor of one. Figure 2 shows formulae for the heat loss and magnetic field, which can be used to calculate the thermal efficiency that can be achieved with different waveforms.

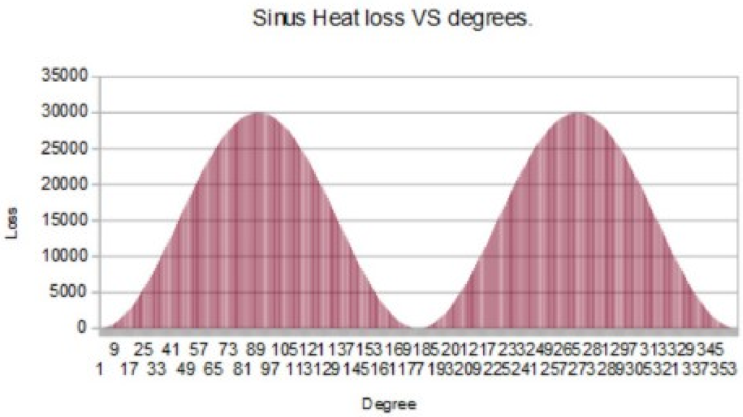
Fig 2.

Heat loss (Joule heating) $Q = I^2 \times R \times t$ > $Q = I^2 \times K$

Magnetic field strength $H = (I \times N) / L$ > $H = I \times K$

It can be seen from the formulae in Figure 2 that the heat loss (Q) essentially increases with the square of the current, while the magnetic field (H) only increases linearly with the current. In practice, this means that the form factor of the waveform affects the thermal efficiency.

Figure 3.



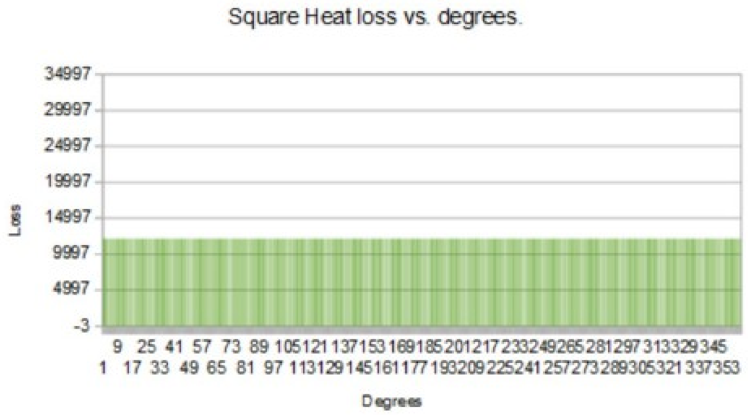


Figure 3 can be explained as follows. Since heat loss increases with the square of the current, while the magnetic field only increases linearly with the current, this means that in practice, the most thermally efficient waveforms (those with the highest magnetic field with the least heat loss) are waveforms with small or no peaks. This is because the greatest heat loss is created at the peak value. Figure 3 shows the heat loss for a sinusoidal waveform (red) and a square waveform (green) for the same average current and thus magnetic field. It can be seen that the sinusoidal waveform (red) has peaks, with much higher values of heat loss. The average heat loss is also larger; this may be more difficult to see from Figure 3, but is demonstrated in the next figure.

Figure 4.
Shows that three different waveforms with the same average current (which therefore create magnetic fields of the same average strength) can give different heat losses.

Fig. 4A

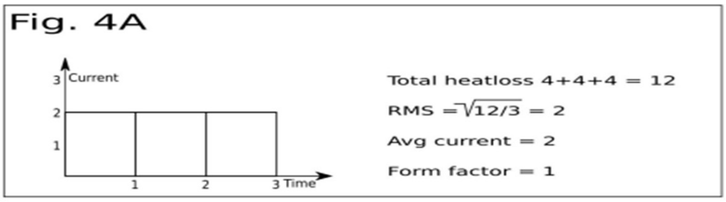


Fig. 4B

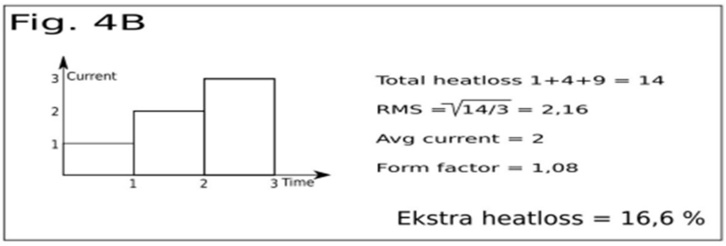


Fig. 4C

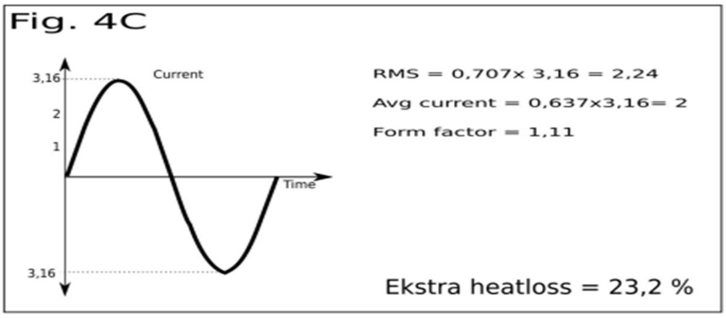


Figure 4 can be explained as follows. It can be seen from the figure that for the same current (and thus the same magnetic field), a waveform with peaks has more heat loss than a waveform that is flat, like the one in Figure 4A. From a technical point of view, the form factor is used to describe whether the waveform is flat or has peaks. It can be observed that when the form factor increases (Figures 4B and 4C), the heat loss also increases.

Figure 4A represents a simple square waveform that is completely flat on top. The average and RMS values are the same, and the form factor therefore has the lowest possible value of one.

Figure 4B shows a ramping value divided into three segments. There is now a difference between the average and RMS values, and the form factor is 1.08. The heat loss can be calculated as the sum of the heat loss in each of the three pieces. From a comparison with Figure 4A, it can be seen that the heat loss for this ramped scheme is 16.6% higher than for the wave in Figure 4A. The heat loss can also be calculated as the square of the form factor, which for Figure 4B is 1.166. This corresponds to a heat loss that is 16.6% higher than for a wave with a form factor of one.

Figure 4C shows a sine wave. This waveform is well-known and well-described, and it is established knowledge that a sine wave has an RMS of 0.707 times the peak value, an AVG value of 0.637 times the peak value, and hence a form factor of 1.11. If a sine wave is divided into smaller pieces and the current and heat loss are calculated for each part, the heat loss can be calculated and compared to a waveform that is flat on top, like the one in Figure 4A. In the same way as for Figure 4B, we can use the square of the form factor to conclude that a sine wave has a heat loss that is 23.3% higher than a wave such as that in Figure 4A, which has a form factor of one.

Analogue system

The three-phase system was invented 100 years before the digital revolution, and relies on the current in the coils following an analogue waveform (sine wave) to operate most efficiently. This was not a problem (and still is not) if the user can live with a motor that can only run at one speed, as it can be directly connected to the power grid.

However, to create a motor that can run at variable speeds, three phases with variable frequency must be generated electronically. This means that one must first create three high-quality analogue sine signals (phases), and then digitise them with PWM (pulse width modulation) to drive the output stages digitally with high thermal efficiency. The phases must then be filtered and converted back to analogue currents in the coils to drive the motor with high thermal efficiency. In other words, the electronics required to drive such a motor based on the three-phase system are relatively complicated and expensive.

What about torque ripple?

All previously known systems suffer from torque ripple, including the three-phase system. Digital methods that have been previously developed to drive an electric motor have also had problems with high torque ripple.

Our new technology does not have the same problems with torque ripple as previous digital methods of motor control. Although the exact reasons for this are not disclosed here to protect the patent, the new technique is able to compensate for torque ripple. This does not mean that it is currently possible to create a motor with no torque ripple, but that the new technology can achieve significantly lower values of torque ripple than previously possible with known techniques. Companies participating in the inventor's seminar will naturally receive a technical explanation for this reduction in torque ripple.