WHITE PAPER

From devices to system: rethinking efficiency to unlock savings in motor control

It is estimated that nearly half of our electricity is consumed by electrical motor-systems. It is thus no surprise that in the past two decades there has been a push for ever more efficient devices in the world of motor control. The progression is evident from the EC 640/2009 directive in Europe and 2013 NEMA Program in USA, to present day EU 2019/1781 that has just taken effect on July 1, 2021.

At first glance, this latest eco-design directive once again pushes for more efficient motors and variable speed drives by imposing IE3 and IE4 efficiency levels. While any push for efficiency is commendable, in practice this will have a very limited impact. The directive doesn't apply to existing installations which represent the vast majority of energy consumed.

It is by digging deeper into the directive and, more specifically, into its reference to IEC 61800-9 that the crux of the efficiency puzzle is unlocked.

System, no longer single component

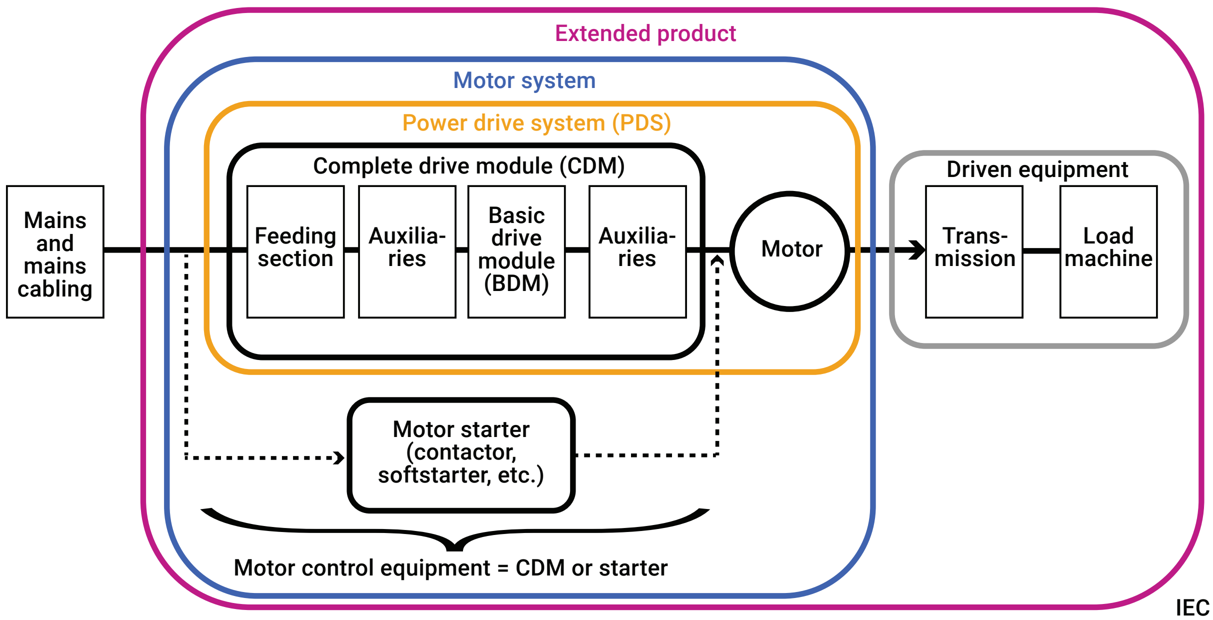
The IEC 61800-9, parts 1 and 2, introduce the concept of an extended product. No longer looking at each component individually, the standard considers the complete chain from energy source to end use (Figure 1).

Let's browse the chain backward: from the end use to the source through a simple example:

A pump needs a certain amount of mechanical energy when displacing a fluid.

- This energy is delivered by a motor through a mechanical transmission.
- The motor receives its energy from a complete drive module system.
- The power drive system is connected to the energy source.

FIGURE 1



Each element of this chain delivers energy to the next element, while losing some amount of energy depending on its structure and operation. It is the efficiency and loss of each component that defines its impact on the rest of the system.

Decision making: efficiency vs. loss

Efficiency and loss are used to tell us about the same concept but they trigger different reactions from a decision maker.

Efficiency is a relative performance indicator. Power delivered divided by power consumed, given in percentage. While efficiency is not a tangible measurement and is stripped from any unit of measure, it is understandable: 96% of efficiency speaks louder than 368 W losses.

This perception could lead the decision maker to make the wrong choice.

The important metric is power losses, power consumed minus power delivered, given in Watts. Understanding what a Watt is in itself is however different than sizing the extent of a loss.

The reality lies in the amount of power that is consumed by the system and invoiced by the power companies. That is kW*$, not % efficiency.

The standard IEC 61800-9 forces the user to pay attention to the losses of the whole system rather than just to a percentage as a performance indicator.

That does not mean that we should forget about efficiency value when choosing between several systems for an application. Verifying the efficiency of the systems is an important preliminary step.

But when estimating the system cost, users must consider the energy cost of the system among the other expenditures. For a motor with drive that will operate for about 20 years, the initial purchasing cost is only 2% of the total expense. Energy will count for 90%, with the remaining expenses being maintenance and impact from downtime. Therefore, a smart selection of the drive system can dramatically impact the overall system cost through a reduced energy bill.

Energy saving with variable frequency drive.

It has been demonstrated repeatedly that controlling a motor with a variable frequency drive, instead of a direct-on-line (DOL) starter, can yield huge savings.

Where are the savings coming from?

Let us take the example where, to get the biggest energy saving, a variable frequency drive (VFD) is used to control a motor driving a centrifugal pump.

As a reminder, the affinity laws of a standard variable-torque centrifugal pump demonstrate: that the power or the energy consumption vary with the cube of the speed, pressure or head varies as the square of the speed, and flow volume varies linearly with the speed.

Controlling the speed of the pump to match the actual need of pressure or flow yields a huge potential of saving as shown in Table 1.

TABLE 1

Speed Ratio	Mechanical Power Required
100%	100%
90%	73%
80%	51%
75%	42%
60%	22%
50%	13%
40%	6%
30%	3%

When the pump turns at 90% of its nominal speed, it only requires 73% of its rated power, and only 42% when turning at 75% of its nominal speed.

Using any variable frequency drive to control the motor of a centrifugal variable pump instead of DOL starter unlocks those savings by matching the pump speed to the required flow or pressure.

The savings are easy to estimate

For example, let us imagine that this pumping equipment requires 13 HP to perform its work of producing the desired output flow and pressure.

Without going into all the details of motor choice optimization, the common practice is to choose a motor with a nameplate power rating greater than that required by the pump. A 15 HP motor (average FLA 27 A for a 3-phases 460 V motor), being the next nominal size above 13 HP would commonly be chosen.

When selecting an IE3 class motor, the system uses a motor with an efficiency of about 92%.

Driving a 13 HP pump (excluding any transmission in between), its load ratio is 13/15=85%.

In order to estimate the savings that will be realized when a DOL is replaced by a VFD, it is necessary to calculate the full load power consumed by the DOL solution. Full load power = motor HP x 0.746 x load ratio / efficiency. In this example, 15 HP x 0.746 x 85% / 92% = 10.33 kW.

When comparing this solution against a VFD one must estimate the amount of time the system operates at each speed ratio. A typical example is shown in Table 2.

TABLE 2

Speed Ratio	Time Ratio	Mechanical Power Required
100%	20%	100%
90%	0%	73%
80%	0%	51%
75%	40%	42%
60%	0%	22%
50%	40%	13%
40%	0%	6%
30%	0%	3%
20%	0%	1%
10%	0%	0%
	100%	

The final step in the analysis is to calculate the time weighted power consumed by the VFD equipped system. Table 3 shows this simple spreadsheet calculation where the time ratio and full load power are used to calculate time weighted power at each speed ratio. In our example the time weighted power is 4.33 kW.

With a system running 24/7 all year long, it's 365 days * 24 hours = 8,760 hours of operation.

TABLE 3

Speed Ratio	Time Ratio	Mechanical Power Required (%)	Mechanical Power Required (kW)	Time Weighted Power
100%	20%	100%	10.34	2.07
90%	0%	73%	7.54	0.00
80%	0%	51%	5.29	0.00
75%	40%	42%	4.36	1.74
60%	0%	22%	2.23	0.00
50%	40%	13%	1.29	0.52
40%	0%	6%	0.66	0.00
30%	0%	3%	0.28	0.00
20%	0%	1%	0.08	0.00
10%	0%	0%	0.01	0.00
	100%			**4.33**

Then simply 8,760x4.33 = 37,930 kWh consumed by the system over one year.

This has to be compared with 8,760x10.33 = 90566 kWh consumed by the system with DOL starter.
A huge saving of 52,636 kWh, with an energy cost of $0.1 per kWh, it's more than $5,000 saved per year.

VFD savings as part of the overall system

Now let's continue with this example and look at the requirements of the IEC standard.

With a 3-phase power line, the basic choice of the VFD shall be a 480V/11 kW (15 HP) device. Remember that the VFD choice must be made according to the current drawn by the load. Power only serves as a rough guide during the initial pre-selection process.

To mitigate the negative impacts of the PWM signal generated by the VFD, this example will include a passive filter on the input side of the VFD (to reach a THDi <= 5%) as well as a dv/dt filter or a sine wave filter (depending on the cable length) on the output side of the VFD.

Finally, to complete the drive module specified in IEC 61800-9, we need to add a circuit breaker and fuses upstream of the VFD.

The bill of material that industry best practice dictates is presented in Table 4 with its estimated average losses.

The total loss of this complete drive system is simply the sum of the losses from each component as shown in Figure 2.

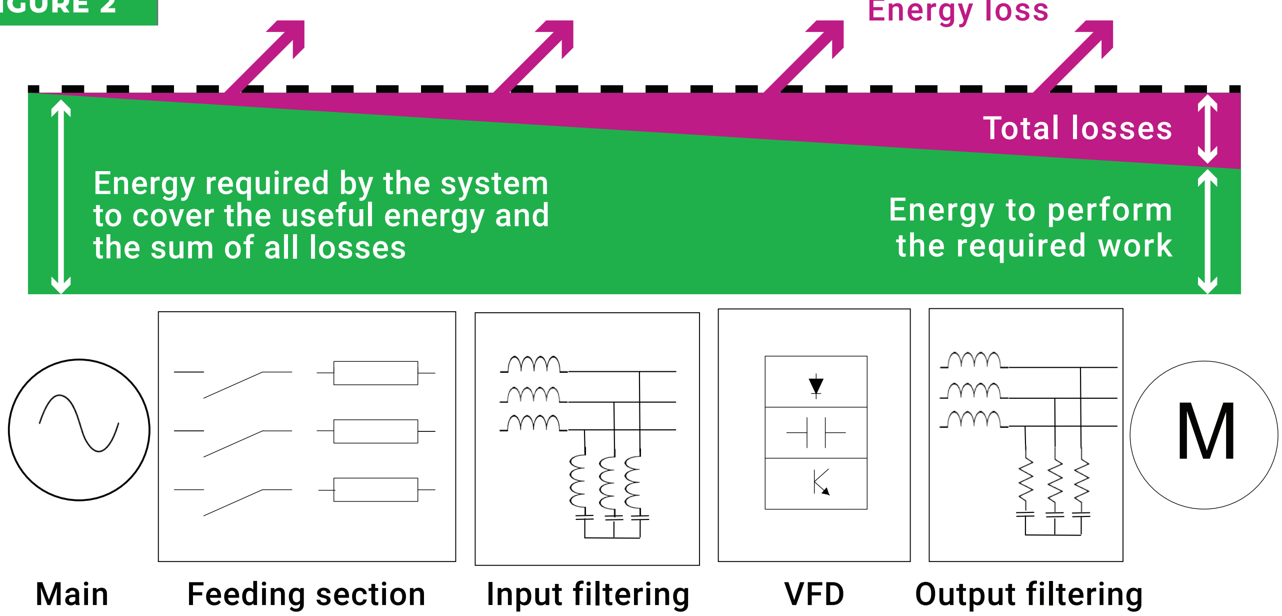
Increasing attention to energy efficiency coupled with heightened enforcement of standards and regulations, has led most equipment manufacturers to publish their efficiency data. The estimations in Table 4 use average efficiency values published by major equipment manufacturers. In our example, 715 W of power are wasted to control a 15 HP motor.

It is possible to reduce the up-front cost and the overall loss of the system by replacing the Passive Input Filter with an AC Input Choke and by replacing the Sine Wave Output Filter with a dv/dt filter (assuming short cable length between the VFD and the motor). The typical loss of an AC Input Choke is

TABLE 4

Component	Estimated Average Loss
Circuit Breaker	25W
Fuses	7W
Passive Input Filter	183W
Variable Frequency Drive (6-Pulse)	350W (at 90% of speed/100% of torque)
Sine Wave Output Filter	150W
Total	**715W**

FIGURE 2



100 W and the corresponding loss for a dv/dt filter is 55 W, yielding a net efficiency improvement of 178 W. However this comes at the cost of much higher harmonics injected onto the electrical network and also experienced by the motor itself.

Selecting lower purchasing solution impacts negatively the overall energy efficiency

The performance of the motor itself is of critical importance when evaluating the overall efficiency of a power drive system as defined by the standard. The PWM output of a typical 6-Pulse VFD increases the motor losses by an average of 15% compared with a clean sinusoidal signal. Continuing with our previous 11 kW (15 HP) example, this yields a loss of 672 W.

In order to realize the benefits of a VFD while simultaneously minimizing end-to-end power losses, the innovative solution is to use a clean power VFD with an integrated active front end (AFE) which delivers a pure sine wave to the motor. In this solution, filters are not needed on either the input or the output side. For the power loss estimation, the common 6-pulse VFD is replaced by the clean power VFD, having an average power loss of 400 W at 90% of speed / 100% of torque.

Returning again to our 11 kW example, a clean power device will experience losses of 432 W. The THDi of this solution is less than 5% and the motor experiences lower losses and longer life expectancy due the clean sinusoidal output signal. Figure 3 illustrates this clean power VFD setup and Table 5 summarizes the performance of each solution.

Lower power loss is saving money.

With the clean power VFD, the losses are reduced by 40% compared with a 6-pulse drive properly filtered and reduced by 32% compared with a 6-pulse drive with limited filtering.

In a scenario where the equipment is running 24/7/365, this yields up to 2,472 kWh in energy savings for a single motor drive system.

By multiplying the savings by the equipment lifetime and by the number of motor systems in a plant, it is easy to realise substantial savings by replacing conventional direct on line (DOL) starters and conventional 6-Pulse drives with clean power VFDs.

A water treatment plant for a population of 200,000 frequently uses between 50 and 100 VFDs. Using a very conservative estimate of 50 VFDs all at 11 kW the annual savings would be $12,000 per year.

Looking at a life expectancy of 15 years for equipment in a water treatment station, the savings would be about $180,000. Extended over the 45 to 60 years lifespan of a water treatment plant, our scenario yields $540,000 to $720,000 in energy savings.

FIGURE 3

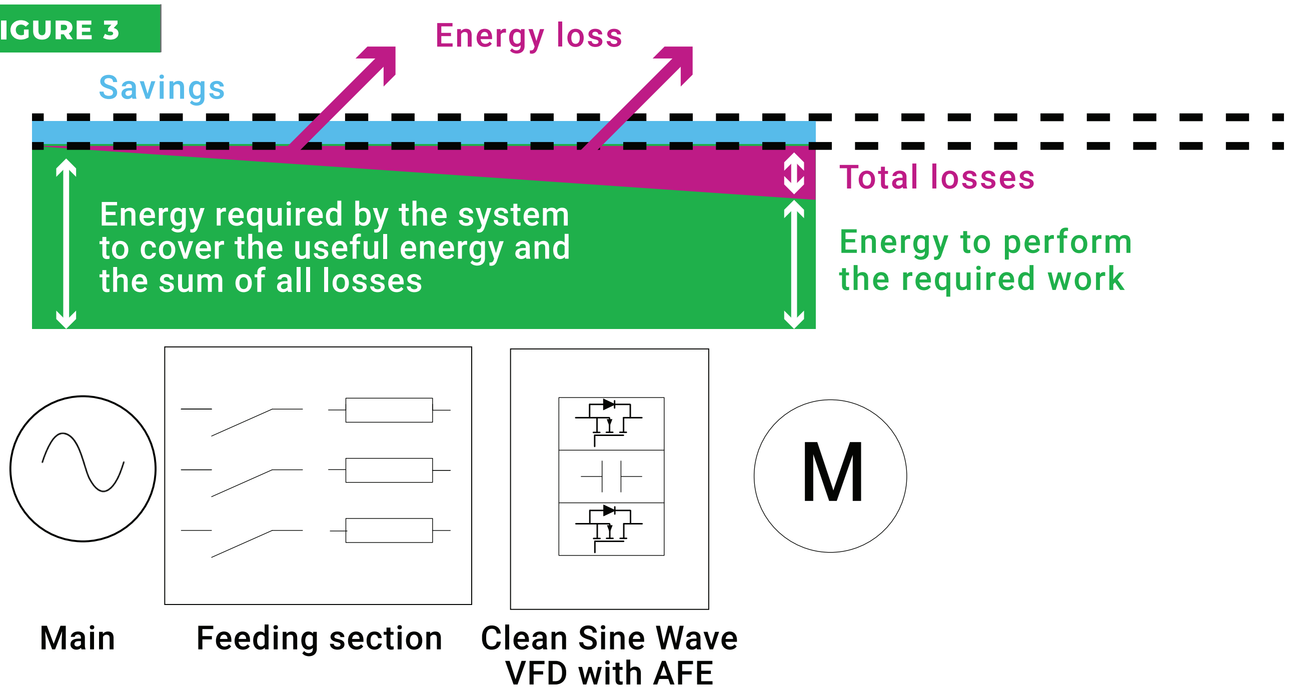


TABLE 5

		Solution 1	Solution 2	Solution 3
Fuses average losses	Type J	7W	7W	7W
Circuit breaker average losses		25W	25W	25W
Input Filter	Type	Passive input filter	AC choke	None
	Average power loss	183W	100W	0
VFD	Type	Common 6 pulses	Common 6 pulses	Clean-Sine-Wave
	Average power loss at 90% speed / 100% torque	350W	350W	400W
Output filter	Type	Sine Wave	dv/dt	None
	Average power loss	150W	55W	0
System impact on motor loss		0	+15% ~135W	0
Total Loss		**715W**	**672W**	**432W**

The link between electrical energy and carbon emissions is clear. Therefore the smart selection of a motor drive system reduces its overall carbon footprint.

Conclusion

The environmental impact of energy savings is real: with nearly half of the world's electricity flowing through motors, it is no surprise that ever more stringent standards are being released for variable frequency drives and motors. However, more attention should be paid to the overall efficiency of the motor system than to the discrete devices. By deploying an optimized system, significant energy savings and lower maintenance costs can be realized.

As demonstrated in this white paper, VFD producing a clean-power-signal can greatly improve the overall system efficiency by allowing motors to run more smoothly and removing other energy-hungry components from the system.

New technologies such as wide-bandgap transistors are now available and are making clean-power VFDs a reality. This new generation of variable frequency drives exceed the energy efficiency requirements at the extended product level and translate into opex saving and smaller environmental footprint.

Active front end contribution

There are more savings coming from a VFD with AFE.

An AFE VFD will provide additional cost savings through power factor control and regenerative braking.

When the power factor of a drive is low (< 1) it must draw higher current to feed its load. Most energy providers apply penalties to compensate for the costs associated with low power factor. While the threshold varies by provider, a power factor of 0.9 or lower is commonly subject to some form of increased cost. Since an AFE drive operates at close to unity power factor, it does not draw additional current and does not impair the power factor within the facility. This makes an AFE drive more cost effective in many environments.

An AFE VFD is also able to feed the energy generated by a decelerating motor back onto the electrical grid. This is in contrast to a typical 6-pulse VFD where the regenerated energy is dissipated as heat inside a braking resistor and within the VFD itself. Thus the AFE VFD saves energy by returning it to the grid rather than wasting it as heat. The actual energy and cost saving will obviously depend on the number of deceleration cycles experienced during normal operation.

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References:

European directive EU 2019/1781 can be downloaded here:
https://eur-lex.europa.eu/homepage.html?locale=en

IEC 61800-9 part 1 and part 2 standard can be purchased from:
https://webstore.iec.ch/

Nema publication General Specification for Consultants -- Industrial and Municipal: NEMA Premium Efficiency Electric Motors (600 Volts or Less) can be download here:
https://www.nema.org/standards/view/general-specification-for-consultants-industrial-and-municipal-nema-premium-efficiency-electric-motors