VARIABLE SPEED DRIVES AND MOTORS

Measuring Efficiency in **Power Drive Systems**

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AUTOMATION INSTRUMENTATION & CONTROL ABORATORY TECHNOLOG

Executive Summary

- Modern VSDs are highly efficient devices
 - typically in the range 96 98% at full load
- Losses in the VSD are small compared to the reduction in losses in a correctly designed system for example a VSD installed in an appropriate fan or pump system may save 30 40% depending on the application compared to a 3% intrinsic VSD loss.
- Manufacturers published data tends to be quoted for worst case load / ambient conditions and should be used for panel ventilation and cooling requirements
- A high claimed VSD efficiency is not a guarantee of high overall "system" efficiency as this is affected by parameters such as switching patterns, device characteristics and inclusion of auxiliary components such as filters and reactors.
- Simplistic assessments or comparisons of "VSD efficiency" are invalid
- No standards exist for measuring VSD efficiency
- Direct "input / output" electrical measurements of VSD efficiency are invalid
- Correct efficiency measurements for VSD systems is difficult and requires considerable expertise and equipment
- GAMBICA Members are able to offer simulated values for the overall system losses, given the appropriate duty points
- VSD losses can be increased by incorrect installation and commissioning
- Maximum benefits are achieved in correctly engineered, installed and maintained systems

Measuring Efficiency in Power Drive Systems

FOREWORD

Typically electronic variable-speed drives are used for process control, matching the delivery to the demand of the process, and as such they can result in substantial improvements in energy utilisation in comparison with fixed speed techniques.

It is desirable to establish methods for measuring the efficiency of drive systems and their individual components, in order to quantify the benefits and to focus on opportunities for further improvement. Measuring the efficiency of the drive system is however relatively difficult, requiring considerable specialist expertise and equipment.

This guide is intended to assist in system evaluation.



SCOPE

This guide provides information about the nature and disposition of losses that must be considered when examining a drive system.

The guide also considers the potential measurement points and instrumentation that may be used to achieve valid and repeatable measurements.

SUMMARY

The guide shows that the drive system and driven load should be treated as a system, and that the total energy usage should be treated as a single input. Any attempt to split and measure the individual components is subject to such errors as to make the practice extremely difficult, and potentially unreliable, due to the relatively small magnitudes of some of the individual component losses.

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1 INTRODUCTION

The principles enumerated here apply equally to centrifugal pump and fan drive systems, with similar system characteristics,



Figure 1 - Typical close coupled centrifugal pump



Figure 2 - Typical centrifugal fan

The characteristic curves for a typical fluid circulating system, utilising a centrifugal pump, are shown in Figure 3. In this installation it can be seen that to change the flow, the head will also change, this is shown by the "System Curve" which represents the increase in friction as the flow increases. For the pump itself the head or pressure generated will fall as the flow increases, and this is shown by the "Head/Volume Curve."

The power required is equal to the product of the flow volume, the head and the density all divided by the efficiency with a constant to convert the units.

In this case

Power Required [kW] = Flow $[m^3/h]$ x Head [m] x specific gravity

Efficiency [%] x 367.9 [Constant]

In a fixed speed system a reduction in flow is generally achieved by a restriction such as a valve, and therefore in the example to reduce the flow from point "A" to point "C", the pump will pass back up its curve to point "D". The power required will include that wasted producing the additional head between "C" and "D".

The wasted power is mainly transferred into the fluid as heat. The net cost of the waste depends upon the application. Where the fluid is required to be heated in the process, the wasted power contributes toward the heating, whereas in a cooling application it introduces additional energy costs because the waste heat has to be removed.

The use of a restriction will also give rise to wear on the valve, which represents a hidden addition to the running costs.





If we vary the speed as shown in Figure 4, it is clear that the duty is matched precisely by the system, and no energy is wasted producing unwanted head. As the user is paying for the "wire to water" losses, while the efficiency of the different components will vary, the overall energy consumption will drop as the speed reduces.

Defining these losses is of primary importance in optimising a system, and it is only by considering the system that a full appreciation of the potential can be achieved.

Figure 5 gives a typical numerical example, and shows that at virtually any reduced flow a saving can be achieved.



Figure 4

	Fixed speed full flow	Variable speed full flow	Fixed speed minimum flow	Variable speed minimum flow
Flow [m ³ /h]	725	725	600	600
Head at pump discharge [m]	49	49	52	32
Pump efficiency [%]	85.5	85.5	84.5	85.5
Pump input power [kW]	112.9	112.9	100.4	61
Motor efficiency [%]	95.8	95.8	95.8	96.5
Motor input power [kW]	117.9	117.9	104.8	63.2
Converter efficiency [%]		98.0		98.4
Converter input power [kW]		121.2		64.2
SAVING		117.9 – 121.2 =		104.8 - 64.2 =
		- 3.3 kW		40.6 kW or 38.7%

Figure 5

This shows a turndown of less than 20% in flow requires approximately 40% less energy when using a drive compared to the fixed speed solution.

The characteristic manner in which these losses vary is shown in Figure 6

As only a very few systems ever run at full output, the small penalty at this point is generally acceptable, compared to the savings that can be made when running at real duty points.





After the driven machine, it is the motor that has the largest loss. The difficulty that remains is to separate these losses and to measure them reliably.

2 MEASUREMENTS

Figure 7 shows the constituent parts of the losses within a typical induction motor. Similarly a drive will have losses which may be split down between the constituent parts as shown in **Figure 8**..





Figure 7 Relative losses in a network fed 160 kw induction motor, with total losses of 6.8 kW



Currently there is a great deal of dissatisfaction with the levels of accuracy achieved by the European motor testing standard EN 60034-2:1996.

Figure 9 shows how the relative losses are reduced in a motor by variation of load, but the stray load loss is basically an arbitrary estimate, and leads to substantial uncertainty in the results published.



Figure 9 Motor losses vs power output

2.1 Electric Motors

Standards exist for measuring the efficiency of electric motors, at the time of writing two basic standards exist, EN 60034-2:1996 and IEEE 112-B.

In Europe the harmonised standard is normally specified, including for the establishment of the efficiency classes "Eff 1", "Eff 2" and "Eff 3".,

It is however an "indirect" method, involving calculation, and the stray load losses are arbitrarily set at 0.5% of the full load power. This results in considerable uncertainty, especially when modern high efficiency and premium efficiency motors are being measured.

The IEEE method used in the United States is a direct method involving real measurements, with much smaller tolerances.

This method, an indirect method using measured stray load losses, and a further indirect method known as Eh-star, have been incorporated into International standards, as IEC 60034-2-1:2007¹.

One area that is quite clear is the variation in instrumentation accuracy required for the different standards²

¹ Discussed further in Appendix A

² Information taken from Market Transformation Programme Briefing Note BNM06, Version 2.3, available from www.mtprog.com.

	EN 60034-2	IEEE 112-B	
Parameter	% accuracy required	% accuracy required	
Voltage [V]	± 0.5%	± 0.2%	
Current [A]	± 0.5%	± 0.2%	
Power [W]	± 1.0%	± 0.2%	
Frequency [Hz]	± 0.5%	± 0.1%	
Speed [r/min]	± 2	± 1	
Torque [Nm]	n/a	± 0.2%	
Resistance [Ω]	± 0.5%	± 0.2%	
Temperature [⁰ C]	± 2	± 1	

Figure 10

A new harmonised standard EN 60034-2-1:2007 has now been approved, and this will affect the way in which all manufacturers give their catalogue details.

2.2 Results of changes to standards

Due to the use of the old standard it is clear that in many cases the efficiencies claimed are well above those which can be measured directly, and especially when these motors are directly tested with converters the values achieved tend to indicate (wrongly) that the converter losses are higher than predicted.

The effect of the arbitrary assumption of stray load loss in the old EN 60034-2 can be quite dramatic, as shown in Figure 11, where a difference in the losses of up to 15% can be seen:-

Rated output	Quoted in accordance with EN 60034-2:1996 Estimated SLL		Quoted in accordance with IEC 60034 – 2 -1 :2007 Measured SLL	
	Catalogue value	Loss [kW]	Catalogue value	Loss [kW]
7.5 kW 2 pole speed	88.4%	0.87	87.9%	0.91 = +5%
11 kW 4 pole speed	90.9%	1.00	90.3%	1.07 = +7%
160 kW 4 pole speed	96.0%	6.40	95.4%	7.36 = +15%

2.3 Testing converter fed motors

The only standard currently available covering the testing of an a.c. drive system is BS EN 61800-2:1998, Section 7, which cross references BS EN 60146-1-1:1993. These standards are extremely old in terms of the developments in a.c. drive technology and the measurement instrumentation is defined by the now discredited EN 60034-2.. The full requirements of BS EN 61800-2 are very difficult to implement for the majority of low voltage drives as it provides limited accuracy and limited useful information. It is therefore little used by manufacturers who have developed their own procedures.

Testing of an a.c. drive system must necessarily be undertaken by a direct method, and should be undertaken at the appropriate duty points, in terms of both speed and torque. There is little or no justification in looking at Full, $\frac{3}{4}$, and $\frac{1}{2}$ load points, as are specified for a fixed speed motor, as these terms have little meaning in the context of a variable speed system.

In the factory or test laboratory situation it is generally possible to test "back to back" using a second rotating machine with a regenerative converter and a torque transducer to determine the load

In a field situation the duty driven load may be utilised, and the outputs monitored, however, the measurement accuracy is limited by the accuracies of the transducers, and of the load efficiency over the operating range.

2.4 Practical measurements

When considering test and measurement devices, a number of standards exist, and the basic standards for analogue metering are the IEC 60051 series, which tends to be referenced by the IEC standards. In current practice, however, digital metering tends to be utilised due to the ease of storage and data transfer.

Different capabilities will exist between laboratory and test field fixed metering installations and portable equipment designed for field measurements.

The problems in achieving accurate and repeatable measurements are made more difficult by the harmonics of power at the input to the drive, the output from the drive to the motor and the evaluation of the output power of the motor.

Frequency converter drives pass harmonic currents to the mains, which are controlled by design of the drive system to be acceptable to the supply authority. They will vary with the power being drawn and to some extent with the supply network impedance.

These harmonics therefore make the accurate determination of the input power difficult. Complications arise from the fact that the mains supply voltage is itself distorted by computers, consumer goods and other drives so that power may flow in the harmonics as well as the fundamental.

The drive also supplies harmonically rich current and voltage waveforms to the motor which may induce extra losses in it. The significance of these losses changes with the power rating of the motor and is influenced by the lowering of PWM switching frequencies with increasing drive power ratings.

There is a wide variety of modern equipment, which will indicate consumption of electrical power and measure voltage and current. Much of this is relatively simple and is not capable of accurately coping with the wide spectrum of drive system voltage and current

harmonics. The result can be uncertainty and pessimism with respect to results which leads to missed opportunities for energy savings.

The most widely available standard equipment designed for multifunctional metering is so called "Power Quality Monitoring equipment", which generally includes facilities for examining the voltage, current and power of a network, as well as the harmonic content, and power factors.

Taking BS EN 61000-4-7, we get the following allowable limits for a "Class 1" instrument

Parameter	Conditions	Maximum error	
Voltage	U _m ≥ 1% U _{nom}	± 5% U _m	
	U _m < 1% U _{nom}	± 0.05% U _{nom}	
Current	I _m ≥ 3% I _{nom}	± 5% I _m	
	I _m < 3% I _{nom}	± 0.15% I _{nom}	
Power	I _m ≥ 150 W	± 1% P _{nom}	
	I _m < 150 W	± 1.5 W	
U_{nom} , I_{nom} = Nominal range of the measurement instrument, U_m , I_m = Measured values			

Figure 12³

It can be seen that these requirements may allow rather wider tolerances than the IEE motor measurement standard. This is mainly due to the capability of the instrument to also measure the harmonic content of the waveforms, which is inevitable if a VSD is present.

Typical values achieved by commercially available equipment are rather better than required by this standard, portable equipment can offer $\pm 0.1\%$ of reading for Voltage and Current inputs, while fixed instruments can offer $\pm 0.01\%$, however, the limitations of the current transducers will need to be taken into account as well.

For fixed installations, where the bus bars can be correctly located or special shunts used an accuracy of $\pm 0.1\%$ is practical, while for portable instruments $\pm 1\%$ is more likely for a direct measurement.

2.5 The effect of measurement uncertainty on VSD efficiency estimation.

Figure 13 illustrates typical power flows in a VSD with an efficiency of 98%.

³ Source BS EN 61000-4-7 Table 1



Figure 13 Measurement uncertainty for separated losses

It can be seen that the drive efficiency estimated from this separated measurement would lie in the range of 100.0% to 96.1%, while the estimate for the entire power input to motor and drive varies by only $\pm 1\%$.

Some reduction in the uncertainty of the efficiency measurement might be achieved through using the identical instrument and transferring it between the VSD input and output, or by carrying out a special cross-calibration exercise during the test. However since the voltage and current waveforms and potentially the frequency at input and output differ greatly, the benefits of such a process are limited.

A more attractive method for estimating VSD efficiency is to measure the losses, i.e. the heat output. The measurement uncertainty then only applies to the small loss power rather than the large power throughput. Calorimetric methods are possible, although the equipment required is specialised, laboratory based and not readily available.

The most reliable way of estimating losses is probably to use the VSD manufacturer's data, they will have reliable information since it is essential in the design of the VSD cooling system.

It is also important to note that if a single figure for losses is published in a catalogue it will always be based on the maximum possible output from the drive, with the worst case ambient temperature. This may well represent a level substantially higher than normally encountered due to the need to cater for short time overload situations in equipment with potentially very short thermal time constants.

It should also be noted that the losses of a particular drive will also vary depending on the motor connected, the typical split of losses is shown in **Figure 8**. If we consider a range of motors rated at 160 kW. On a sinusoidal supply, the efficiency and power factors will vary with the number of poles, thus varying the motor current, and inverter losses. Figure 14 shows the relative figures for a range of motors running at 50 Hz when tested on the same variable speed drive

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No. Poles	Base Speed [r/min]	Full load Motor Efficiency [%] EN 60034-2	Motor Power Factor [Cosφ]	Motor Loss [kW]	Drive Loss [kW]	Total Loss [kW]
2	3000	96.1	0.89	6.7	3.7	10.4
4	1500	96.0	0.85	6.8	4.0	10.8
6	1000	96.0	0.83	6.8	4.1	10.9
8	750	95.7	0.80	7.3	4.2	11.5
10	600	95.5	0.77	7.6	4.4	12.0

Figure 14

3 CONCLUSION

Even with the availability of modern accurate instruments, it is difficult to make meaningful measurements of the efficiency of a variable speed power drive system, and even more difficult to measure the efficiency of the constituent parts (i.e. the motor and the drive).

The power losses in the drive and the motor are generally small compared with the power savings which can be achieved by a correctly designed variable speed control system.

Although the benefits of using a high-efficiency motor (e.g. Eff1) are significant, there is little benefit in trying to assess or further optimise the efficiencies of the individual components of a drive system. Attention should rather be focussed on optimising the overall control scheme to ensure that the potential benefits of variable speed are realised.

Annex A

A.1 Motor Losses & Loss Reduction Techniques

The function of a motor is to convert electrical energy into mechanical energy able to do useful work. The only way to improve efficiency is to reduce the motor losses, and since motor losses result in heat rejection to the atmosphere, reduction of losses will significantly reduce cooling loads.

Motor losses can be segregated into five major areas, each of which is influenced by design and construction, and these can impinge on the cost of the motor.

Typically considering the air gap between stator and rotor, a large air gap is less costly to manufacture, while an optimised small air gap will result in better efficiency and power factor.

Motor losses can be split between the fixed losses – generally known as no-load losses, which occur due to the energisation of the motor, and remain constant for a given voltage and speed, and those that will vary with load.

A.1.1 No Load Losses

These can be split into two main areas

A.1.1.1 Iron Loss

This represents the energy required to overcome the opposition due to changing magnetic fields within the core material (hysteresis) and includes losses caused by the creation of eddy currents within the core.

Iron losses can be reduced by use of improved permeability electrical steel, and lengthening the core to reduce magnetic flux density together with utilising thinner laminations with better insulation between the laminations to minimise eddy current losses.

A.1.1.2 Windage and friction Loss

These losses occur due to the mechanical operation of the motor where improved bearing and seal selection, and fan design can be used to reduce these losses.

In an efficient motor there will be good heat transfer from the core components to the air circuit, and a reduction in core losses will allow a reduced air flow and hence a smaller fan system.

Friction losses are minimised by good alignment, any angular displacement of the driven coupling can substantially increase losses.

A.1.1.3 Effects of Variable speed on no load losses

Iron, Windage and Friction losses will be constant at a fixed speed with a fixed supply voltage, and are virtually independent of motor load.

When run at variable speed the windage and friction losses will vary with speed, and the iron losses can be reduced by reducing the flux at low load.

Iron losses are related to (frequency)², and the majority is due to the fundamental frequency.

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Losses due to harmonics acting counter to the direction of rotation (5th, 11th, 17th, etc) may lead to additional air gap torque and increased slip. This tends to be a major problem with highly distorted supply networks, and was formerly a problem, especially with current source inverters.

A.1.2 Load Losses

These can be split into three main areas

A.1.2.1 Stator Losses

These appear as heating due to the current flow, through the resistance of the stator winding – commonly referred to as the l^2r loss.

These losses can be reduced by modification of the stator slot design to improve the "slot fill" of the windings, or by reducing the insulation thickness to increase the volume of wire in the winding.

A.1.2.2 Rotor Losses

These appear as l^2r loss. in the rotor winding. This can be reduced by increasing the size of the conductors and end rings to produce a lower resistance. This can sometimes be at the expense of an increase in starting current, or reduction in available torque when switched direct on line.

A.1.2.3 Stray load Losses

These are a result of the leakage fluxes induced by load currents. In the older EN 60034-2 indirect testing method, which was generally used for standard designs, the level of stray loss was assumed to be 0.5%, of power input at rated load, while in practice the value will vary from ~1.0 % to as much as 2.5%, which has led to motor efficiencies in Europe being consistently overstated.

The new measurement standard EN 60034-2-1 allows direct measurement and three methods of indirect measurement, either with a stray load loss determined by measurement, an estimated value based on rated power or by Eh Star calculation.

It is now very important that any comparison of motor efficiencies is made by the same measurement technique, and the reference standard should be noted in any catalogue data.

In addition to the testing standard a further new standard EN 60034-30 is in preparation, which will replace the old CEMEP "Eff1", "Eff2", and "Eff3" efficiency designations. The new designations will become "IE 1", "IE 2", "IE 3" and potentially "IE 4", with efficiency increasing by increase in number. "IE 2" is generally comparable with the existing "Eff 1".

Some manufacturers also offer "Premium efficiency" motors which should reach the requirements of IE3.

A.1.2.4 Effects of Variable speed on load losses

A VSD will affect the motor efficiency in a number of ways. With a voltage sourced PWM inverter the designer will produce a pulse train to the motor with a minimum of low frequency harmonics, which will result in little effect on the RMS current, and hence on the l^2r losses, however, because the inverter is controlling the voltage to the motor, the level of flux will in general be optimised.

Motors when "over fluxed" and fed at too high voltage will have a reduced power factor, and hence pass more current, with resulting increased I^2r loss as well as increased iron

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losses. The inverter must be set up correctly to prevent over-fluxing, either by a suitable choice of the voltage/frequency profile or by using one of the many automatic flux optimisation features offered by modern drives.

One area of possible concern is that few inverters with a "good" output waveform are capable of achieving 100% volts out, when compared to the volts input.

A.2 Drive Losses & Loss Reduction Techniques

The function of a drive is to convert electrical energy at fixed voltage and frequency to a variable voltage and frequency.

Drive losses can be segregated into four major areas, each of which is influenced by design and construction.

- Standing loss (drive disabled)

Some level of standing loss is inevitable. The efficiency as the load power approaches zero is always zero. For a drive system which spends a substantial part of its life without any load, consideration should be given to removing its power supply when not required.

- Standing loss (drive enabled)

Some additional power circuit losses are incurred when the drive is enabled, even if it is delivering no useful power at the motor shaft. A flux optimising controller should minimise this loss, but a drive which must deliver full torque at zero speed with good dynamic response is likely to incur added fixed losses because of the need to maintain motor flux.

- Losses depending on power

There will be elements of loss mainly associated with the input rectifier which depend upon the power consumed. The proportional element results in an efficiency which remains constant as the load increases, whilst the square-law element may result in a decline in efficiency at the highest loads.

- Losses depending on torque

The most substantial losses occur in the inverter (output) stage and are dependent on the motor current, and hence its torque, regardless of speed. Again there will be linear and square-law elements. This results in a decline in efficiency as the speed reduces, especially for loads where the torque remains high, but of course the actual power consumed is reduced as the speed reduces.

Note that for the most common pump and fan applications, the torque is proportional to the square of speed, so that all except the fixed losses decline rapidly with reducing speed and power output.

A.2.1 Standing Losses

These can be split into three main areas

A.2.1.1 Control and cooling

Depending on the rating and construction of the drive system, there will be a requirement for internal power supplies, and for ventilation. Some modest reduction in standing losses can be achieved by adapting the speed of the fan, where fitted, to the actual cooling requirement.

A.2.1.2 Main circuit

Capacitor leakage currents and discharge resistors have a small level of standing loss

A.2.2 Variable Losses

Variable losses are almost totally associated with main circuit components

These appear as an l^2r loss. This can be reduced by increasing the size of the internal conductors to produce a lower resistance.

A.2.2.1 Rectifier

The current flowing through the rectifier represents the active current doing work, plus the drive and motor losses, but as the displacement power factor is close to unity the fundamental current will almost always be lower than the motor current.

The loss is primarily proportional to the active current. There will also be a component of loss associated with the harmonic components.

A.2.2.2 Inverter

The current flowing through the inverter represents the total current in the motor, both active and reactive. At lower speeds the voltage will be reduced, and especially with constant torque loads, this current will be substantially higher than the rectifier current.

The loss has some elements which are proportional to the load current, and some which are proportional to the square of load current. This loss is usually the single largest factor in the drive loss.

A.2.2.3 Switching Loss

Each switching on or off event of a semiconductor has an associated loss, therefore the higher the switching frequency the higher the loss. Switching loss is proportional to output (motor) current.

Higher switching frequencies lead to lower levels of motor noise, and potentially to improved output waveforms with resulting lower motor losses, especially for low power equipment, therefore the switching frequency is always a trade off which should be considered by the drive system designer.