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FINAL REPORT - APPENDICES

Project: **Assessment of Energy Efficiency Performance Standards for Three-Phase Induction Motors**

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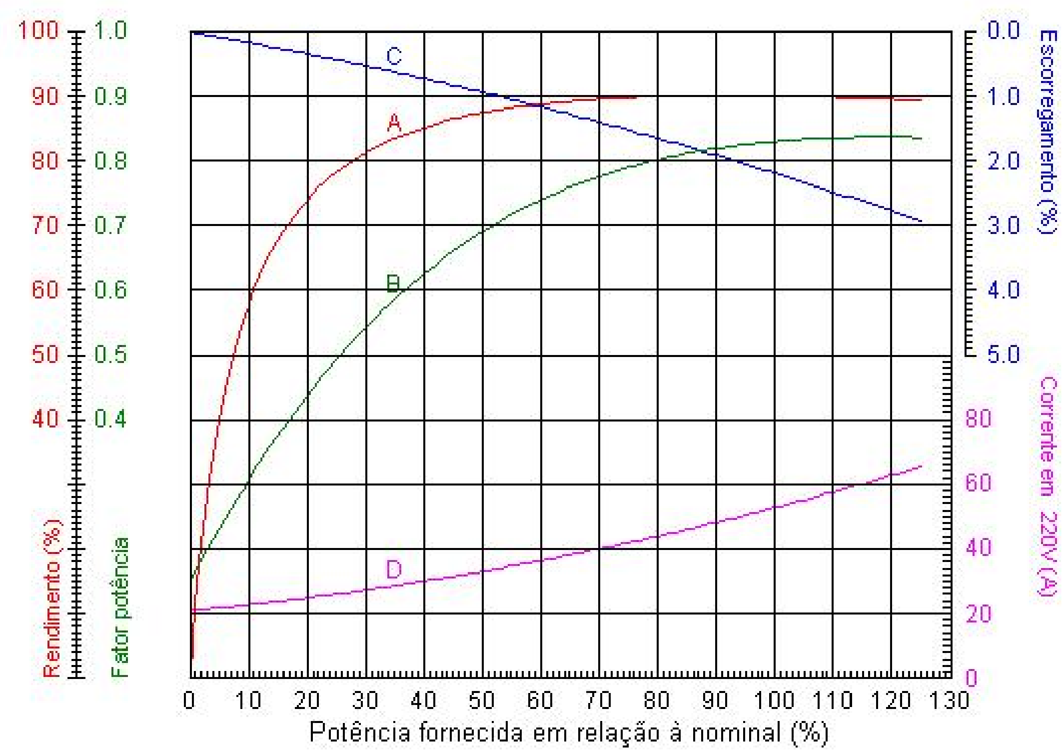
Appendix A MOTOR ELECTRICITY CONSUMPTION METHODOLOGY

In order to present the logical sequence for presenting the formulas used, we first outline the assessment of the operating efficiency, assuming that the loading is known, after which the load is estimated. Obviously the normal data processing scheme is to first estimate the loading and then assess the efficiency.

A good assessment of the estimation methods available may be found in Shindo (1997) comparing the possible field implementation assessments with precise laboratory measurements. The intention here is to merely seek a fast and easy method that allows for quick data processing.

A.1 Efficiency Assessment



A: Efficiency (%)
B: Power Factor
C: Slip (%)
D: 220V Current (A)

Power Supplied / Rated Power (%)

Figure A-1 – Motor Performance Curves

Source: WEG Catalog. Available at: http://www.weg.com.br/. Accessed on August 27, 2003.

With the loading known, and assuming an Efficiency x Loading curve (in fact, the Catalog curves are given through three points at 50%, 75% and 100% of the rated load), the efficiency assessment is carried out through interpolation. In this Report, due to the similarity between the exponential and empirical curves (see Figure 34), it is assumed that this curve follows the shape of:

$$\eta = A \cdot \left(1 - e^{-a \cdot \gamma}\right) \text{ .... Equation 1}$$

η	Efficiency	[1]
A	Curve Parameter	[1]
a	Curve Parameter	[1]
γ	Loading	[1]

The known points of the curve – efficiency at 50%, 75% and 100% of the load – are called η_{50}, η_{75} and η_n. This consequently leads to the following deduction:

$$A = \frac{\eta_{50}{}^2}{2 \cdot \eta_{50} - \eta_n} \text{ .... Equation 2}$$

A	Curve Parameter	[1]
η_{50}	Efficiency at 50% of load	[1]
η_n	Rated Efficiency	[1]

$$a = -\ln\left(1 - \frac{\eta_n}{A}\right) \text{ .... Equação 3}$$

A	Curve Parameter	[1]
η_n	Rated Efficiency	[1]
A	Curve Parameter	[1]

The application of these formulas to the Weg motor curves provided good results: the η_{50} and η_n values are identical and the η_{75} has an average error of 0.4%, a standard deviation of 0.4% and a maximum of 2.7%.

Through the catalog data (efficiency levels at 50%, 75% and 100% of the load) the ***A*** and ***a*** parameters may consequently be estimated and, through Equation 8, the efficiency level for each loading value.

A.2 Loading Assessment

A.2.1 Through power metering

Using a clamp wattmeter, the capacity is measured for one phase (the motor capacity will be three times the reading) or the capacity is measured at all three-phases, adding them together. The double wattmeter method may also be used, first metering the Phase A current capacity, for instance, and the voltage between phases A and B, adding the phase C current and the voltage between phases B and C to the metered capacity (however, this method requires much concentration and is not recommended when carrying out a series of measurements). When using an electrical magnitude analyzer with three plier ammeters metering the voltages at all three-phases at the same time, the total capacity has a precise metering all the time.

Having obtained the electric power value, it is necessary to estimate the loading. A combination of the various equations presented above and the expression of the mechanical power of the motor leads to Equation 4, which expresses the loading as a function of the electric power.

$$\frac{1-e^{-a\cdot\gamma}}{\gamma}=\frac{P_{rated}\cdot 0,736}{A\cdot P} \quad \text{Equation 4}$$

a	Curve Parameter	[1]
γ	Loading	[1]
P_{rated}	Rated Capacity	[cv]
0.736	Conversion from cv to kW	[kW/cv]
A	Curve Parameter	[1]
P	Metered Three-Phase Capacity	[kW]

Referring to the function in Equation 5, the root will correspond to the solution obtained by applying Equation 4 and may be found through the Newton-Raphson method.

$$f\left(\gamma\right)=\frac{1-e^{-a\cdot\gamma}}{\gamma}-\frac{P_{rated}\cdot 0,736}{A\cdot P} \quad \text{Equation 5}$$

a	Curve Parameter	[1]
γ	Loading	[1]
P_{rated}	Rated power	[cv]
0.736	Conversion from cv to kW	[kW/cv]
A	Curve Parameter	[1]
P	Metered Three-Phase Power	[kW]

The algorithm in the Excel spreadsheet is described below.

$$
\begin{aligned}
&Function \quad \gamma\left(a, P_{mec}, A, P\right)\\
&\gamma = 0{,}0001\\
&For\ i = 1\ to\ 100,\ \Delta i = 1\\
&f(\gamma) = \frac{1 - e^{-a\cdot\gamma}}{\gamma} - \frac{P_{mec}\cdot 0{,}736}{A\cdot P}\\
&f'(\gamma) = \frac{\gamma\cdot a\cdot e^{-a\cdot\gamma} - 1 + e^{-a\cdot\gamma}}{\gamma^2}\\
&If \quad \left|f(\gamma)\right| \le 0{,}0001 \quad Then\ End.\ Else\\
&\gamma = \gamma - \frac{f(\gamma)}{f'(\gamma)}\\
&Next \quad i
\end{aligned}
$$

A.2.2 Through current metering

In the case of current metering, which is less accurate, the current is metered at one of the phases, or preferably an average is taken of the three-phases. A good alternative is to meter the voltages between the three-phases and take the average. The apparent capacity percentage can then be calculated in relation to the rated value.

$$i = \frac{E_{mes}\cdot I_{mes}}{E_{rt}\cdot I_{rt}} \quad \text{Equation 6}$$

i	Percentage current	[1]
E_{mes}	Metered voltage between phases (average)	[V]
I_{mes}	Metered current (average)	[A]
E_{rt}	Rated interphase voltage	[V]
I_{rt}	Rated current	[A]

To adjust the currents as a function of loading, three points are once again provided at 50%, 75% and 100% of the load. The curve similarity (see Figure 34) indicates a function of the following type:

$$i = A\cdot e^{b\cdot\gamma} \quad \text{Equation 7}$$

i	Percentage Current	[1]
A	Adjustment parameter	[1]
b	Adjustment parameter	[1]
γ	Loading	[1]

This leads to the deduction that the ***b*** parameter is:

$$b = -2\ln\left(i_{50}\right) \quad \text{Equation 8}$$

b	Adjustment parameter	[1]
i_{50}	Percentage current at 50% of the load	[1]

The current at half-load is:

$$i_{50} = \frac{1}{2} \cdot \frac{fp_{rt} \cdot \eta_{rt}}{fp_{50} \cdot \eta_{50}} \quad \text{Equation 9}$$

i_{50}	Percentage Current at 50% of the load	[1]
Fp_{rt}	Rated power factor	[1]
η_{rt}	Rated Efficiency	[1]
fp_{50}	Power factor at 50% of the load	[1]
η_{50}	Efficiency at 50% of the load	[1]

And the loading may be obtained directly:

$$\gamma = 1 + \frac{1}{b} \cdot \ln(i) \quad \text{Equation 10}$$

γ	Loading	[1]
b	Adjustment parameter	[1]
i	Metered percentage current	[1]

The application of these formulas to the Weg standard motors once more shows that the rated and 50% values coincide yet again, with an average error of 2.4% at 75%, a standard deviation of 1.4%, and a maximum of 5.2% (lower than the field metering uncertainty levels).

Appendix B COST-BENEFIT RATIO TABLES

Table B-1 - Cost-Benefit Ratio for Industry (FINAME)

Two and Four Poles

Hours/year		8000	8000	4000	4000
Loading		**1.0**	**0.5**	**1.0**	**0.5**
Viable		**100%**	**98%**	**81%**	**75%**
	cv				
2 Poles	1.0	0.25	0.32	0.50	0.64
	1.5	0.15	0.28	0.30	0.56
	2.0	0.21	0.35	0.42	0.70
	3.0	0.11	0.16	0.23	0.32
	4.0	0.23	0.50	0.45	1.00
	5.0	0.29	0.34	0.59	0.68
	6.0	0.19	0.57	0.37	1.15
	7.5	0.29	0.79	0.58	1.57
	10.0	0.26	0.26	0.53	0.51
	12.5	0.27	0.51	0.53	1.01
	15.0	0.19	0.26	0.38	0.53
	20.0	0.08	0.16	0.16	0.32
	25.0	0.21	0.36	0.43	0.72
	30.0	0.38	1.72	0.76	3.43
	40.0	0.12	0.25	0.24	0.50
	50.0	0.24	0.36	0.48	0.73
	60.0	0.41	0.42	0.81	0.84
	75.0	0.62	0.32	1.24	0.65
	100.0	0.89	0.65	1.79	1.31
	125.0	0.36	0.41	0.72	0.82
	150.0	0.43	0.34	0.86	0.67
	175.0	0.56	0.39	1.13	0.79
	200.0	0.57	0.36	1.13	0.71
	250.0	0.58	0.44	1.15	0.88
4 Poles	1.0	0.34	0.36	0.68	0.73
	1.5	0.41	0.35	0.81	0.70
	2.0	0.47	0.84	0.94	1.67
	3.0	0.37	0.40	0.74	0.81
	4.0	0.23	0.41	0.46	0.82
	5.0	0.29	0.49	0.57	0.97
	6.0	0.16	0.27	0.31	0.55
	7.5	0.24	0.52	0.48	1.04
	10.0	0.26	0.45	0.52	0.91
	12.5	0.21	0.39	0.42	0.78
	15.0	0.18	0.37	0.37	0.73
	20.0	0.17	0.32	0.33	0.64
	25.0	0.33	0.50	0.66	1.00
	30.0	0.23	0.37	0.45	0.73
	40.0	0.26	0.29	0.53	0.57
	50.0	0.39	0.28	0.78	0.56
	60.0	0.61	0.69	1.23	1.37

Hours/year	cv	8000	8000	4000	4000
Loading		**1.0**	**0.5**	**1.0**	**0.5**
Viable		**100%**	**98%**	**81%**	**75%**
	75.0	0.46	0.49	0.93	0.97
	100.0	0.37	0.62	0.73	1.23
	125.0	0.36	0.32	0.71	0.63
	150.0	0.38	0.39	0.77	0.78
	175.0	0.70	0.52	1.41	1.03
	200.0	0.60	0.31	1.21	0.62
	250.0	0.59	0.39	1.19	0.78

Source: Prepared in-house.

Table B-2 - Cost-Benefit Ratio for Industry (FINAME)

Six and Eight Poles

Hours/year	cv	8000	8000	4000	4000
Loading		**1.0**	**0.5**	**1.0**	**0.5**
Viable		**89%**	**70%**	**39%**	**18%**
6 Poles	1.0	0.17	0.24	0.35	0.48
6 Poles	1.5	0.49	0.50	0.99	0.99
6 Poles	2.0	0.18	0.35	0.35	0.70
6 Poles	3.0	0.22	0.54	0.44	1.08
6 Poles	4.0	0.18	0.28	0.37	0.56
6 Poles	5.0	0.26	0.53	0.53	1.05
6 Poles	6.0	0.24	0.53	0.48	1.06
6 Poles	7.5	0.27	0.56	0.55	1.11
6 Poles	10.0	0.35	0.55	0.70	1.09
6 Poles	12.5	0.42	0.62	0.83	1.24
6 Poles	15.0	0.66	0.68	1.32	1.37
6 Poles	20.0	0.82	1.11	1.64	2.23
6 Poles	25.0	0.57	0.91	1.13	1.82
6 Poles	30.0	0.47	1.05	0.94	2.11
6 Poles	40.0	0.82	1.20	1.65	2.40
6 Poles	50.0	0.68	0.52	1.35	1.04
6 Poles	60.0	0.51	0.96	1.02	1.92
6 Poles	75.0	1.04	1.06	2.07	2.12
6 Poles	100.0	0.70	0.63	1.41	1.27
6 Poles	125.0	0.57	0.77	1.14	1.53
6 Poles	150.0	0.79	0.59	1.59	1.17
6 Poles	175.0	0.83	0.70	1.67	1.41
6 Poles	200.0	0.77	0.48	1.53	0.96
8 Poles	1.0	0.30	0.54	0.61	1.09
8 Poles	1.5	0.37	0.40	0.74	0.81
8 Poles	2.0	0.45	0.70	0.89	1.39
8 Poles	3.0	0.24	0.35	0.48	0.70
8 Poles	4.0	0.19	0.33	0.37	0.66
8 Poles	5.0	0.49	0.88	0.99	1.76
8 Poles	6.0	0.57	0.82	1.15	1.64

Hours/year		8000	8000	4000	4000
Loading		**1.0**	**0.5**	**1.0**	**0.5**
Viable		**89%**	**70%**	**39%**	**18%**
	cv				
	7.5	0.52	0.51	1.04	1.02
	10.0	0.77	0.82	1.54	1.64
	12.5	0.57	0.89	1.13	1.79
	15.0	0.76	1.09	1.53	2.19 A
	20.0	0.94	0.90	1.89	1.80
	25.0	0.77	0.71	1.54	1.41
	30.0	1.52	2.52	3.04	5.04
	40.0	1.03	2.44	2.05	4.87
	50.0	1.13	2.24	2.26	4.48
	60.0	1.05	1.80	2.11	3.61
	75.0	0.87	2.69	1.74	5.37
	100.0	0.77	2.40	1.55	4.80
	125.0	0.89	1.74	1.77	3.47
	150.0	0.82	1.66	1.64	3.31

Source: Prepared in-house.

Table B-3 -Cost-Benefit Ratio for Industry (Company Capital)

Two and Four Poles

Hours/year		**8000**	**8000**	**4000**	**4000**
Loading		**1.0**	**0.5**	**1.0**	**0.5**
Viable		**98%**	**94%**	**65%**	**50%**
	cv				
2 Poles	1.0	0.32	0.41	0.64	0.83
	1.5	0.19	0.36	0.38	0.72
	2.0	0.27	0.45	0.55	0.91
	3.0	0.15	0.20	0.30	0.41
	4.0	0.29	0.65	0.58	1.30
	5.0	0.38	0.44	0.76	0.88
	6.0	0.24	0.74	0.48	1.49
	7.5	0.38	1.02	0.75	2.04
	10.0	0.34	0.33	0.68	0.66
	12.5	0.35	0.67	0.71	1.35
	15.0	0.25	0.35	0.50	0.70
	20.0	0.10	0.21	0.21	0.42
	25.0	0.28	0.48	0.57	0.95
	30.0	0.51	2.28	1.02	4.57
	40.0	0.16	0.33	0.31	0.67
	50.0	0.32	0.48	0.64	0.97
	60.0	0.54	0.56	1.08	1.12
	75.0	0.83	0.43	1.66	0.86
	100.0	1.19	0.87	2.38	1.74
	125.0	0.49	0.56	0.98	1.12
	150.0	0.59	0.46	1.18	0.92
	175.0	0.77	0.54	1.54	1.08
	200.0	0.78	0.49	1.55	0.98

Hours/year		8000	8000	4000	4000
Loading		**1.0**	**0.5**	**1.0**	**0.5**
Viable		**98%**	**94%**	**65%**	**50%**
	cv				
	250.0	0.79	0.60	1.58	1.21
4 Poles	1.0	0.44	0.47	0.87	0.94
	1.5	0.53	0.45	1.05	0.90
	2.0	0.61	1.08	1.21	2.17
	3.0	0.48	0.52	0.96	1.05
	4.0	0.30	0.53	0.59	1.06
	5.0	0.37	0.63	0.74	1.26
	6.0	0.20	0.36	0.41	0.71
	7.5	0.31	0.68	0.62	1.35
	10.0	0.34	0.59	0.67	1.18
	12.5	0.28	0.52	0.56	1.03
	15.0	0.25	0.49	0.49	0.97
	20.0	0.22	0.43	0.44	0.85
	25.0	0.44	0.67	0.87	1.33
	30.0	0.30	0.49	0.60	0.97
	40.0	0.35	0.38	0.70	0.76
	50.0	0.52	0.37	1.04	0.75
	60.0	0.82	0.91	1.63	1.83
	75.0	0.62	0.65	1.24	1.30
	100.0	0.49	0.82	0.98	1.64
	125.0	0.49	0.43	0.97	0.87
	150.0	0.53	0.54	1.05	1.07
	175.0	0.96	0.71	1.93	1.42
	200.0	0.83	0.42	1.65	0.85
	250.0	0.81	0.53	1.63	1.07

Source: Prepared in-house.

Table B-4 - Cost-Benefit Ratio for Industry (Company Capital)

Six and Eight Poles

Hours/year		8000	8000	4000	4000
Loading		**1.0**	**0.5**	**1.0**	**0.5**
Viable		**59%**	**52%**	**27%**	**11%**
	cv				
6 Poles	1.0	0.23	0.31	0.45	0.62
	1.5	0.64	0.64	1.28	1.28
	2.0	0.23	0.46	0.46	0.91
	3.0	0.28	0.70	0.57	1.39
	4.0	0.24	0.36	0.47	0.72
	5.0	0.34	0.68	0.68	1.37
	6.0	0.31	0.68	0.63	1.37
	7.5	0.36	0.72	0.71	1.44
	10.0	0.45	0.71	0.91	1.41
	12.5	0.55	0.83	1.11	1.65
	15.0	0.88	0.91	1.75	1.82
	20.0	1.09	1.48	2.18	2.97

Hours/year		8000	8000	4000	4000
Loading		1.0	0.5	1.0	0.5
Viable		59%	52%	27%	11%
	cv				
	25.0	0.75	1.21	1.51	2.42
	30.0	0.63	1.40	1.25	2.81
	40.0	1.09	1.60	2.19	3.20
	50.0	0.90	0.69	1.80	1.39
	60.0	0.68	1.28	1.35	2.56
	75.0	1.38	1.41	2.76	2.82
	100.0	0.94	0.84	1.87	1.69
	125.0	0.78	1.05	1.56	2.10
	150.0	1.09	0.80	2.17	1.61
	175.0	1.14	0.96	2.28	1.93
	200.0	1.05	0.66	2.10	1.32
8 Poles	1.0	0.39	0.70	0.79	1.41
	1.5	0.48	0.52	0.96	1.04
	2.0	0.58	0.90	1.15	1.80
	3.0	0.31	0.46	0.63	0.91
	4.0	0.24	0.43	0.48	0.86
	5.0	0.64	1.14	1.28	2.28
	6.0	0.74	1.06	1.49	2.12
	7.5	0.67	0.66	1.34	1.32
	10.0	1.00	1.06	2.00	2.13
	12.5	0.75	1.19	1.51	2.38
	15.0	1.01	1.45	2.03	2.91
	20.0	1.26	1.20	2.51	2.39
	25.0	1.02	0.94	2.05	1.88
	30.0	2.03	3.35	4.05	6.71
	40.0	1.37	3.24	2.73	6.49
	50.0	1.50	2.98	3.01	5.96
	60.0	1.40	2.40	2.81	4.80
	75.0	1.16	3.57	2.32	7.15
	100.0	1.03	3.20	2.06	6.39
	125.0	1.21	2.38	2.43	4.76
	150.0	1.12	2.27	2.25	4.54

Source: Prepared in-house.

Appendix C THE USE OF POWER ELECTRONICS FOR INDUCTION MOTOR DRIVES

Power electronics are extremely important in industrial automation, power generation and conservation and – indirectly – reducing environmental pollution. With technological progress in semiconductor development and the resultant cost reductions, power electronics is expanding for a wide variety of applications, such as uninterruptible power supplies (UPS), line filters, HVDC systems, photo-voltaic systems, variable frequency machine drives and many others. Motor drives are possibly the main field of action for power electronics, with applications that include computer peripherals, pumps and fans, wind-power generation systems, ship propulsion and others [1].

More efficient conversion processes for the electricity consumed by electro-electronic equipment is also helping cut consumption, with the support of power electronics, while indirectly reducing environmental pollution through lowering power generation levels. According to [1], an estimated 15% to 20% of electricity consumption could well be avoided through the extensive use of power electronics. Some 60% of the power generated in the USA is consumed by motors, with 70% of these motors consisting of pumps and fans [2].

The additional costs associated with adding electronic converters for motor drives may be recovered in the course of their use, through lower electricity consumption tariffs. The basic idea is the same as that associated with the use of high efficiency cage motors powered by conventional constant frequency voltage sources in situations where enhanced operating efficiency close to the rated level will help lower losses. These reductions in losses leads to the recovery of the costs incurred through acquiring a more expensive motor after a certain length of use.

Within a different context of greatly enhanced drive efficiency or better recovery of efficiency under operating conditions at far broader speed variation ranges, the use of electronic converters for induction motor drives in industrial processes may also lead to the recovery of the relatively higher costs incurred through the acquisition of the motor and its associated drive, after a given length of time. For example, the use of power electronics for air conditioning unit compressor drives may result in reductions of up to 30% in global electricity consumption. The potential drop in consumption is so impressive that 70% of the home air conditioning units in Japan are fitted with variable speed drives in order to save electricity [2].

In the lighting area, it is estimated that 20% of the electricity generated in the USA is consumed through this type of use. Supported by power electronics, high-frequency fluorescent light bulbs may result in electricity savings of up to 20% compared to the consumption of conventional fluorescent light bulbs. Consequently, when looking at drives, the energy efficiency enhancement figures presented above function at a far higher scale than those associated with the operations of high-efficiency cage motors used for general purposes, which are normally associated with the need for broad variations in the machine speed that cannot be obtained efficiently without using electronic drives.

These data offer a brief overview of how the use of power electronics in motor drives may help reduce the amount of electricity consumed, making better use of the equipment and consequently extending its useful life. The topics presented below provide grounds for discussion by presenting the impact on the load startup associated with the use of induction motor drives based on power electronics.

- ✓ Development of semiconductor capacity devices and microelectronics;
- ✓ Electronic converters used in drives;
- ✓ Control techniques for induction motors with electronic drives;
- ✓ Effective gains through using scalar and vector controls, compared to conventional operations;
- ✓ Need for technical standards;
- ✓ Future trends and technologies.

C.1 Development of Semiconductor Capacity Devices and Microelectronics

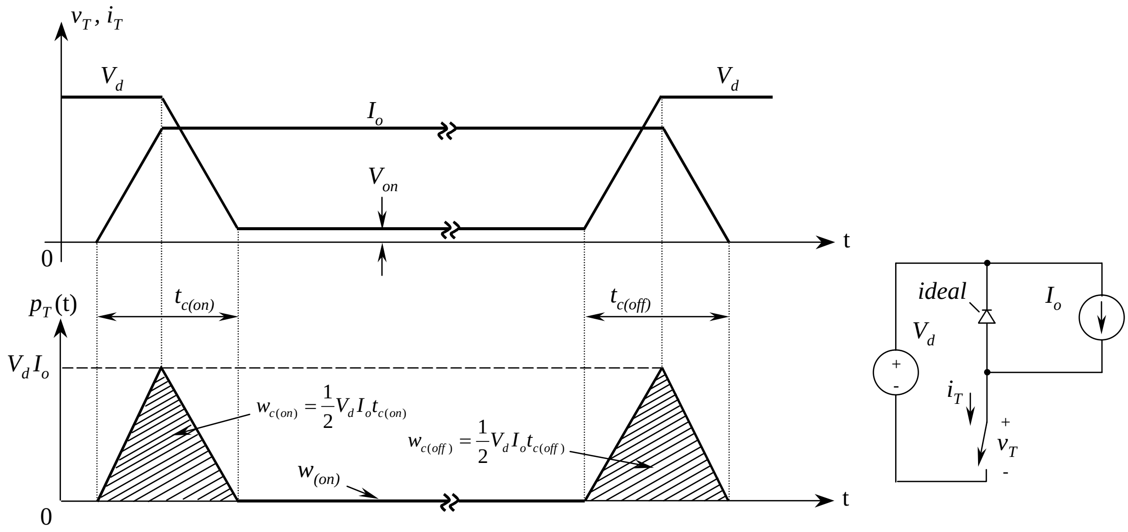
In 1958, the commercial availability of thyristors ushered in a new era for direct current machine drives. Constraints on using thyristors for alternating current machine drives are due to the fact that this is a partial control semiconductor, meaning that only its turn-on can be controlled, with turn-off handled through the temporary behavior of the control circuit itself. During the 1970s and 1980s, power semiconductors appeared with turn-on and turn-off capacities, ensuring the feasibility of the use of these switches for alternating current machine drives. The following Table presents the development of power semiconductors.

Table C-1 — Development of Power Semiconductors

1st generation (1958-1975)	Thyristor
2nd generation (1975-1985)	Power MOSFET GTO (Gate Turn-Off Thyristor)
3rd generation (1985-...)	IGBT (Insulated Gate Bipolar Transistor) SIT (Static Induction Transistor) SITH (Static Induction Thyristor) MCT (Mos Controlled Thyristor)

Source: Prepared in-house.

The energy loss in semiconductors occurs mainly when changes are occurring in the conduction status (turn-on and turn-off). At these moments, the voltage and current in the semiconductor generate a loss that is not negligible, as shown in FigureC-1. This underscores the importance of devices with low losses during commutation, allowing the semiconductor to operate at a higher switching frequency.



FigureC-1 — Semiconductor Losses during Commutation Intervals

During the late 1990s, a new semiconductor appeared on the market, developed by ABB: the Integrated Gate-Commutated Thyristor (IGCT). In addition to ABB, other manufacturers have been developing semiconductor switches operating at higher switching frequencies at increasingly higher voltages and currents.

Research continues, aimed at upgrading these electronic devices. According to [3], there are high hopes for diamond-based semiconductors, and it is believed that this will constitute a new generation of power semiconductors.

In parallel to the advances achieved for semiconductor devices, there has also been significant progress over the past few decades in the field of microelectronics. A good example of this development is the increasing number of microcomputers found today in companies and homes, in addition to more sophisticated electro-electronic equipment and other devices.

For machine drives, the availability of microcomputers, Digital Signal Processors (DSP), optic cables and other factors is ushering in the use of more sophisticated control techniques (vector control, fuzzy control, neural networks, and sensor-free control). The use of microcomputers has triggered a massive leap forward in control systems design, with the support of simulation programs and the design of electric machinery using programs that calculate electromagnetic fields through finite elements.

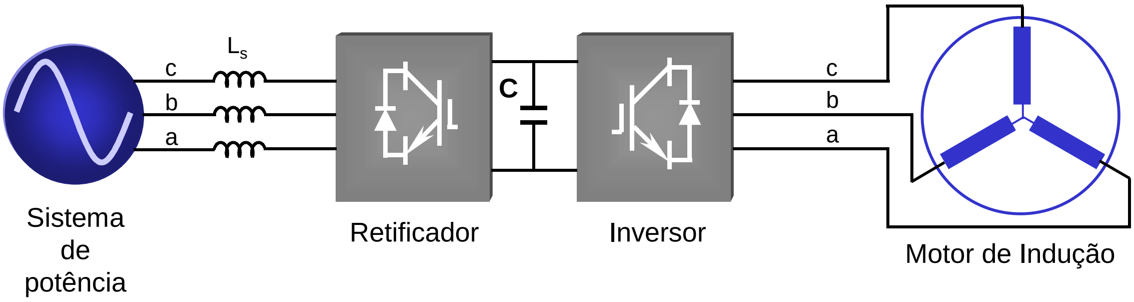
At the moment, research is under way focused on devices blending microelectronics with power electronics, resulting in what are known as “smart power devices” [3]. Technological expertise underpinning the development of efficient and reliable devices is already available [3]. Microelectronics can still contribute greatly to the development of these modules, supplying Application-Specific Integrated Circuits ASIC) components, which will enhance reliability while lessening the electromagnetic compatibility (EMC) problems found in power electronics.

C.2 Electronic Converters used in Drives

A converter consists basically of a set of power semiconductors that turn the input voltage into controlled voltage. In historical terms, converter development has kept pace with the progress of power semiconductors [1].

The modern era of variable frequency drives began with the introduction of force commutated thyristor inverters, such as the McMurray, McMurray-Bedford and Verhoef inverters, among others. Other than the load commutated or line commutated type converters, the forced commutated thyristor inverters are gradually becoming obsolete, due to low efficiency and poor reliability.

A topology common to AC drives is given in Figure 36. This drive consists of using two converters connected to the same DC voltage, in a back-to-back configuration. The converter connected between the AC line and the DC voltage link is called the rectifier, while the converter connected between the DC link and the induction motor is known as the inverter.



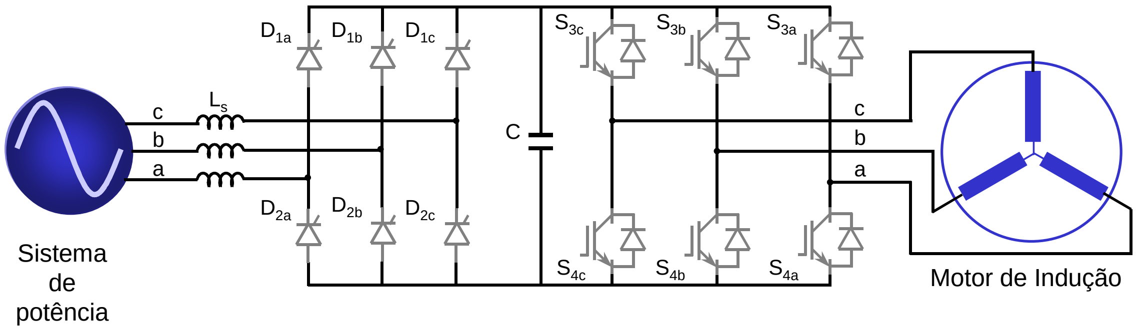
Power System Rectifier Inverter Induction Motor

FigureC-2 — Electronic Drive Consisting of Two Converters Connected Back-To-Back

FigureC-3 presents an electronic drive consisting of two converters connected back-to-back, where the rectifier consists of thyristors and the inverter consists of Insulated Gate Bi-Polar Transistors (IGBTs). This configuration results in a drive with reversible and “regenerative” control at a broad range of speeds, including zero speed and the field-weakening region. This equipment is shielded against power surges through its own control drive.

One of the problems associated with the use of thyristor or diode rectifiers lies in the fact that they introduce currents with high harmonic content into the AC system, polluting the electricity system and resulting in an undesirable power factor.

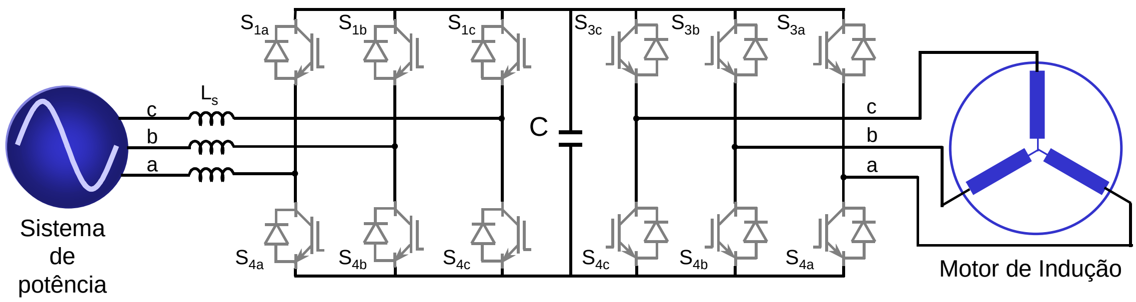
One alternative for dealing with these disadvantages lies in using drives where both converters consist of Insulated Gate Bi-Polar Transistors (IGBTs) as shown in Figure C-4. Although the use of IGBTs requires additional cost, this typology allows the rectifier to operate in a way whereby the AC grid presents an almost sinoidal wave shape in phase with the system voltages, consequently avoiding the deterioration of the power factor and injecting harmonics into the system.



Power system Induction motor

FigureC-3 — Drive Consisting of a Thyristor Rectifier and Integrated Gate Bi-Polar Transistors (IGBTs) Inverter

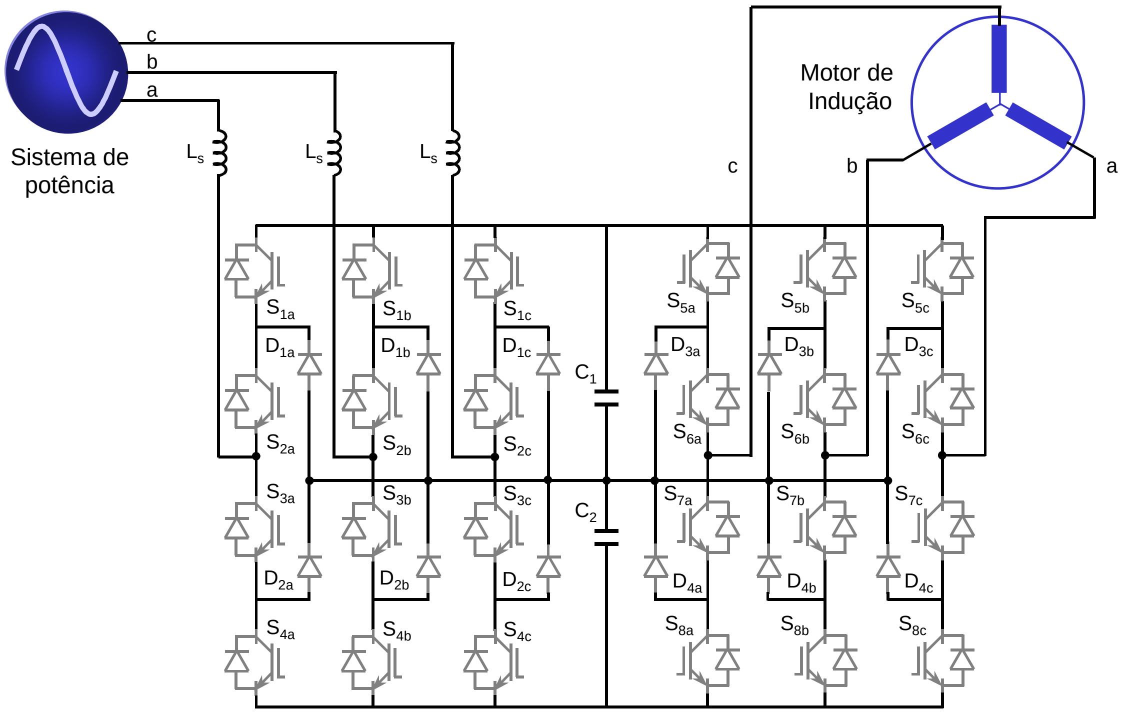
The easy control offered by the IGBT converter allows rapid action for the amplitude and phase angle of the core component of the AC voltage, endowing this type of converter with ample capacity to control the power factor through the associated AC grid.



Power system Induction motor

FigureC-4 — Drive Consisting of Converters with Integrated Gate Bi-Polar Transistor (IGBT) Type Semiconductors

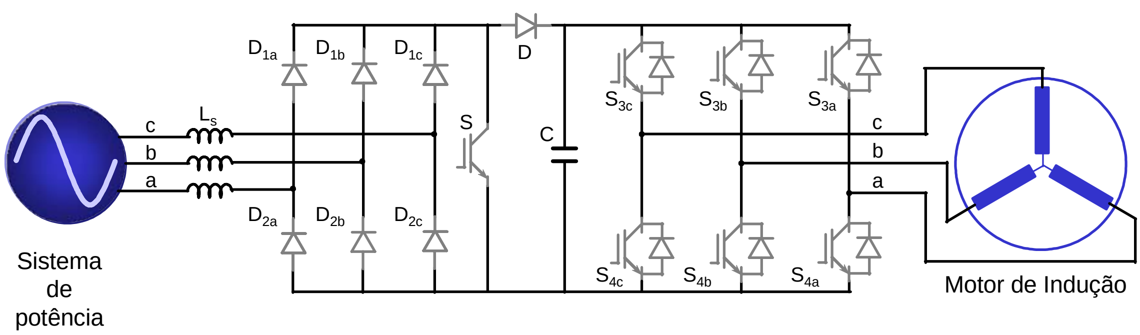
Today, converters with multi-level topology [4] are being used to an increasing extent in motor drives. Figure C-5 presents a three-level Neutral-Point Clamped (NPC) converter. Various multi-level topologies may be found in the literature for different applications [5] [6] [7]. The adoption of multi-level power supplies endows the converter with better controllability, opening up the possibility of establishing a lower switching frequency to synthesize the desired signal and operations at higher power ranges, compared to the power range at which the two-level converter operates.



Power System Induction Motor

FigureC-5 — Drive Consisting of Multi-Level Topology Converters

An old configuration that is nevertheless still widely used is presented in Figure C-6. This configuration shows the rectifier consisting of diodes, resulting in non-controlled efficiency voltage. In order to allow the inverter power supply voltage to be controlled, a DC—DC converter may be used, also known as a chopper. Chopper converters can modulate the DC voltage fed to the inverter, so that it operates more effectively on the DC voltage obtained at the rectifier outlet. Other details of these converters may be noted in the literature [8].



Power System Induction Motor

FigureC-6 — Use of Chopper Converter with Non-Controlled Rectifier

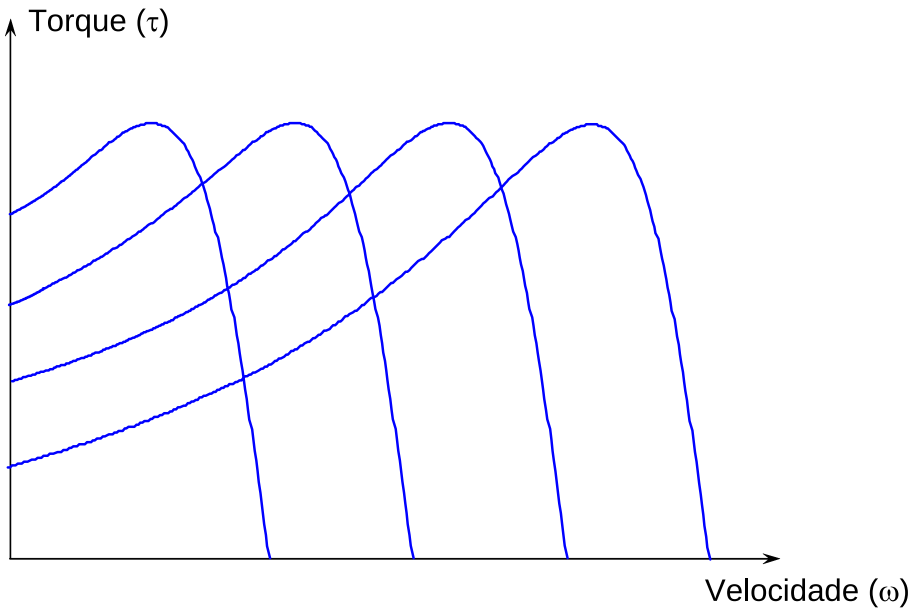
C.3 Control Techniques for Induction Motors with Electronic Drives

Basically, the converters for AC motor drives appeared with the development of the second generation conductors. From then on, AC motors – which had previously been viewed as hard to control – came into use with drives offering a wide variation of speeds, edging out the DC motors [3]. The coordinated variation in voltage (u) and frequency (f) of the motor power supply today allows speed control with no loss in the torque capacity (T). FigureC-7 presents the curve (T x ω) characteristics of an induction motor (MI), with the additional possibility of variations in power supply voltage and frequency.

The first frequency converters operated with SCALAR control (or V/f) and PWM switching. The scalar speed control mode technology was based on using voltage [V] and frequency [f] control variables.

In the scalar control mode (also known as V/f), voltage and frequency are used as the variables, which are applied directly to the polyphase winding of the induction motor stator in order to maintain a constant V/f ratio.

This Voltage / Frequency (V/f) ratio is supplied proportionally, with these magnitudes being limited to the inflection frequency (grid frequency) and the converter power supply voltage (also the grid voltage).



FigureC-7 — Induction Motor Curves (Torque x rotational speed: T x ω) Maintaining a Constant Ratio between Power Supply Voltage and Frequency

Above the inflection frequency (60 Hz in Brazil) frequency converters can boost the output frequency, although this is limited by the voltage (limited to the grid voltage).

Another restrictive characteristic of scalar control is that this is based simply on the non-stop operations of the induction motor. Consequently, for high-efficiency dynamic applications such as robotics, the performance of the induction motor will not be optimized when operating in this control mode.

The so-called “vector control” techniques for these motors will breach this gap in scalar control in terms of dynamic performance. This technique shifted from the academic world to industry in less than twenty years. Induction motor drives using vector control are today supplied by several manufacturers.

According to [3], one of the main difficulties in using vector control lies in the fact that it is based on the rotor winding flux reference. This requires at least information on speed and some machine parameters, some of which vary by saturation and temperature. In order to deal with this problem, microelectronics has helped introduce methods for identifying and processing signals that eliminate the need for speed sensors.

C.4 Effective Gains through using Scalar and Vector Controls, Compared to Conventional Operations

The operation of a direct current machine whose magnetic flux is produced by its armature winding acting orthogonally compared to the field flux due to the angle imposed by the commutator ring and the ideal positioning of the brushes is taken as the reference status for an induction machine operating with an oriented vector field. This is a condition that minimizes the currents in the windings for determining the range of the electromagnetic torque or maximizes the torque produced by specific field current and armature values.

While the use of enhanced efficiency induction motors is linked only to minimizing mechanical and magnetic losses through design and lessening ohm losses caused by the use of larger-gauge copper conductors. The adoption of scalar and vector control represents respectively the intermediate and final steps forward in the quest for greater efficiency in the electromechanical electricity conversion process, with both of these steps taken within the context of the need to operate at a broad range of drive speeds.

Through scalar control, the production of torque is guaranteed at a specific maximum level, as well as operations with significant reductions in rotor copper losses, which cannot be obtained within the context of the need for broad speed variations. This effect on the ongoing efficiency of the machine, in parallel to the adoption of scalar controls cannot be obtained solely through the use of high-efficiency motors alone.

In turn, the adoption of vector controls has an even greater impact on the efficiency of the electricity conversion process, bringing the performance of the induction machine close to that normally posted by direct current motors in terms of the production of electromagnetic torque, minimizing rotor and stator losses, as well as operations within a broad range of speed variations. This enhanced efficiency and lower electricity consumption for the drive operations in the vector control mode helps offset the additional cost of the drive and controls over a given period of time.

C.5 Need for Technical Standards

The purpose of the technical standards should be to draw up documentation that describes the experience built up over the years in operation of specific items of the equipment using equally specific technology. This documentation is intended to provide a solid basis for proper use of the equipment, as well as future designs and projects [9].

While the standards establishing the guidelines that define the operating efficiency of conventional and enhanced-efficiency induction motors have been covered in other Sections of this Report, the purpose of this section is to discuss the possibility and propriety of defining operating standards for induction motors fitted with frequency converters for their power source functions.

Consequently, in terms of establishing technical standards covering the operations of induction motors within the context of electronic drives, it may be said that this is a matter that, although not very new, still suffers from a relative lack of understanding in terms of operating difficulties and performance. Establishing technical standards for the operation of drives with oriented field control seems somewhat remote. Some of the problems are associated with the injection of harmonics generated by most of the converters currently used by industry, as well as rapid voltage variations inherent to the types of wave produced. The IEEE 519-1992 and IEC 555-3 standards already cover the problem of harmonics in electrical systems, with a Brazilian standard still being required that introduces these regulations within the context of electronic drives.

There are however some aspects that have still not yet been dealt with. For example, traditional mobile iron and electro-dynamic instruments are frequently not appropriate for metering purposes [10]. Another matter is related to the difficulty in the rapid derivation of models in order to represent the motor within this context of a wide range of speed variations and frequency, as well as establishing the appropriate trials for obtaining the parameters for these models. On the other hand, there are some standards already established in Brazil for semiconductor devices and DC machine electronic drives [e.g. EB-1405, EB-1125, EB-1727, EB-1733, and EB-1313].

However, no standards have yet been established covering electronic inverters for AC machine drives. According to [3], the EB-2077 standard, based on the IEC 146-2 standard, may be taken as a starting point. To do so, broad-ranging discussions among manufacturers, users, research groups and government entities must be organized in order to draft a document establishing the parameters for the design and manufacture of AC machine drives, in order to minimize the effects on the power supply system. Quite naturally, the task of modeling and deriving the parameters underpinning these standards would be quite complex, within the context of the AC machine drives. The most commonly-used applications may be taken as the starting point, as significant experience has been built up in this field in all important aspects, from the standpoint of the manufacturers and the consumers.

C.6 Future Trends and Technologies

Modern engineering stresses the development of increasingly more robust and versatile equipment that is less harmful to the environment. Power electronics has been contributing greatly to this new trend, offering the requirements needed to face up to this challenge. There are many applications for variable speed drives that help conserve electricity, with these fields of application ranging from the use of electro-electronic equipment in industries as well as homes, to applications in the transportation and trade sectors, as well as power systems.

New devices with conduction and turn-off command capacities, together with multi-level topologies will quite possibly replace thyristor converters for capacities of 10 MW or more.

Parameter identification methods, self-commissioning, eliminating position and speed sensors, adaptive and fuzzy controls are already available at the commercial level.

With steady advances in the field of electronic converters, together with microelectronics, signal processing should become more closely integrated with power electronics. This will help shrink the size and probably also lower the prices of static converters.

The use of fiber-optic cables will ensure more reliable converter control, eliminating the problem of possible interference through electrical magnitude metering.

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Appendix D OPTIMIZED EFFICIENCY MOTORS

Among the loads noted in the electricity system, motors are probably the most common, varying from low-capacity versions used for household appliances to high-capacity motors found in the drives of industrial pumps and fans. Motors consume more than half of all electricity generated, with two-thirds of this load found in industry [1]. Consequently, there is vast potential for enhancing the efficiency of these motors, reducing electricity consumption with lower costs.

Induction motors are found most commonly in electrical systems, due to their low cost, reliability and efficiency. Synchronous motors are used for applications where constant speed is required, in parallel to high operating efficiency and controllable power factors. These latter two aspects are particularly important for motors with capacities of over 1,000 HP. DC motors are used by some industries for electrical traction purposes.

After World War II through to the early 1970s, there was a tendency to design inefficient motors making minimal use of materials such as aluminum, copper and silicon steel. Despite lower acquisition costs, these motors generated high operating costs, due to their losses.

When electricity costs began to rise more steeply during the mid-1970s, most motor manufacturers decided to include Energy-Efficient Motors (EEMs) in their sales lines. With fine-tuned designs, these motors featured electrical and magnetic circuits made from top-grade materials. Enhanced efficiency may be achieved through using special materials such as amorphous silicon steel, for example. Designs may be upgraded on the basis of the technologies developed with the help of computers. The efficiency enhancement of optimized efficiency motors typically varies from 6% for 5 HP motors to 3% for 150 HP motors [1].

The cost of Energy Efficient Motors (EEMs) is some 15% to 25% higher than that of their conventional (standard) counterparts, which may be translated into an additional cost of US$ 8 to US$ 12 HP. For new applications and for motors with lengthy operating periods, the return on investment takes some two years [1].

A comparison of two types of motors is presented in [2], one conventional and the other with optimized efficiency, based on a series of parameters. In order to carry out an accurate comparison, the motors were subjected to trials under similar operating conditions.

Table D-1 and Table D-2 offer comparisons of designs and performance criteria for conventional and optimized efficiency motors. The differences in the electrical designs are described in Table D-1, in general terms, while Table D-2 presents the differences in the mechanical designs of these motors.

Table D-1 - Electrical Designs for Conventional and Optimized Efficiency Motors

TYPE / PART	STANDARD	ENERGY EFFICIENT
Electrical Steel	2.5 – 3.0 Watts/Lb.	1.5 – 2.0 Watts/Lb.
Lam. Thickness Range	.0185” —.035”	.0185” —.025”
Slot Comb. of Rotor & Stator	SAME	
Stator Slot	Small	Large
Rotor Slot	Single or Double Cage	
Rotor Skew	Range from 0 to one slot	
Air Gap	Normal	Same or Slightly Larger
Rotor Construction	Die Cast	Die Cast
Winding	Machine or Hand Wound	

Table D-2 - Mechanical Design for Conventional and Optimized Efficiency Motors

TYPE / PART	STANDARD	ENERGY EFFICIENT
Frame	SAME	
Brackets	SAME	
Fan Cover	SAME	
Fans	May be Different	
Shaft Seals	Optional	IP 54 or IP 55
Outlet Box	SAME	

Bearing	Usually the Same	
Lubricant	Usually the Same	
Shaft	SAME	
Bearing Caps	Optional	Required

The graphs presented below provide information on the operations of conventional and optimized efficiency motors compared to the parameters established in [2], which are described in this Report. Due to strong connections among the parameters mentioned, it will be interesting to note that it is almost impossible for the draughtsman to develop a motor that complies with all these conditions at the same time. In some situations, these parameters clash, forcing the designer to assign a higher priority to some of these characteristics.

Consequently, the study carried out in [2] was intended to enhance the efficiency of some of the parameters mentioned, while keeping the others at acceptable levels. Subsequently, graphs are presented that illustrate the performance of motors tested in compliance with the parameters used.

Figure D-1 and Figure D-2 compare the motors in terms of aspects related to efficiency and power factors. The efficiency characteristics and the power factors are classic for optimized efficiency motors [2]. Based on information about a specific quantity of materials (steel, copper and aluminum) used in a specific project design, optimization may be undertaken in order to maximize the efficiency and power factor of the motor, for instance.

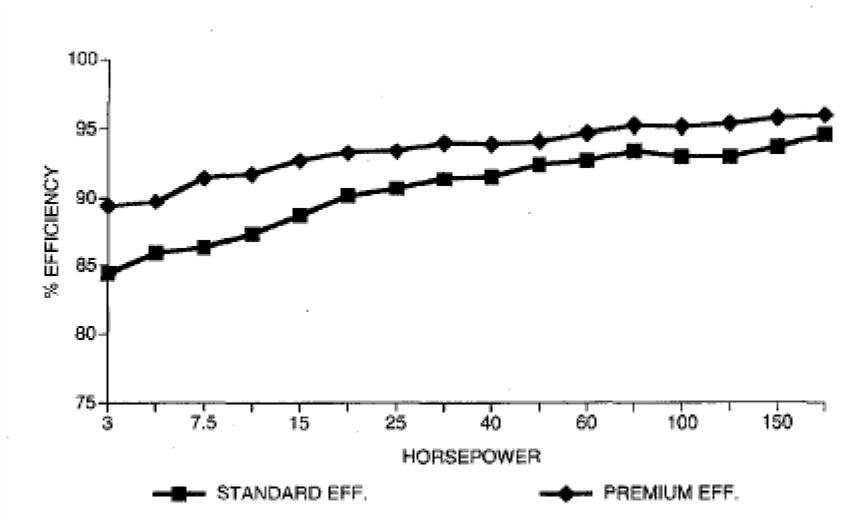

Figure D-1 - Efficiency of Motors Subject to Similar Conditions

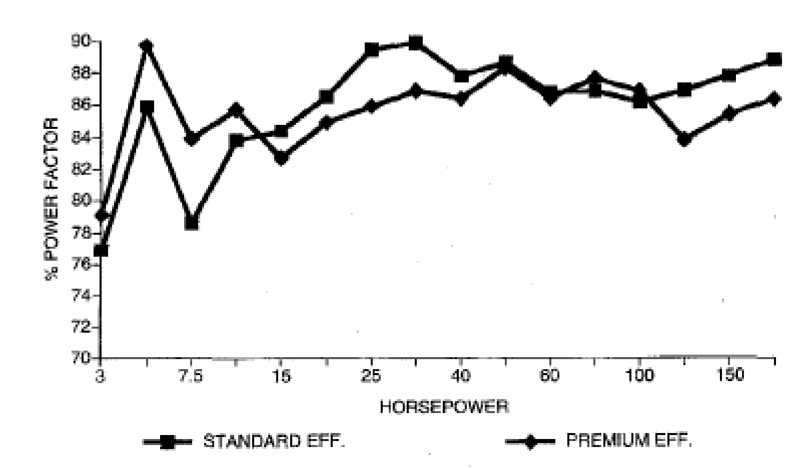

Figure D-2 - Motor Power Factors

A direct comparison between the expected useful life of the machine and the temperature is presented in Figure D-3. These values were derived from the fact that the useful life of the winding insulation is doubled for each 10% drop in the average operating temperature.

Figure D-4 presents information on the average winding temperatures of the motors in operation. As might be expected, due to the mechanical modifications introduced in the optimized efficiency motors, they operate at lower temperatures at capacities of under 50 HP. For motors with capacities of over 50 HP, this temperature difference is considerably less marked, and is almost non-existent for motors with a capacity of over 100 HP.

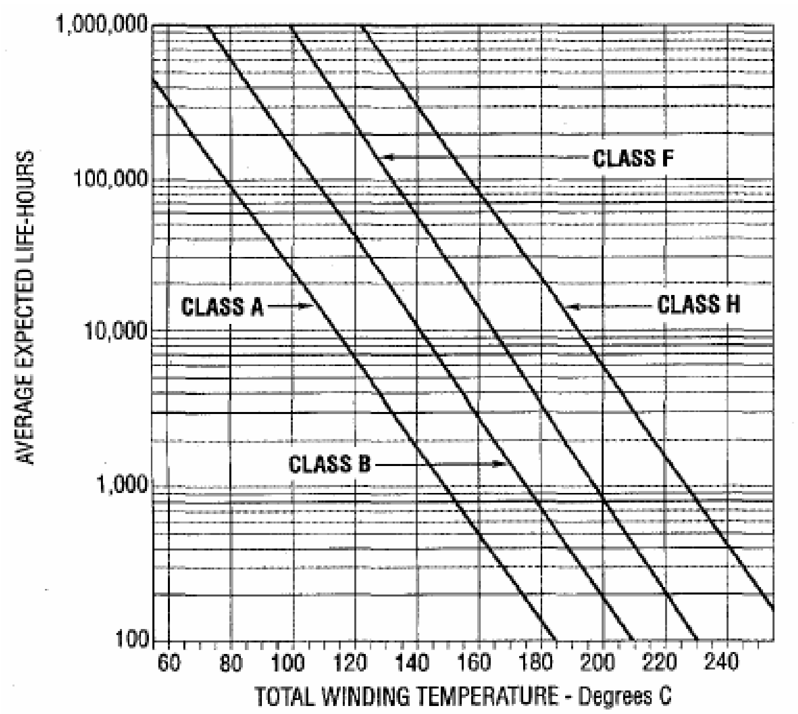

Figure D-3 - Graph Relating Temperature and Expected Useful Life of Machine in Operation

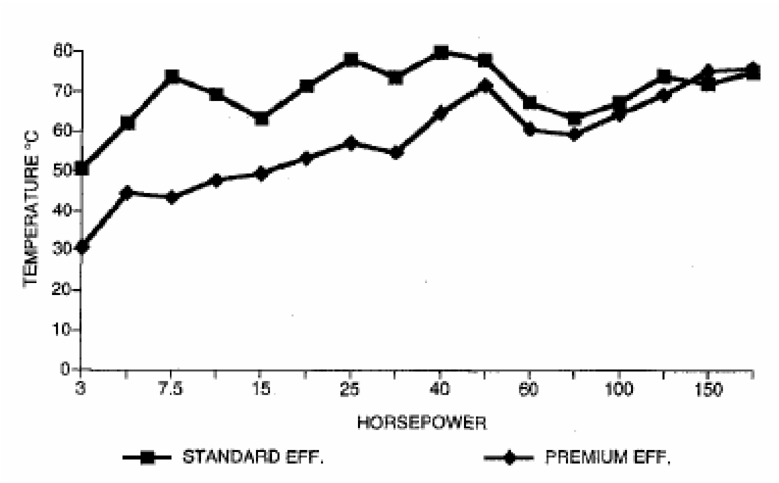

Figure D-4 - Average Winding Temperatures of Motors in Operation

0 illustrates the start-up torque of conventional and optimized efficiency motors. As may be noted, the torque for the motors in question does not vary significantly. Figure D-6 shows the full-load rotation of the motors under analysis. The optimized efficiency and low capacity motors (1-30 HP) present high rotation or low slip. These low slip levels help reduce rotor losses and temperatures (Figure D-7), extending the useful life of the rotor and the bearings.

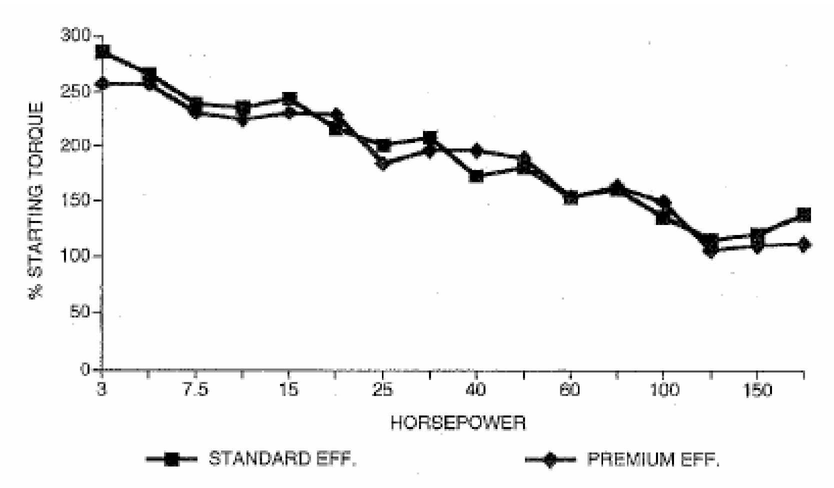

Figure D-5 - Start-Up Torque of the Motors

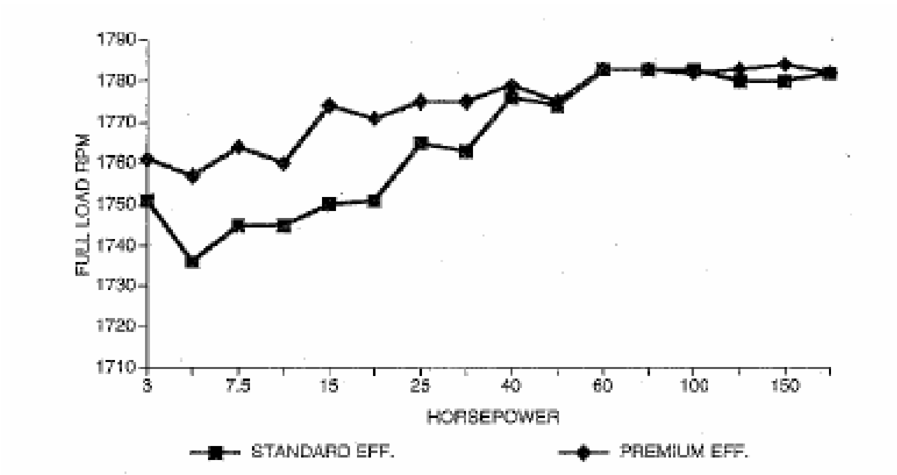

Figure D-6 - Motor rotation (rpm) at full load.

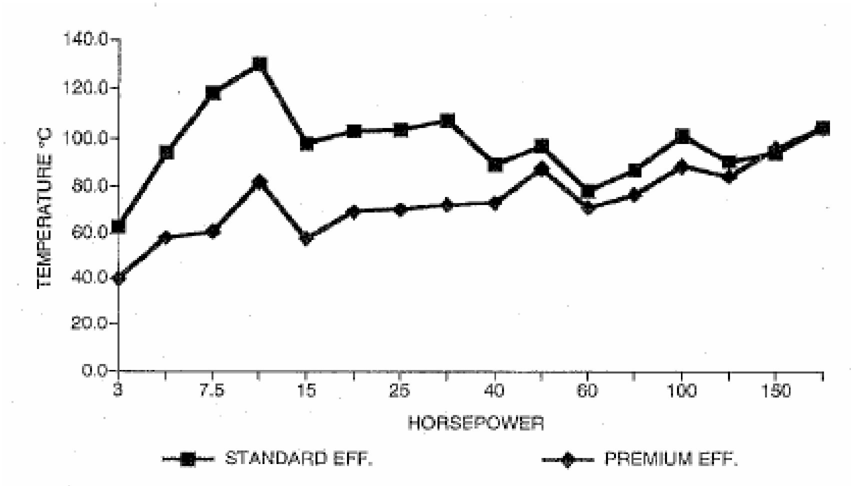

Figure D-7 - Maximum rotor temperature

Figure D-5 offers a comparison of the gap used in the motors under analysis. As may be noted, the gap is normally not reduced in optimized efficiency motor designs.

However, the gap may be reduced when the objective is to introduce an additional increase to the power factor.

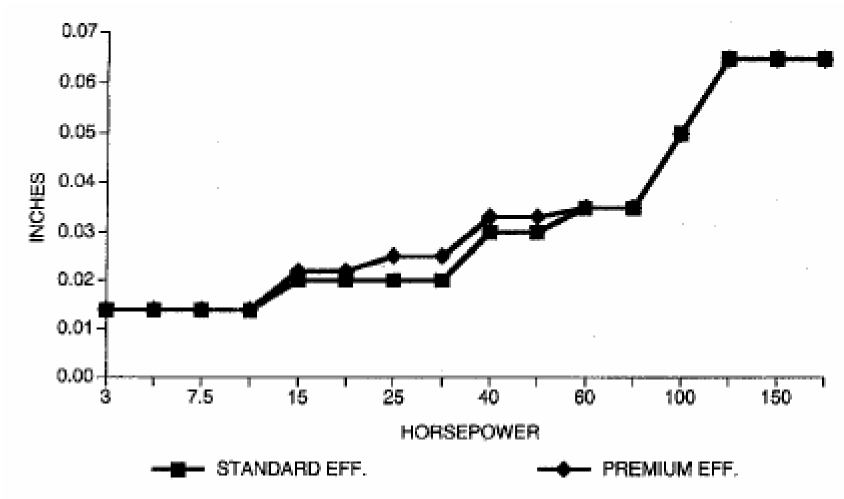

Figure D-8 - Comparison of the Motor Gap

Figure D-9 presents the X/R ratio between conventional and optimized efficiency motors. As may be noted, there is no significance for motors with capacities up to 100 HP. The X/R ratio is basically controlled by the electromagnetic design of the motor.

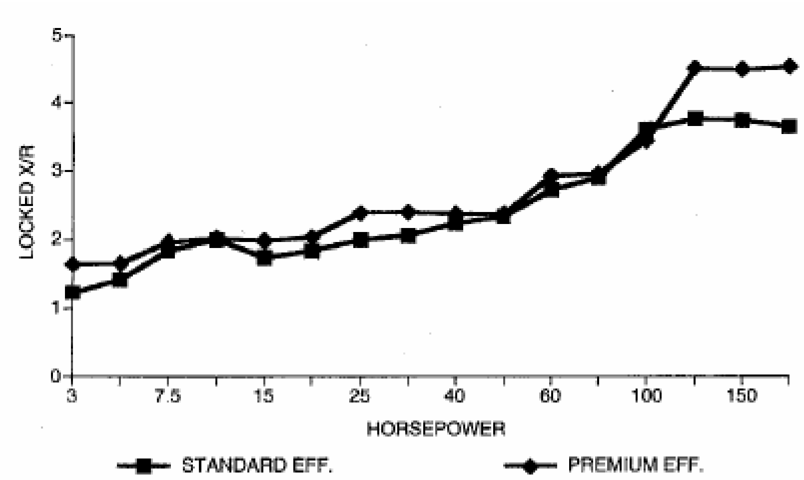

Figure D-9 - Comparison of the X/R Ratio Between Motors

Another aspect that should be taken into consideration is the effective gain obtained through using optimized efficiency motors [3]. As 30% of the electricity provided by power systems is consumed by low-voltage induction motors, a study is required to determine the effective global gains that could be obtained through the use of optimized efficiency motors.

Three types of motor applications are outlined in the Table D-3 and Table D-4, each presenting a conventional and an optimized efficiency motor. The motors are Totally Enclosed Fan-Cooled (TEFC) type, 460 V operating at a temperature of 40ºC.

As may be noted in Table D-3, the mechanical load driven by the motor is an important factor, as this directly affects its efficiency and power factor. According to this Table, motors operate with maximum efficiency at 75% of their rated loads. The power factor is at a maximum for operations at 100% of the rated load. The load factor should be controlled in order to reduce distribution system losses, also avoiding companies being penalized by the power distribution utilities.

The Loading and Work Cycles presented in Table D-4 are typically for industrial operations involving cement and mortar. The motors in question were subjected to two operating conditions. Initially, they operated for eight hours a day, five days a week, resulting in a total of 2,000 hours. Next, they were run for 24 hours a day, seven days a week, for a total of 8,000 hours. For all these examples, the significance of the difference in the initial cost of the optimized efficiency motor compared to the conventional motor may be minimized, when looking at the total operating costs over a given period for the useful life of the motor.

Due to the energy lost by the motor, turned into heat, less efficient motors tend to operate at higher temperatures, with shorter useful lives and higher costs. Consequently, initial investments in motor maintenance may help lower the end-cost, while also upgrading the motor efficiency.

Table D-3 - Motors Studied

Motor	Efficiency	HP	Efficiency: 50% of load	Efficiency: 75% of load	Efficiency: 100% of load	Power Factor: 50% of load	Power Factor: 75% of load	Power Factor: 100% of load
I	Conventional	5	87.5%	87.7%	87.5%	70.9%	80.6%	85.9%
I	Optimized Efficiency	5	89.5%	89.7%	89.5%	67%	78%	84%
II	Conventional	25	92.3%	92.6%	92.4%	74.3%	80%	83.8%
II	Optimized Efficiency	25	93.6%	93.8%	93.6%	76%	83%	86%
III	Conventional	100	94.4%	94.7%	94.5%	80.8%	85.3%	85.8%
III	Optimized Efficiency	100	95.4%	95.7%	95.4%	81%	86%	87%

Table D-4 - Cost of motors

Motor	Efficiency	HP	Voltage	Speed (rpm)	% Load	Hours/Year	Initial Cost (US$)	Total Cost (US$)
I	Conventional	5	460/3ph/60	1.800	75	2,000	388	5.715
I	Optimized Efficiency	5	460/3ph/60	1.800	75	2,000	428	5.484
I	Conventional	5	460/3ph/60	1.800	75	8,000	388	11.943
I	Optimized Efficiency	5	460/3ph/60	1.800	75	8,000	428	11.571
Motor	Efficiency	HP	Voltage	Speed (rpm)	% Load	Hours/Year	Initial Cost (US$)	Total Cost (US$)
II	Optimized Efficiency	25	460/3ph/60	1,800	75	2,000	1,659	20,704
II	Conventional	25	460/3ph/60	1,800	75	8,000	1,614	50,771
II	Optimized Efficiency	25	460/3ph/60	1,800	75	8,000	1,659	49,795
III	Conventional	100	460/3ph/60	1,800	75	2,000	6,697	74,219
III	Optimized Efficiency	100	460/3ph/60	1,800	75	2,000	7,751	73,764
III	Conventional	100	460/3ph/60	1,800	75	8,000	6,697	189,463
III	Optimized Efficiency	100	460/3ph/60	1,800	75	8,000	7,751	187,791

In this Report, we highlight some characteristics of optimized efficiency motors, their advantages and the costs associated with their use. In parallel, emerging motor technologies are being developed, such as the electronic commutation reluctance motors, among others. It is important to note that the motors drives running on new technologies are based on electronic converters. Consequently, the importance of power electronics becomes quite clear, fostering the development of new and more efficient motors while underpinning the feasibility of their use for special applications. The Appendixes to this Report present some of the benefits offered by power electronics for induction motor drives.

References

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