Round Robin for converter losses:
Uniform Testing Protocol and results from tests in phase 1,

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Abstract

Variable frequency converters (VFC) are becoming more and more important elements of an energy efficient electric motor driven system (EMDS). They help to adjust the speed and torque of the motor output to the required load of the application and thus are a major source of energy savings. On the other hand, a variable speed driven system adds more cost and complexity and the converter causes additional losses both in its own electronics as well as in the driven motor. The losses of converters for electric motor driven systems have never been systematically and independently verified, as there are no consensus test standards on the subject. Following the publication of IEC 61800-9-2, edition 1, 2017 [1], the need for a more robust testing protocol and repeatable results of tests from independent laboratories emerged and was recognized both by 4E EMSA[1] and IEC SC 22G WG18[2].

Also, the move by the European Commission to introduce in 2019 Minimum Energy Performance Standards for converter losses in the draft for the revision of the Ecodesign regulation no. 640 for motors [2], stimulated the research effort. Four independent labs (CalTest/Australia; DTI/Denmark; BFH/Switzerland and Advanced Energy/USA) agreed to team up for this project, financed by the four respective governments. Phase 1 of the Round Robin project started by the end of 2017 through early 2019. The goal of the project was to define/refine a proposed test method, known as Uniform Testing Protocol (UTP) and a Standard Reporting Format (SRF). By testing a number of converters, the project expected to provide a first feedback on the validity of the reference losses of the IEC standard.

The phase 1 report of March 2019 [3] shows the results of 58 tests on 9 converters between 0.75 kW and 11 kW. It documents excellent agreement of the results for losses and efficiencies. Between the 4 laboratories a high level of repeatability was achieved despite the fact that 24 different load motors were used in the tests. The newly defined UTP testing methodology includes the precise definition of the product under test and its auxiliaries (filters, cooling fan, etc.), the selection of the nominal output current (rated or adapted to motor), the status of the converter (out-of-the-box, no automatic self-test run), the type and size of cabling and the preferred characteristics of the load motor (size vs. converter, rated current, IE-class, pole number, etc.). After the completion of the phase 1, the UTP was updated with lessons learned into a new version (UTP2). About 60 converters are planned to be tested in phase 2 [4] from 2019 - 2020. With the updated UTP2 a sufficient quantitative data will be made available to WG 18 to revise the reference losses in IEC 61800-9-2 which are widely seen as too high. Eventually, also the efficiency classification can be revised in an edition 2 of the standard which is planned for 2021 publication.

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[1] IEA Technology Collaboration Programme on Energy Efficient End-Use Equipment (4E), Electric Motor Systems Annex (EMSA)

[2] IEC, Subcommittee (SC) 22G for Adjustable speed electric drive systems incorporating semiconductor power converters, Working Group (WG) 18 for Energy efficiency of adjustable speed electric power drive systems

Electric motor driven systems: efficiency

The complete Electric Motor Driven System (EMDS) consists of the following four major elements:

- Motor control, such as switch gear, control gear and variable frequency converters (IEC 61800-9-2) [1]
- Electric motor (IEC 60034-2-1 [5], IEC 60034-30-1 [6])
- Mechanical equipment, like belts and gears (respective ISO standards from TCs 41 and 60)
- Application, such as pumps fans and compressors, etc. (respective ISO standards from TCs 86, 117, 117, 118)

In many applications, only the motor and the applications exist. The system energy efficiency of the EMDS is always the product of the efficiencies of the four component efficiencies.

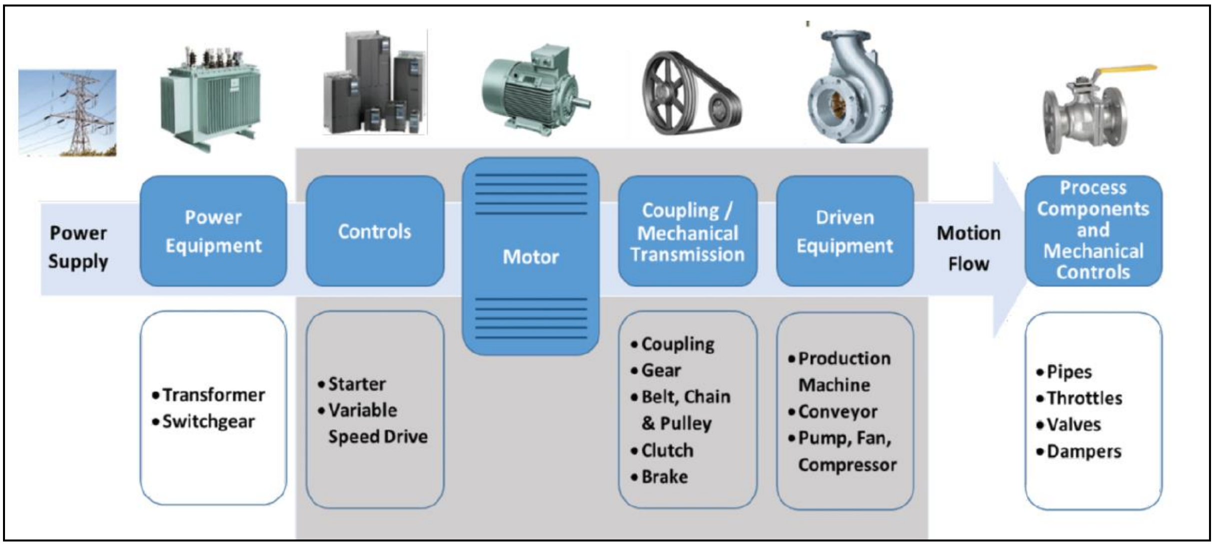

Figure 1 The complete Electric Motor Driven System (Source: IEC TS draft 60034-31, edition 2, 2019)

The need to change the fixed speed of an electric motor that is defined by its pole number, has existed for a long time. Many machines used mechanical or hydraulic means (gears, transmissions, etc. still used in automobile engines today) to adapt the motor speed to the necessary speed of the application and to easily accelerate. Also, early on, DC motors had the capacity to vary their speed which was necessary for instance to start and accelerate an electric train.

The use of electronic VFCs based on pulse-width-modulation (PWM) are considered a major innovative element for energy savings in EMDS. The VFC has added to the EMDS the possibility of easily and continuously varying the rotating speed. Sensors for continuous measurement of the demand of the application (pressure, temperature, flow, etc.) can be used as an input signal to control the rotating speed of the application by varying the input frequency of the electric motor. Thus, process control can be adapted to the necessary load, acceleration and deceleration can be easily adjusted and the energy efficiency can be highly improved by reducing losses. The elimination of dampers and throttles that were used to mechanically reduce the flow pump systems makes for big savings both in installation cost and energy consumption.

A number of international manufacturers have expanded and perfected their portfolio with all types and sizes of VFCs.

Converter losses

The use of a converter does have tremendous advantages. But it does not come for free:

- The VFC induces considerable added investment costs (roughly in the same order of magnitude as the motor of the same output size).
- The VFC has an added loss at nominal speed.
- The VFC also has considerable losses through reduced efficiency at part load at reduced speed and frequency.
- The electric motor efficiency is reduced due to the non- sinusoidal current and voltage delivered from the PWM power supply.

Thus, the use of VFCs in an application is always an optimization procedure that considers the added costs and the added energy losses vs. the lower energy use in the EMDS.

The genesis of IEC 61800-9-2

Since the publication of the European ecodesign regulation no. 640 for electric motors [2] in 2009 that allows to also use IE2 plus VFC instead of a required IE3 motor, the discussion was launched to better understand VFC efficiencies.

One of the first data set of VFC efficiencies in full and part load was published by the US Department of Energy as part of their Tip Sheets in 2008 [10]. The first publication to specify a testing protocol and an efficiency classification for converters in IEC standards was published at EEMODS 2009 [9]. The need arose to define an efficiency classification similar to the motor IE code (IEC 60034-30-1 [6]). In order to speed up this process, the European Commission issued shortly after the regulation for motor efficiency in 2010 a mandate to Cenelec (M/476) [7] to define:

"Procedures and methods for measuring the energy efficiency, efficiency classes, load and speed profiles and associated characteristics of variable speed drives and/or of Power Drive Systems (PDS) equipped with variable speed drives, as appropriate."

Contrary to the parallel issued EC mandate for electric motors (M/470 in 2010), which was immediately handed to IEC, CENELEC decided to keep the VFC mandate at the European level and to setup a working group to deal with it. In 2014 CENELEC published a first version of EN 50598-2 that included an efficiency classification scheme and a calculation model for VFC losses. Subsequently, IEC took over and published a slightly improved version in IEC 61800-9-2, edition1, in 2017.

The published standard contained a calculation method and a test method as well as reference losses for comparing and classifying VFCs into IE classes. The calculation method was criticized by industry experts as being arbitrary and not useful for other industrial programs, the test method was considered incomplete and not applicable for check testing by market surveillance authorities. The reference VFC losses were considered to be way too high compared to market products and arbitrarily set without a transparent scientific base.

In September 2017, an international group of experts met at EEMODS'17 in Rome and decided to setup a Round Robin Program to develop an improved test method and to provide statistically relevant data of converter losses. The group decided to cooperate both with the team of experts in IEC SC 22G WG18 and to agree on a management platform provided by 4E EMSA to secure independence and funding by the involved governments. The Australian, Danish, Swiss and US governments provided the majority of funding for the RR'C through their respective agencies.

Round Robin RR'C

The RR'C program is divided in two phases:

Phase 1

From November 2017 to the end of February 2019
phase 1 serves as a pilot phase of the RR'C with a small number of laboratories and converters to elaborate a testing method. The published final Report of the RR'C phase 1 is available at www.motorsystems.org .

Phase 2

From beginning of March 2019 to the end of 2020
phase 2 tries to provide sufficient evidence of a larger number of converters to serve as a basis to define reference losses and efficiency classes.

With the project management from EMSA (phase 1: Conrad U. Brunner, Impact Energy), the co-financing from the four EMSA member countries Australia (AU), Denmark (DK), Switzerland (CH) and USA, the following four independent motor testing laboratories have been involved in the definition of the UTP and the converter testing of RR'C phase 1 (see Figure 2): Advanced Energy, CalTest, Danish Technological Institute (DTI) and Bern University of Applied Sciences (BFH).

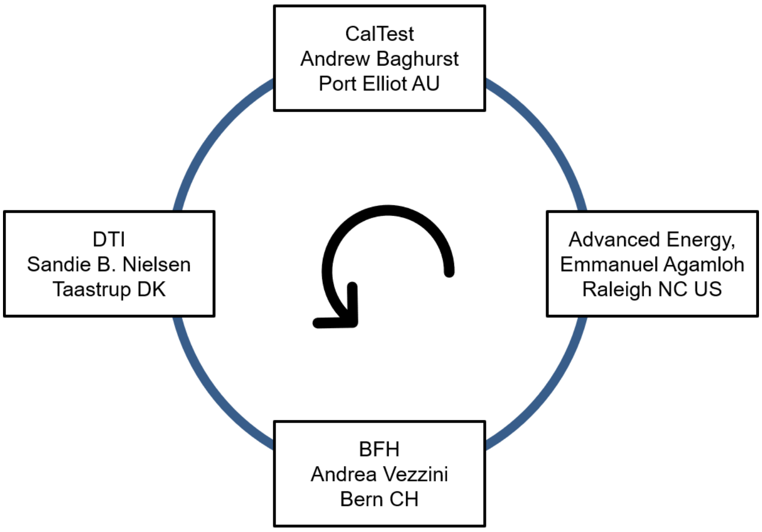

Figure 2 **The Round Robin circle with the four testing laboratories**

The Uniform Testing Protocol (UTP)

The testing needed a much more clearly defined basis and procedural sequence as given in IEC 61800-9-2, edition 1. The nominal and the Zero load points got special attention. The 17 operating points (see Figure 3) are spread over the entire field of frequency and current. They were chosen for this scientific exercise only (the number will eventually be reduced to the most important points). Tests at 50 Hz and 60 Hz, with 1-phase and 3-phase motors and using IE1, IE2 and IE3 motors were conducted. Also, the use of VFC auxiliaries, filters, cooling fans, cables and the setting of the converter "out-of-the-box" etc. had to be defined in order to get highly repeatable results. It was also tested whether "any motor" could be used as a load for the tests, and whether motor size needed to precisely match converter output rating was important.

The choice of the 17 operating points has shown not to be feasible for currents below 50%. Therefore, the tables of results only show 100 % / 75 % / minimum current values and therefore don’t follow strictly the 17 points of the UTP.

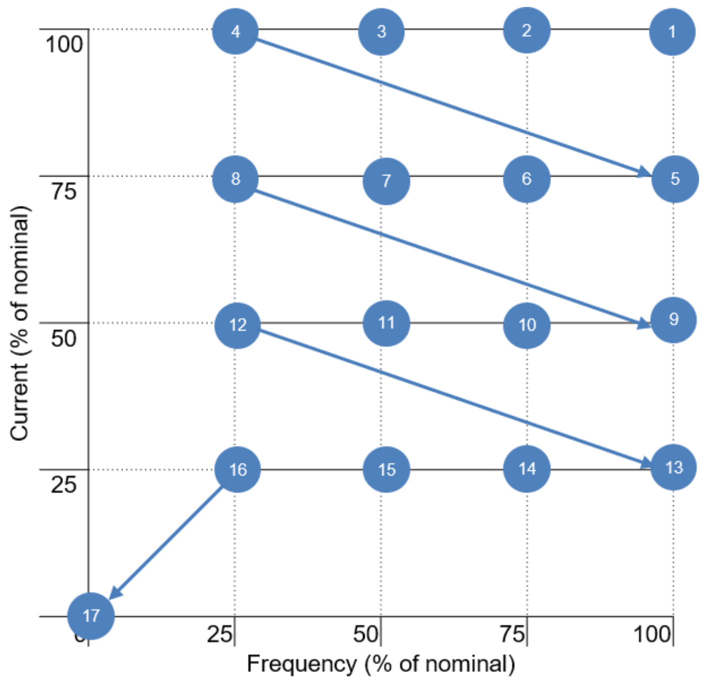

Figure 3 **17 operating points of the converter tests according to the UTP in phase 1**

The UTP test method is based on the idea that the VFC acts as a power source to the motor and there are three types of loss dependencies; namely loss which is load independent, loss which is proportional to load current, and loss which is proportional to load current squared. It is therefore possible to characterize total converter losses by means of a quadratic equation in load current, with the constant term representing standby losses (see Figure 4).

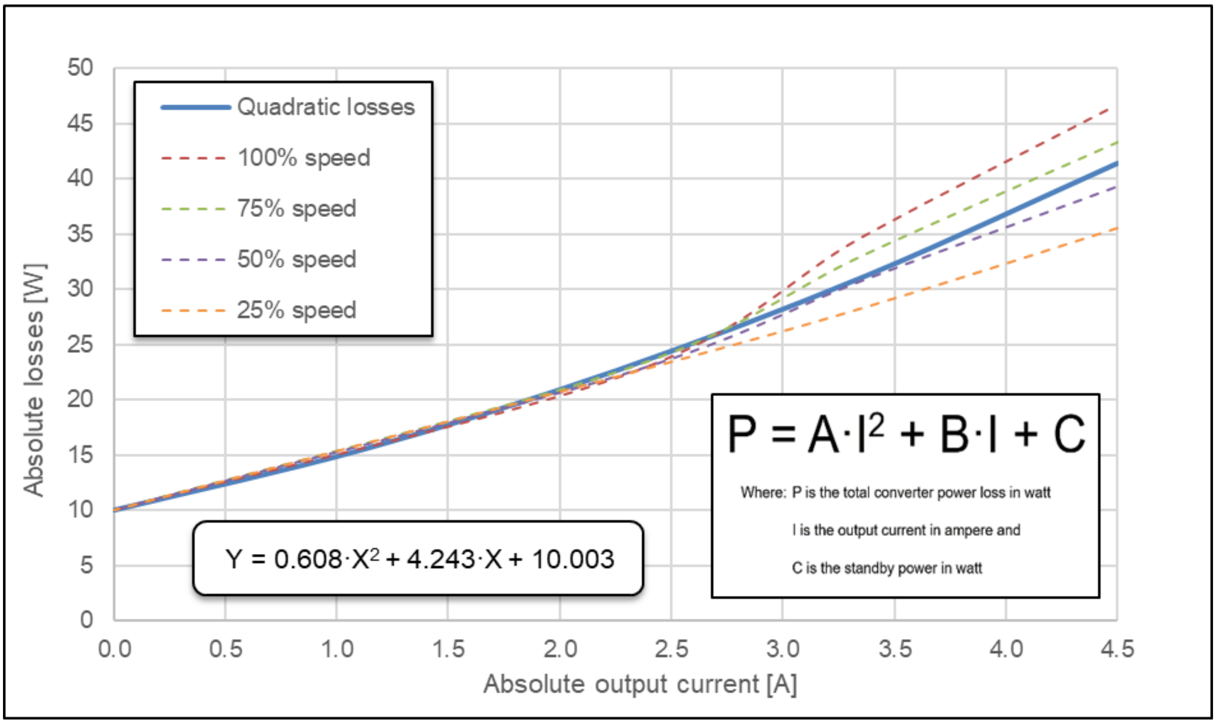

Figure 4 **Quadratic equation for curve fit of the relation between output current and losses**

A standard Reporting Format (SRF) was defined that included a data table and a quadratic curve fit (Figure 5) to demonstrate the consistency of the test results and to allow the interpolation for any intermediary load point.

In the SRF, all test results were reported in data table in Figure 5 that documents input and output, shows the efficiency (eta), the absolute losses (W) in four frequencies plus zero and stopped. It also calculates the parameters directly for the quadratic equation in Figure 4.

Converter tested: 650-21140010-0F0PR0-A1 **Nominal current: 3,40**

Load Point		Supply			Output				Calculation	
Frequency	Current	V	I	Power	Flux V	$V_{(rms)}$	I	Power	Eta	Losses
% / 50 Hz	% rated	(V)	(A)	(W)	(V)	(V)	(A)	(W)	(%)	(W)
100%	100%	230	7,51	1071		232	3,80	1034	96,6	36,5
	75%	229	5,20	695		239	2,66	670	96,4	24,8
	Min.	231	1,18	139		255	1,66	125	89,7	14,3
75%	100%	231	6,01	825		212	3,40	793	96,1	32,2
	75%	230	4,28	564		214	2,56	541	95,8	23,6
	Min.	230	1,03	114		224	1,72	99	86,8	15,0
50%	100%	231	4,44	591		174	3,49	561	95,0	29,6
	75%	232	3,15	405		177	2,59	383	94,6	21,9
	Min.	230	0,82	88		183	1,69	73	83,3	14,7
25%	100%	231	2,40	309		122	3,48	283	91,4	26,5
	75%	231	1,81	220		123	2,57	200	90,9	20,2
	Min.	230	0,73	76		127	1,62	62	81,3	14,2
0,0%		230	0,13	9		1	0,10	0	-0,5	9,0
Stopped		230	0,10	4,6		0	0,00	0	0,0	4,6

Resulting quadratic equation:

x^2	x^1	x^0	R^2
0,76	4,87	4,59	0,999

Example:

Amps	A^2 losses:
3,40	29,9 W

Figure 5 Test results presented in table in Standard Reporting Format

Results from VFC tests in RR'C phase 1

The goal of the tests in phase 1 was to check the repeatability of the UTP method. The testing program in phase 1 included 9 converters from 0.75 kW to 11 kW from four different manufacturers (see Figure 6). A total of 58 tests were conducted by four independent laboratories, using 24 different load motors from 12 different manufacturers. The motors were in efficiency classes of IE1, IE2 and IE3. The tests were run at 50 Hz and 60 Hz line frequencies.

To further the knowledge on converter losses a number of special tests were also run to find out about the feasibility of the selected load motor by type, size, poles, efficiency class, etc. Some of these results (2-pole, larger size motors, etc.) showed higher deviations and some of these results were not included in the final compilation and evaluation of repeatability of the test results. However, the insights gained from those deviations helped to inform the criteria for selecting motors for phase 2.

Owner	Brand	Size [kW]	RR'C No.	CalTest	DTI	BFH	AE
Australia	ABB	1.1	01A	X	X	X	X
	ABB	11.0	01B	X			
Denmark	Schneider	2.2	02A		X	X	X
	Parker	0.75	02B		X	X	X
Switzerland	Lenze	5.5	03A	X		X	X
	ABB	5.5	03B	X		X	X
	ABB	2.2	03C			X	
USA	Schneider	2.2	04A	X	X		X
	Schneider	3.0	04B	X	X		X

Figure 6 List of tested products and the testing laboratories

A sample result table on a 2.2 kW 3-phase Schneider VFC comparing all 9 tests conducted by three labs are shown in Figure 7:

	AE1 IE3	AE2 IE3	CalTest1 IE2	DTI1 IE2	DTI2 IE1	AE1 IE3	AE2 IE3	DTI1 IE1	DTI2 IE2	Mean value	Max/Min span
Equations	-0,72	-0,74	-0,79	-0,96	-0,84	0,04	-0,27	-0,36	-0,31		
	13,50	13,65	13,58	13,88	13,49	10,44	11,32	11,87	11,65		
Absolute Current	6,73	6,77	5,80	5,67	5,60	6,68	6,74	5,61	5,57		
	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00		
1,80	28,7	28,9	27,7	27,5	27,2	25,6	26,3	25,8	25,5	27,0 W	± 1,7 W
1,93	30,1	30,4	29,1	28,9	28,5	27,0	27,6	27,2	26,9	28,4 W	± 1,7 W
2,06	31,5	31,8	30,4	30,2	29,9	28,4	29,0	28,6	28,3	29,8 W	± 1,7 W
2,20	32,9	33,2	31,8	31,5	31,2	29,8	30,3	29,9	29,7	31,1 W	± 1,8 W
2,33	34,2	34,5	33,1	32,8	32,5	31,2	31,7	31,3	31,0	32,5 W	± 1,8 W
2,46	35,6	35,8	34,4	34,0	33,7	32,6	33,0	32,6	32,3	33,8 W	± 1,8 W
2,59	36,9	37,1	35,7	35,2	34,9	34,0	34,3	33,9	33,7	35,1 W	± 1,7 W
2,72	38,1	38,4	36,9	36,4	36,1	35,4	35,6	35,2	35,0	36,4 W	± 1,7 W
2,86	39,4	39,7	38,1	37,5	37,3	36,8	36,9	36,5	36,3	37,6 W	± 1,7 W
2,99	40,6	40,9	39,3	38,6	38,4	38,2	38,2	37,8	37,6	38,8 W	± 1,7 W
3,12	41,8	42,1	40,4	39,6	39,5	39,6	39,5	39,1	38,9	40,1 W	± 1,6 W
3,25	43,0	43,3	41,6	40,6	40,6	41,1	40,7	40,4	40,2	41,3 W	± 1,6 W
3,38	44,2	44,4	42,6	41,6	41,6	42,5	42,0	41,6	41,4	42,4 W	± 1,5 W
3,51	45,3	45,6	43,7	42,6	42,7	43,9	43,2	42,8	42,7	43,6 W	± 1,5 W
3,65	46,4	46,7	44,8	43,5	43,6	45,3	44,5	44,1	43,9	44,7 W	± 1,6 W
3,78	47,5	47,7	45,8	44,4	44,6	46,7	45,7	45,3	45,1	45,9 W	± 1,7 W
3,91	48,5	48,8	46,8	45,3	45,5	48,1	46,9	46,5	46,4	47,0 W	± 1,8 W
4,00	49,2	49,5	47,4	45,8	46,1	49,1	47,8	47,3	47,2	47,7 W	± 1,8 W
4,30	51,5	51,7	49,5	47,6	48,1	52,3	50,5	49,9	49,9	50,1 W	± 2,4 W
4,60	53,6	53,8	51,5	49,2	49,9	55,6	53,2	52,5	52,6	52,4 W	± 3,2 W
4,90	55,6	55,8	53,3	50,6	51,6	58,8	55,8	55,1	55,2	54,6 W	± 4,1 W
5,20	57,5	57,6	55,0	51,9	53,1	62,1	58,4	57,5	57,7	56,8 W	± 5,1 W

Figure 7 Collected results of converter No. 04A – Schneider 2.2 kW

This converter was tested both at 3.91 A and 5.1 A nominal currents, using different load motors with IE1, IE2 and IE3 efficiency class. The colors indicate "red" higher and "green" lower losses or deviations from mean values. The losses at 4.6 A, the defined “nominal” output current corresponding to a standard 2.2 kW 4-pole motor, shows very good agreement.

The statistics at the 4.6 A load point are as follows:

Mean value: **52.4** W with a standard deviation of **1.87** W

The averaged efficiency of the converter at this operating point was measured to **98.0%.**

For reference it should be noted that the testing standard for converters IEC 61800-9-2, edition 1, has a suggested reference IE1 converter loss for a 3.3 kVA unit (2.2 kW informative) of 237 W. This would lead to a relative value of 52.4/237 ≈ 0.22. In the specific case with this converter, the reference becomes even higher. Considering the calculated rated apparent power of this converter which is, $S_R = \sqrt{3} \cdot U_R \cdot I_R$ = 1.73·460·4.6 = 3.66 kVA, the reference losses would then be 299 W, corresponding to a relative value of 0.18.

The compiled test results of all the 58 tests on the 9 converters are shown in see Figure 8.

Brand	Size [kW]	RR'C No.	Supp.	UTP rated Current [A]	Loss [W]	Span [W]	Max [W]	Min [W]	Std. dev. [W]	% of mean
Parker	0,75	02B	1 ph	3,40	30,3	± 0,5	30,9	29,9	0,3	1,08%
ABB	1,10	01A	1 ph	4,50	41,6	± 0,8	42,4	40,8	0,5	1,23%
Schneider	2,20	04A	3 ph	4,60	52,4	± 3,2	55,6	49,2	1,9	3,56%
Schneider	2,20	02A	3 ph	4,75	57,4	± 1,6	58,9	55,6	1,2	2,04%
ABB	2,20	03C	3 ph	4,90	63,1	± 1,3	64,0	61,4	1,2	1,84%
Schneider	3,00	04B	3 ph	8,65	58,1	± 0,8	59,1	57,5	0,6	0,97%
Lenze	5,50	03A	3 ph	12,00	124,3	± 0,7	125,0	123,7	0,5	0,39%
ABB	5,50	03B	3 ph	12,00	126,2	± 6,3	130,8	118,3	4,3	3,39%
ABB	11,00	01B	3 ph	21,40	220,9	± 1,0	221,9	219,9	0,9	0,39%

Figure 8 List of aggregated results of all tests

For the sample of 9 converters between 0.75 and 11 kW the losses range from 30 to 221 W. The Standard Deviation is between 0.3 W and 4.3 W, which amounts to between 0.39 % and 3.56 %. Overall, the achieved repeatability is very good. With the more stringent definition of the load motor (IE2 or IE3, 4-pole) the results will be even better in the future.

The key results of the RR'C tests in phase 1 show:

- The UTP is a valuable test method that returns highly repeatable results from tests in different laboratories.
- It was shown that selection of the load motor has some sensitivity with respect to power rating and number of poles whereas manufacturer and efficiency class are less important. Based on this finding, it is suggested that load motors must be (kW) sized to the converter in question and fulfill energy class IE2 or IE3. All load motors must be 4-pole asynchronous motors.
- The tests can be equally conducted at 50 Hz and 60 Hz fundamental frequency without any impact on the losses.
- High precision measuring instruments from at least two different manufacturers have been used without any influence on the results.
- In the tested group of 9 converters from 0.75 kW to 11 kW the maximum span between minimum and maximum loss at full load was between 0.5 W and 6.3 W. The relative span was between 0.39 % and 3.56 %. The standard deviation was between 0.3 W and 1.9 W.
- The measured converter losses were all less than one third of the reference losses of IE1 in IEC 61800-9-2, edition 1.

Recommendations and conclusions

The recommendations for the improvement of the converter testing method for the phase 2 include the following:

- The nominal and rated output current in ampere of any converter must be clearly defined. A solution has been introduced to use the reference output current in the standard.
- The converters can be tested with any asynchronous motor to return reasonable results. But it is recommended to use IE2 or IE3 and only 4-pole motors of the same nominal rating as the converter to keep repeatability of the test results high.
- The no load/off point must be precisely defined to return repeatable results. Auxiliaries like fans, etc. can distort the measured results.
- So far, the 17 operating points have been chosen because of the scientific necessity to have the measurements covering the entire operating field. The necessary operating points for the tests will be reappraised for practical reasons to be required in IEC 61800-9-2, edition 2. In RR'C phase 2, only 13 operating points will be used.
- For phase 2 of the RR'C it is recommended to include converters with all typical accessories, filters, 4Q etc. to evaluate the influence of these factors on the losses. Matrix converters shall also be included.
- The comparison of losses and performance in basic drive modules and in complete drive modules (including auxiliaries) shall be more clearly distinguished in phase 2.

And, the cooperation between IEC SC 22G WG 18 and 4E EMSA proved to be both inspiring and productive and will be continued in RR'C phase 2.

References

[1] IEC 61800-9-2, edition 1: *Adjustable speed electrical power drive systems - Part 9-2: Ecodesign for power drive systems, motor starters, power electronics and their driven applications - Energy efficiency indicators for power drive systems and motor starters*, Geneva, Switzerland, 2017

[2] European Commission (EC): *Commission Regulation No. 640/2009 of 22 July 2009 implementing Directive 2005/32/EC of the European Parliament and of the Council with regard to ecodesign requirements for electric motors*, Brussels, Belgium, 2009

[3] Emmanuel Agamloh, Andrew Baghurst, Conrad U. Brunner, Sandie B. Nielsen, Andrea Vezzini, EMSA IEC WG 18: *Round Robin of Converter Losses, Report of Results of Phase 1*, Zurich, Switzerland, March 2019 (available at www.motorsystems.org)

[4] Sandie B. Nielsen, Andrea Vezzini: *Preliminary results from (RR'C) round robin for converter losses, phase 2*, in: EEMODS'19 conference proceedings, Tokyo, Japan, 2019

[5] IEC 60034-2-1, edition 2: *Rotating electrical machines - Part 2-1: Standard methods for determining losses and efficiency from tests (excluding machines for traction vehicles)*, Geneva, Switzerland, 2014

[6] IEC 60034-30-1, edition 1: *Rotating electrical machines - Part 30-1: Efficiency classes of line operated AC motors (IE code)*, Geneva, Switzerland, 2014

[7] European Commission: *Mandate M/476 CENELEC for Standardisation in the field of variable speed drives and/or Power Drive System products*, Brussels, Belgium 2010

[8] CENELEC EN 50598-2: *Ecodesign for power drive systems, motor starters, power electronics & their driven applications - Part 2: Energy efficiency indicators for power drive systems and motor starters, Brussels*, Belgium, 2014. (withdrawn)

[9] Anibal T. de Almeida, Pierre Angers, Conrad U. Brunner. Martin Doppelbauer: *Motors with Adjustable Speed Drives: Testing Protocol and Efficiency Standard,* in: conference proceedings EEMODS'09, Nantes, France, 2009

[10] U.S. Department of Energy, Advanced Manufacturing Office: *Motor Systems Tip Sheet #11, Adjustable Speed Drive, Part-Load Efficiency,* Washington DC, USA, 2008 (edition 1), 2012 (edition 2)