Electric Motor Systems
EMSA

Photo: BFH

Report on Round Robin of Converter Losses

Final Report of Results

Elaborated by: DTI, Denmark and BFH, Switzerland

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Technology Collaboration Programme
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Electric Motor Systems Annex – 2022

The report was prepared under the IEA Technology Collaboration Programme on Energy Efficient End-Use Equipment (4E) – **Electric Motor Systems Annex** (EMSA) program.

The report has been formally approved by the EMSA Members.

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About EMSA, the IEA 4E TCP Electric Motor Systems Annex

Electric motor systems consume about 10,700 TWh annually worldwide and were responsible for 53% of the global electric energy consumption in 2016. This corresponds to approximately the combined electricity consumption of China, the European Union (28 countries) and the USA. The goal of the Electric Motor Systems Annex EMSA is to increase energy efficiency and reduce greenhouse gas emissions worldwide by promoting highly efficient electric motor systems in the EMSA member countries, industrialised countries, emerging economies and developing countries.

Further information on EMSA is available at: www.iea-4e.org/emsa

About 4E

The IEA Technology Collaboration Programme on Energy Efficient End-Use Equipment (4E TCP) has been supporting governments to coordinate effective energy efficiency policies since 2008.

Fourteen countries and one region have joined together under the 4E TCP platform to exchange technical and policy information focused on increasing the production and trade in efficient end-use equipment. However, the 4E TCP is more than a forum for sharing information: it pools resources and expertise on a wide a range of projects designed to meet the policy needs of participating governments. Members of 4E find this an efficient use of scarce funds, which results in outcomes that are far more comprehensive and authoritative than can be achieved by individual jurisdictions.

The 4E TCP is established under the auspices of the International Energy Agency (IEA) as a functionally and legally autonomous body.

Current members of 4E TCP are Australia, Austria, Canada, China, Denmark, European Commission France, Japan, Korea, Netherlands, New Zealand, Switzerland, Sweden, UK and USA.

Further information on the 4E TCP is available from: www.iea-4e.org

Disclaimer

Acknowledgement

The RR'C team would like to thank the sponsors of this work, namely the governments of Australia, Austria, Switzerland and USA. Also, we would like to thank the 8 participating laboratories for providing their facilities and skilled engineers as well as to the manufacturers who helped to acquire the converters and the motors for the test. We also thank the EMSA operating team for providing the operational base to manage the RR'C project. And we appreciate the support of IEC SC 22G and WG18 and its officers to improve the scientific basis for IEC 61800-9-2 and its second edition.

Zurich, 22 April 2022

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1 Executive summary

The test method described in IEC 61800-9-2:2017 (edition 1) for converters (and in IEC TS 60034-2-3:2013 for motors driven by converters) has not been used for sufficient time to know their accuracy and repeatability.

At its meeting on 6 September 2017 at EEMODS'17 in Rome, representatives from IEC SC22G/WG18, 4E EMSA and several independent testing labs (“project group”) decided to have 4E EMSA undertake the project leadership and the organisation of a round robin exercise for converters in cooperation with WG18.

The Round Robin for Converters (RR'C) project was launched in the fall of 2019, with Denmark and Switzerland responsible for the organisation, monitoring and documentation of the interlaboratory test for converter losses. During the RR’C, 8 laboratories were able to perform a total of 179 tests on 57 different converters. The power range within participating laboratories was limited to the range between 0.12 to 55 kW.

The results of the RR'C provided key evidence for the revision of IEC 61800-9-2 Ed.2, especially the design of an updated and robust test procedure and the provision of sufficient solid and impartial measured data to correct the current reference values for converters losses.

There are four main conclusions which can be taken now from the results of the RR’C:

1. The Uniform Testing Protocol (UTP) of the RR’C has proven to be a valuable test method that returns highly repeatable results from converter tests in different laboratories. IEC SC22G/WG18 subsequently included the proposed modifications to eliminate the testing ambiguity in the second revision of IEC 61800-9-2.
2. The measured converter losses were all less than 30 to 50% of the reference losses of IE1 and therefore well below the margin for the highest IE class for converters (IE2). Therefore, almost all converters on the market are within this IE classification. Although the absolute losses can differ for the same nominal output current up to a factor of two, no difference in IE class is possible.
3. The correction factors introduced for converters (Complete Drive Modules, CDMs) with modified functionality tend to slightly overcompensate the additional losses. In extremis this means, that adding a sinusoidal current output filter could shift the converter’s IE class from IE1 into IE2.
4. Finally, the test results show a very good match between manufacturer catalogue data and measured data using the input-output method. Assuming that most manufacturer data are calculated and not measured such an alignment is to be judged positively. Nevertheless, most manufacturers will not completely disclose the assumptions and parameters for their calculations, so that an independent third-party recalculation is not possible. The standard IEC 61800-9-2 only gives a prototype calculation model with some standard parameters.

The authors would like to thank all the participating laboratories, the IEA 4E EMSA Annex for sponsoring and the IEC SC 22G/WG18 for the intensive but always very constructive discussion within the second revision of IEC 61800-9-2.

2 Background

2.1 Origin and History

Advanced electric motor driven systems for pumps, fans, compressors, etc. today often use variable frequency converters to adjust the electric power demand to the required torque and speed of the application. Use of a converter can lead to large energy savings by reducing the amount and quantity of electric power consumed. On the other hand, frequency converters are costly electronic devices that need to be well designed, carefully matched to the required task and well programmed during the operation of the motor system. Also, converters have intrinsic electricity losses in standby and in operation, and they cause further losses in the driven electric motor due to the non-sinusoidal voltage and current delivered from its pulse width modulation.

The test method to determine the losses in converters described in International Electrotechnical Commission (IEC) 61800-9-2:2017 (edition 1[1] and IEC TS 60034-2-3:2013[2]) have not been in existence for sufficiently long to have confidence that they deliver accurate and repeatable results. The test laboratories around the world using this test method are not yet familiar with it. Also, the electric losses and efficiency of converters for motor driven systems have not yet been systematically and independently verified, analysed, and compared.

In the context of the revision of IEC 61800-9-2:2017 and the publication of an upcoming edition 2, several issues around converter losses needed to be clarified. In its meeting on 6 September 2017 at EEMODS'17 in Rome, representatives from IEC SC22G/WG18, 4E EMSA and several independent testing labs ("project group") decided to have 4E EMSA undertake the organisation of a round robin exercise for converters in cooperation with IEC SC22G/WG18.

Subsequently the round robin testing program for converter losses (RR'C) was established to serve as scientific base for establishing both a robust test method and the necessary database for converter losses through the entire range of 0.12 kW to 1000 kW to be included in the revision of IEC 61800-9-2.

In Phase 1 (from November 2017 to February 2019) a limited number of converters were tested within the project group to clarify questions regarding the test method based on IEC 61800-9-2:2017, and so that the results of the RR'C would be both accurate and repeatable and practical for industry and research testing labs.

In Phase 2 (from May 2019 to December 2021) the main goal was to validate the revised test method as well as establish a sufficiently wide data base of testing results over the entire range of converters.

The final results of RR'C phase 2 – Converter losses has been published in coincidence with EEMODS'22 in Stuttgart.

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[1] IEC 61800-9-2:2017: 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

[2] IEC TS 60034-2-3:2013: Rotating electrical machines - Part 2-3: Specific test methods for determining losses and efficiency of converter-fed AC induction motors. Replaced by IEC 60034-2-3:2020 during the Round Robin Converters (RR'C)

2.2 Inverter, Converter, AC Drive: What's the difference?

Often the terms Inverter, Converter, frequency converters, AC drives, Variable Speed Drive (VSD) or Variable Frequency Drives (VFD) are used interchangeably.

Based on the standard IEC 61800-9-1 Edition 2[3], the correct term to be used should be: Complete Drive Module (CDM) or Basic Drive Module (BDM). *Figure 1* shows the Extended Product and the position of the CDM and the BDM.

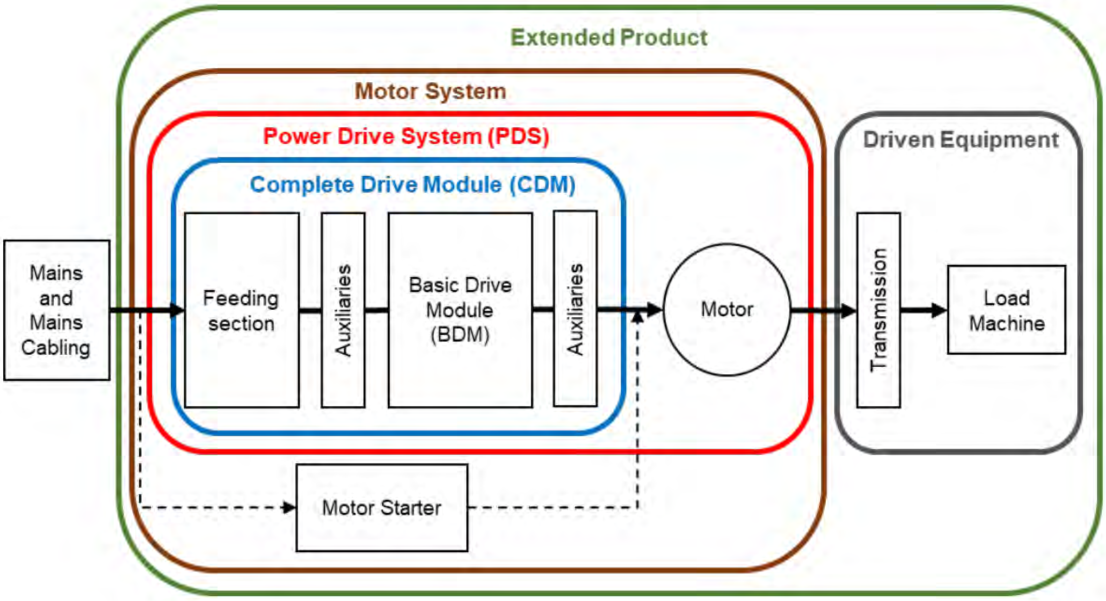

Figure 1 Illustration of the extended product with embedded motor system

The Complete Drive Module (CDM) contains the basic drive module (BDM) consisting of the electronic power converter, specifically the variable speed drive (VSD), connected between the electric supply and the motor, as well as its extensions as protection devices, internal transformers, internal cooling system, filters and auxiliaries. In this report we will use the term ***Converter*** to describe CDMs and BDMs. This will be consistent with the original title of the study and correctly describes the fact that the electric power is converted between input and output of the converter.

[3] "IEC 61800-9-1: Adjustable speed electrical power drive systems - Ecodesign for power drive systems, motor starters, power electronics and their driven applications - General requirements for setting energy efficiency standards for power driven equipment," International Electrotechnical Commission (IEC), nº 1.0, p. 66, 2017.

2.3 Goals

The first goal of the Round Robin Converters (RR'C) was to define a robust and practical testing method that will return highly repeatable results within the Uniform Testing Protocol[4] and Standard Reporting Format[5]. The focus was therefore to compare results of multiple tests of the same converter and check the repeatability (and not the individual product performance).

The second goal was to check the relevant IE classes based on test results across the full scope of the converter market between 0.12 kW and 1000 kW and a re-examination of the reference losses in IEC 61800-9-2, edition 1. The entire Round Robin was to be guided by a transparent and scientific approach.

The Round Robin for Converters (RR'C) organised by 4E EMSA and supported by IEC SC 22G/WG18 therefore included the following tasks in their RR'C guideline[6] document:

1. Clarify and verify the test method
2. Check laboratory performance
3. Verify the performance of converters and their losses based on a variety of products from different manufacturers
4. Establish a database of measurement data
5. Clarify the spread of product performance by different drive variants and/or manufacturers.

2.4 Organisation

The RR'C Task Force and its leadership from 4E EMSA, IEC SC22G WG18 and industry was selected and mandated at the EEMODS'17 meeting in Rome on 6 September 2017. The cooperation between IEC SC22G WG18 and 4E EMSA was clarified at the IEC SC22G WG18 meeting on 26-28 February 2018 in Tampa FL USA.

The project management from 4E EMSA included Sandie B. Nielsen/DK as Task Force leader and Andrea Vezzini/CH as Deputy.

- Sandie B. Nielsen is the head of the accredited test laboratory facilities on electric motors, circulators, water pumps & fans at the Teknologisk Institut in Aarhus, Denmark. As such he has been eco-design consultant on motors, pumps & circulators to Danish authorities since 2009. He is also member of two technical committees within the IEC: TC 2 - Rotating machinery and TC 22 - Power electronic systems and equipment. He has also been task leader representing Denmark since 2008 in the Electric Motor Systems Annex (EMSA) of the IEA Technology Collaboration Programme Energy Efficient End-use Equipment (4E) https://www.iea-4e.org/emsa
- Prof. Dr Andrea Vezzini obtained his doctorate in electrical engineering from ETH Zurich in 1996 and successfully completed the Mastering Technology Enterprises (MTE) programme at IMD Lausanne in 2002. He has been a professor at Bern University of Applied Sciences since 1996. He has been a member of the Swiss Federal Energy Research Commission (CORE)

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[4] RR'C PHASE 2 – UTP version 4.0: Converter loss measurement Uniform Testing Protocol (UTP), including step-by-step measurement procedure; (UTP, edition 4, 20181001)

[5] Standard Reporting Format (SRF 20180927)

[6] Round Robin Converter Losses (RR'C): Phase 2 Guidelines, version 6.0: RR'C Phase 2 V6_20190911

since 2015 and an official member of the Scientific Advisory Board of AEE Suisse, the umbrella organisation of the renewable energy and energy efficiency industry, since 2018.
Since 2017, he has been an active member of IEC working groups TC2 WG 28 & WG 31, which define international motor test methods and classifications, and IEC SC22G WG18, which publishes the IEC 61800-9 series of standards covering frequency converters, motors and combinations thereof. Dr Vezzini holds 23 patents / 8 patent families in the field of electric drives and battery management systems.

2.4.1 Participating Labs and Industry

A group of independent test laboratories, qualified for converter tests, was selected to be invited to participate in the RR'C. As a result of a questionnaire sent to all labs in August 2018, the following 8 laboratories agreed to participate by 18 September 2018 (for more details of selected laboratories see Annex 1):

- China National Center for Quality Supervision and Test of Electrical Control and Distribution Equipment, Tianjin City; China
- Danish Technological Institute, Aarhus; Denmark
- Karlsruhe Institute for Technology (KIT); Germany
- Fuji Electric Co., Ltd., Suzuka-shi, Mie; Japan
- Bern University of Applied Sciences (BFH), Biel; Switzerland
- Ghent University, Kortrijk; Belgium
- Advanced Energy, Raleigh NC; USA
- CalTest, Port Elliot SA 5212; Australia

3 Setup of the Round Robin for Converters

After the first phase of the RR’C, the project team established a set of documents for participants in the second phase based on the experience and results from phase 1.

This included the following 4 documents:

- Guideline to Round Robin Converter Losses (RR'C): Phase 2
  Document name: RR'C Phase 2 V6_20190911.pdf: includes a complete explanation of the setup and organisation of the RR’C Phase 2
- Documentation RR’C PHASE 2 – UTP version 2.0
  Document name: UTP 2.0 - 20190601.pdf: Converter loss measurement utilising a combination of the existing testing procedure in IEC 61800-9-2 and the experience gained from RR’C Phase 1, UTP 1.0
- Addendum RR’C2, UTP 2.0 – Updated order of points
  Document name: UTP 2.0 - Supplemental paper 20190923.pdf: Updated step-by-step measurement procedure for UTP 2.0
- Standard Reporting File
  Document name: RR'C 2 - SRF ver. 1.2 - 20191003.xlsm: Excel file to follow Input-output measurement of converter losses following UTP 2.0

The four documents are part of an extended annex which is available on request through EMSA.

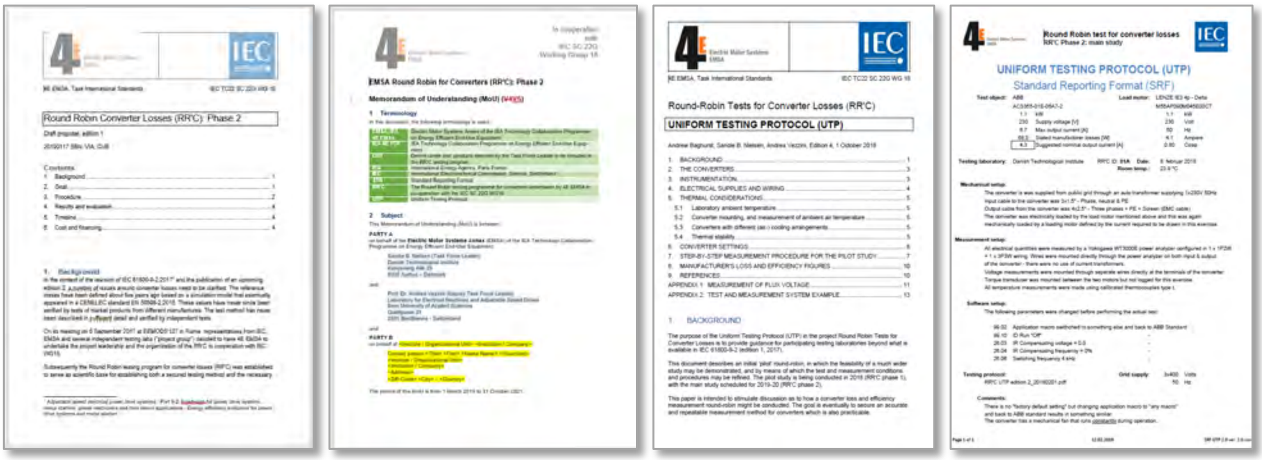


Figure 2 Cover pages of the documents used to organise the participating laboratories and to harmonise reporting for later analysis

3.1 The Uniform Testing Protocol (UTP)

During the first phase of the Round Robin Converter the participating laboratories concluded that the test procedure as described in IEC 61800-9-2:2017 could lead to misinterpretation of the load points that needed to be measured. To allow testing laboratories the option of using electronic loads in place of electric motors, the load points are defined as percentage of the load current contributing to the torque production («RCDM relative torque producing current») and the stator frequency («RCDM relative motor stator frequency») of the reference complete drive module (RCDM). This could lead to several problems as follows:

1. Most manufacturers define two or even four values for nominal output currents of the converter (light/heavy duty & 50/60 Hz grid mounting). These values would in most cases be higher than the nominal currents of a typical IE3 motor in the same power class. As an example, the nominal current of an IE3 5.5kW motor would be 11.5A and the Light Duty current of a so called 5.5kW

converter would be 15.6A (higher output current defined on the nameplate). Consequently, labs running tests using the input-output method as described in chapter 7.7 of IEC 61800-9-2:2017 would have to seriously overload the test load, i.e. the 5.5kW motor.

2. The IEC test standard defines a total of 8 load points to test, with three load points at zero percent relative motor stator frequency. There would be two issues arising out of this. Firstly, at 100% relative torque current, the losses in the winding and the missing self-cooling of the machines would result in a sharp increase of the winding temperature. Secondly, with lower power rating machines (e.g. < 5.5kW) the calculated stator current at 25% relative torque current will often be smaller than the magnetizing current of the electric motor, which makes it impossible to accurately measure this load point.

3. To allow the use of an electronic load, IEC 61800-9-2:2017 defines a test load displacement factor cos Φ as a function of the apparent power range $S_{r,equ}$ of the converter for each load point. Again, labs running tests using the input-output method as described in chapter 7.7 with an electric motor as test load would have no control over the displacement factor. Fortunately, the standard allowed for testing with a motor a tolerance of ±0,08 for the test load displacement factor at 100% torque current.

4. Finally, some advanced converters may come out of the box with sensorless speed control, which would require the reference speed to be adapted each time the relative torque current changes, as a higher load torque would lead to increased slip frequency and therefore higher stator frequency.

The revised UTP, UTP 2.0, addressed these ambiguities and tried to avoid too many of the standard parameters of the converters. The basic idea is that converters should be tested based on their factory settings and only the nominal parameters of the test motor and a nominal switching frequency of 4kHz have to be programmed.

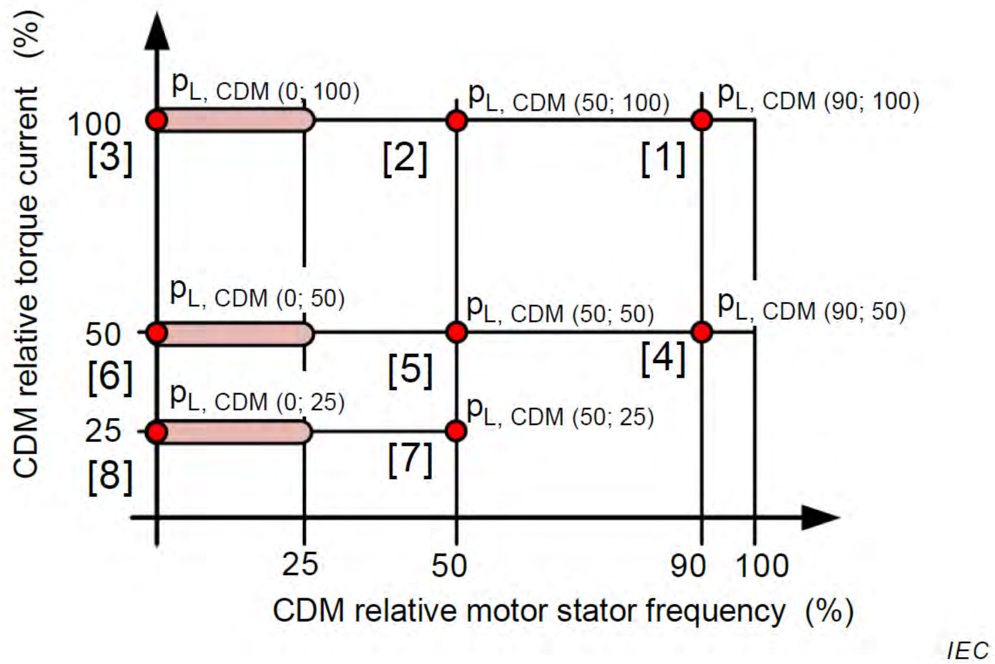


Figure 3 Order of CDM measurements from [1] to [8]

As a direct consequence of the RR'C, chapter 7.5 'Determination of losses by measurement, Input-output method' has been rewritten in the upcoming second revision of the IEC 61800-9-2 Ed.2, which also extends the zero-speed range up to 25% of the nominal stator frequency as illustrated in Figure 4.

Other notable points from the UTP 2.0 which are now included in the second revision of the IEC61800-9-2 include:

- UTP 2.0 recommended that the converter setting shall be 'factory default'.
  Some converters allow a software reset which is highly recommended even when the converter is delivered "out of the box".

- The displacement factor of the load's fundamental current in relation to the fundamental voltage shall be according to Table 2 for the (90;100) operating point. For all other operating points the displacement factor shall be recorded but has not to be met.

3.2 Measurement uncertainty

IEC 61800-9-2 Ed.2 defines that the uncertainty of the power meters used for the input-output method shall be 0.2% or better of the rated apparent power $S_{r,equ}$ at 50 Hz/60 Hz. This is the total uncertainty of the power meter including potential probes and sensors. The measurement range shall be chosen adequately in relation to the measured currents and voltages.

The bandwidth of power meters and sensors shall be sufficiently wide to ensure an error of the total active power of less or equal to 0.3% of $S_{r,equ}$.

The losses required for an IE energy efficiency classification are calculated from the determined losses $P_{L,CDM,determined}$ and the measurement uncertainty $\Delta P_{L,CDM}$ according to the following formula:

$$P_{L,CDM} = P_{L,CDM,determined} + \Delta P_{L,CDM} = P_{L,CDM,determined} \cdot (1 + \Delta p_{L,CDM}) \quad \text{(Eq.: 1)}$$

While it is possible and recommended to calculate the measurement uncertainty for each operating point, as this changes with frequency and resolution, it has been shown that all modern power analyzers used in this round robin[7] have a measurement uncertainty for the determined losses of about 10%.

To validate this assumption, the laboratory at BFH calculated the measurement accuracy of its power analyzer and current shunt box used to measure a 11kW converter (ABB ACS 355 | RR'C Id. 13B), as shown below.

The test report shows 255W losses for the 90/100 point, which is used to determine the IE class, with the following measurements for the input and output side:

90/100 point (ACS 355):

- Input values:
  - VAC = 400VRMS
  - IAC = 20.6ARMS
  - PAC = 12'834W

[7] Andrea Vezzini, Sandie B. Nielsen: "Preliminary results from RR'C 2 Round Robin for Converter losses, phase 2"; EEMODS'19 Tokyo, 42

- Output values:
  - VAC = 412VRMS
  - IAC = 23.1ARMS
  - PAC = 12’579W
- Losses: 255W

Based on these values and using the accuracy calculator provided by Hioko International Munich, the total accuracy for the load point is calculated separately for input and output.

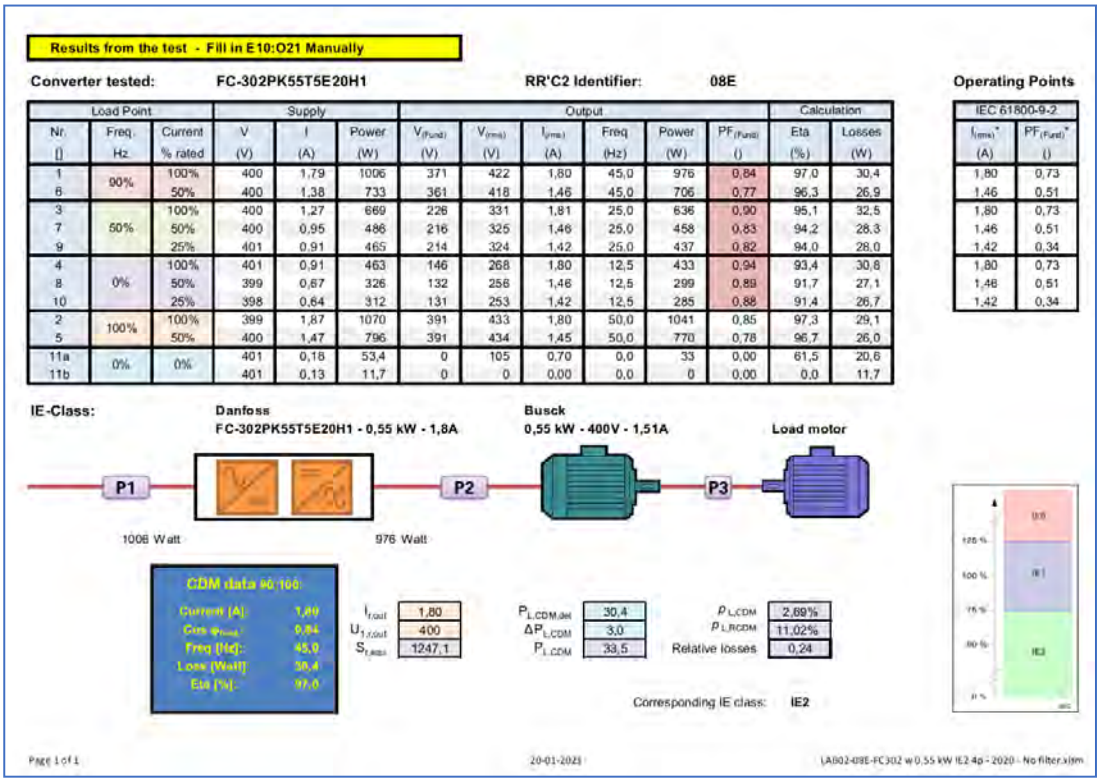
- Input Power max positive error
  - power accuracy: 0.14%
  - measured value incl. positive error: 12’854W
- Output Power max negative error
  - power accuracy: 0.13%
  - measured value incl. negative error: 12’562.6W

Assuming a worst-case scenario, where the maximum positive error would happen at the input side and the maximum negative error would happen at the output side, the calculated losses are now 289.3W, which is 13.5% higher than the (assumed) correct values from the example:

		Unit accuracy		Total accuracy		Error	
		rdg.	f.s.	rdg.	f.s.		
DC	PW6001	0.04%	0.057%	0.04%	0.06%	**0.27%**	Combined accuracy when using PW9100
	PW9100						
10Hz	PW6001	0.10%	0.20%	0.11%	0.23%	**1.01%**	
	PW9100	0.01%	0.02%				
50/60Hz	PW6001	0.04%	0.035%	0.04%	0.04%	**0.18%**	Combined accuracy when using PW9100
	PW9100						
100Hz	PW6001	0.02%	0.03%	0.03%	0.06%	**0.25%**	
	PW9100	0.01%	0.02%				
1kHz	PW6001	0.04%	0.05%	0.05%	0.08%	**0.35%**	
	PW9100	0.01%	0.02%				
10kHz	PW6001	0.15%	0.1%	0.16%	0.13%	**0.66%**	
	PW9100	0.01%	0.02%				
100kHz	PW6001	1.2%	0.2%	1.21%	0.23%	**2.11%**	
	PW9100	0.01%	0.02%				
1MHz	PW6001	28%	2%	28.01%	2.03%	**36.11%**	
	PW9100	0.01%	0.02%				

Figure 4 Example calculation of the total accuracy using a Hioki PW6001 power analyser and a Hioki PW9100 current shunt box. This equipment meets the accuracy requirement as demanded in IEC 61800-9-2 ED2

Given the fact that most modern power analysers used today (Yokogawa, Ziemer, Hioki) have a similar performance, the organisers of the RR'C therefore prepared a standard reporting file format, which automatically adds 10% losses to the measured losses, as shown in Figure 5.


Results from the test - Fill in E10:O21 Manually

Converter tested: FC-302PK55T5E20H1 RR'C2 Identifier: 08E

Load Point			Supply			Output						Calculation	
Nr. ()	Freq. Hz	Current % rated	V (V)	I (A)	Power (W)	$V_{(Fund)}$ (V)	$V_{(rms)}$ (V)	$I_{(rms)}$ (A)	Freq (Hz)	Power (W)	$PF_{(Fund)}$ ()	Eta (%)	Losses (W)
1	90%	100%	400	1,79	1006	371	422	1,80	45,0	976	0,84	97,0	30,4
6		50%	400	1,38	733	361	418	1,46	45,0	706	0,77	96,3	26,9
3	50%	100%	400	1,27	669	226	331	1,81	25,0	636	0,90	95,1	32,5
7		50%	400	0,95	486	216	325	1,46	25,0	458	0,83	94,2	28,3
9		25%	401	0,91	465	214	324	1,42	25,0	437	0,82	94,0	28,0
4	0%	100%	401	0,91	463	146	268	1,80	12,5	433	0,94	93,4	30,8
8		50%	399	0,67	326	132	256	1,46	12,5	299	0,89	91,7	27,1
10		25%	398	0,64	312	131	253	1,42	12,5	285	0,88	91,4	26,7
2	100%	100%	399	1,87	1070	391	433	1,80	50,0	1041	0,85	97,3	29,1
5		50%	400	1,47	796	391	434	1,45	50,0	770	0,78	96,7	26,0
11a	0%	0%	401	0,18	53,4	0	105	0,70	0,0	33	0,00	61,5	20,6
11b			401	0,13	11,7	0	0	0,00	0,0	0	0,00	0,0	11,7

Operating Points

IEC 61800-9-2	
$I_{(rms)}$* (A)	$PF_{(Fund)}$* ()
1,80	0,73
1,46	0,51
1,80	0,73
1,46	0,51
1,42	0,34
1,80	0,73
1,46	0,51
1,42	0,34

Figure 5: Output of the RR'C standard reporting file calculation based on the determined losses the relative losses and therefore the IE class of the converter

As a sidenote, it should be noted that problems with assessing measurement accuracy is often mentioned to avoid establishing more IE classes (e.g., IE3 and IE4 for converters). The argument being that you cannot define IE class steps smaller than the accuracy of the power analysers. The problem is that some laboratories could come up with an IE classification different than others just because their equipment is not as precise.

However, the RR'C has shown that the accuracy of all participating laboratories has been much lower than the worst-case scenario accuracy.

3.3 Test Setup and Data Collection

At the end of 2021, the RR'C had recorded the following results:

- 179 test reports from 8 different test laboratories
- 57 different converters (on average each converter was tested in three different labs)
- Converters ranged from 0.12 kW to 75 kW

Test variables included:

- "Out of the box" (Factory default settings)
- Adapted settings (motor data, switch frequency, etc.)
- Converters mounted with in- & output filters
- 4Q converters (active front end converters)
- Test comparison of cable length and shielding configuration

3.4 Definition of the IE Efficiency classes

The efficiency classes IE0 to IE2 of the converter (CDM) that are specified in IEC 61800-9-2 (EN 50598-2) refer to the 90;100 operating point, i.e. 90% motor stator frequency and 100% torque current. It compares the measured losses $P_{L,CDM\ (90;100)}$ in Watt with the losses $P_{L,RCDM\ (90;100)}$ of a reference converter (RCDM). In this report we call this ratio IE Index.

A CDM shall be classified as IE1 if its relative losses are within ±25% of the RCDM. The definition of IE0 and IE2 are illustrated in Figure 6.

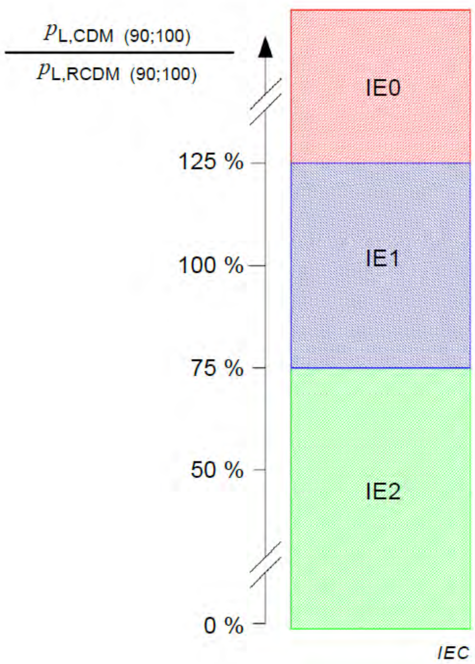


Figure 6: Illustration of IE classes and IE Index, for a CDM

4 Round Robin for Converters, RR'C2: Test results

4.1 Results for three phase converters

One of the outcomes is that all converters tested (Basic Drive Module (BDM), with and without filters) met the requirements of the highest IE class (IE2).

While it is well known that the losses are proportional to the square of the phase current in each converter, it is interesting to observe that for all 150 tests the losses tend to vary linearly with output current measured at the 90% frequency, 100% torque (see Figure 7).

As shown in Figure 7, where the same converter is measured several times the results tend to be clustered, showing good repeatability. The results of the different labs tend to be within a very small accuracy band.

Another issue can be observed where the testing laboratories used different supply configurations (50/60Hz and 400/460V), for example at an output current of 60 Amps. These tests cover 3 converters tested by 3 independent laboratories, with those using a 60Hz/460VAC supply clustered above the interpolated line, whereas the results below use a 50Hz/400VAC supply.

The main reason is that when we assume that all converters are having the same maximum output voltage (i.e. 400VAC when supplied with a three phase 400VAC supply) the output power of the VFD will increase proportional to the output current. If we assume that all the VFD's are having a similar efficiency (as was presented in [8]), then we will also see a linear increase of absolute losses over the output currents.

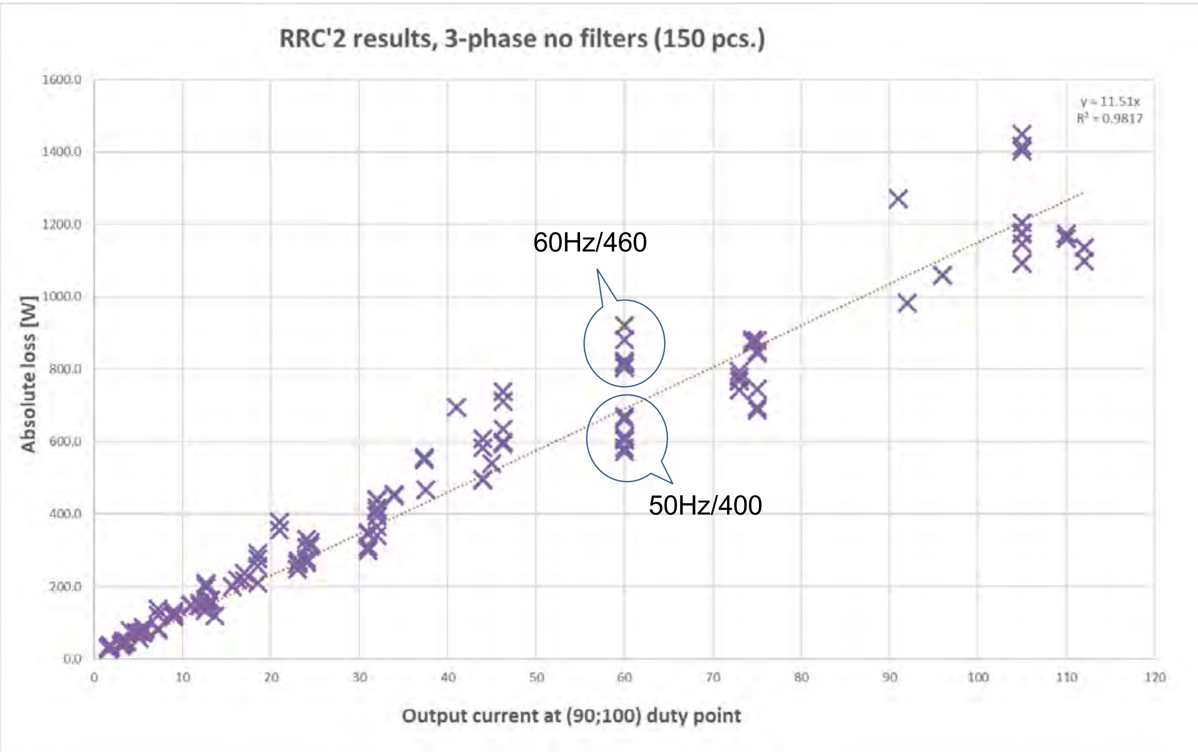


Figure 7: Absolute losses for 3-phase Basic Drive Modules over nominal output current at (90:100) duty point

In theory the relation between losses and output current for an individual converter is quadratic (meaning that doubling the output current results in 4 times the losses), it had been shown by CEMEP[8] that the resulting efficiency of converters is typically very similar over a large power range. Figure 8 confirms this as it plots the efficiency for all tested converters over the nominal output current at (90:100) duty point.

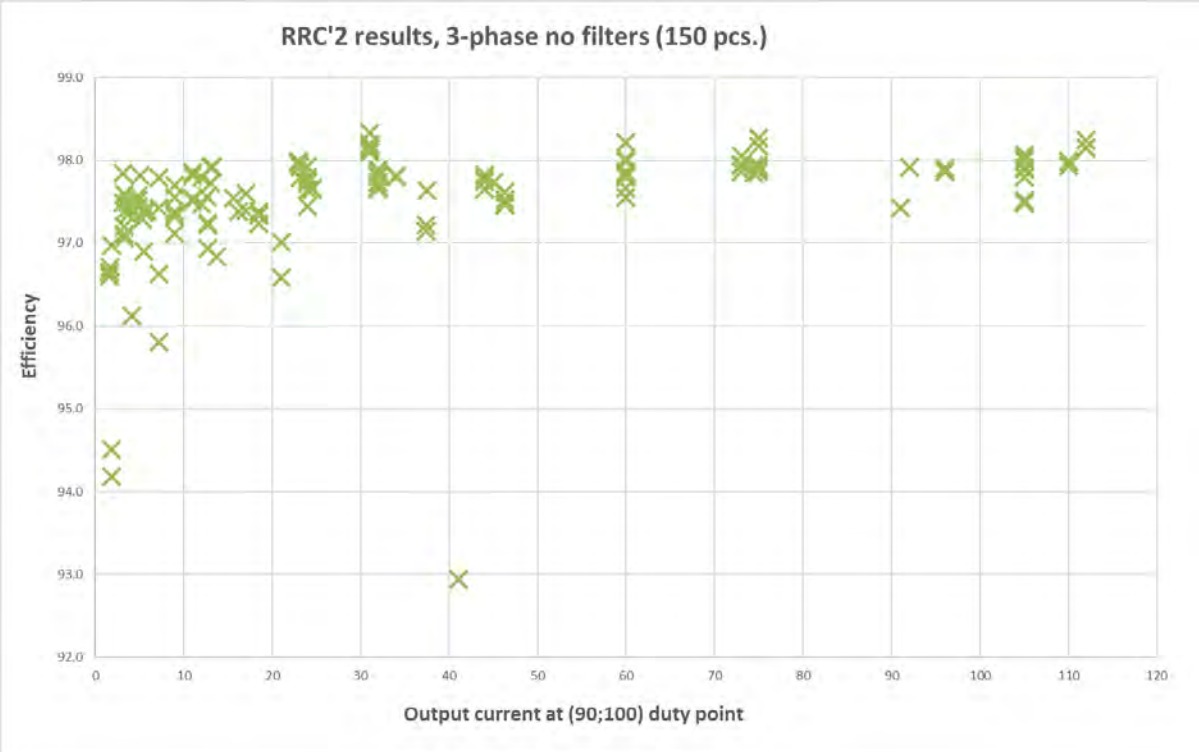


Figure 8: Efficiency for 3-phase Basic Drive Modules over nominal output current at (90:100) duty point

Consequentially the IE classification stays within a relatively small band even when including the 10% measurement uncertainty as has been done in Figure 9. While the red crosses are test results from BDM or CDM without external filters, the blue crosses are the results from the same converter but having an output or input filter or both.

There are three main conclusions which can be taken from this:

1. The new version of the input-output measurement method in IEC 61800-9-2 Ed.2 provides repeatable results, since the RR'C shows that results for the same converter tested at different labs are closely grouped together. In an earlier analysis[9], it has been shown that the standard deviation between the measurement results of different labs for the same converter normally is between 1-3%.
2. The spread of the power losses for different converters with the same power rating (i.e., output current) is large if referenced to the lower of both values. It can be over 100%, meaning that the loss values of the worst converter can be double of the best converter. Due to the definition of efficiency and the IE class, even a considerable difference in absolute values of the

[8] Dr. Benno Weis, Chair CEMEP Technical Board: CEMEP position on future energy efficiency regulation of motor systems and applications; EEMODS 2019, Tokyo, Japan

[9] Andrea Vezzini, Sandie B. Nielsen: "Preliminary results from RR'C 2 Round Robin for Converter losses, phase 2"; EEMODS'19 Tokyo, 42

converter losses will only result in a small difference in the efficiency and even less in the IE class.

3. The impact of filters for sinusoidal output currents does not appear sufficient to alter the IE-class for the tested converters, based on the current IE classes, even without adding the correction factor proposed in the second edition of the IEC 61800-9-2.

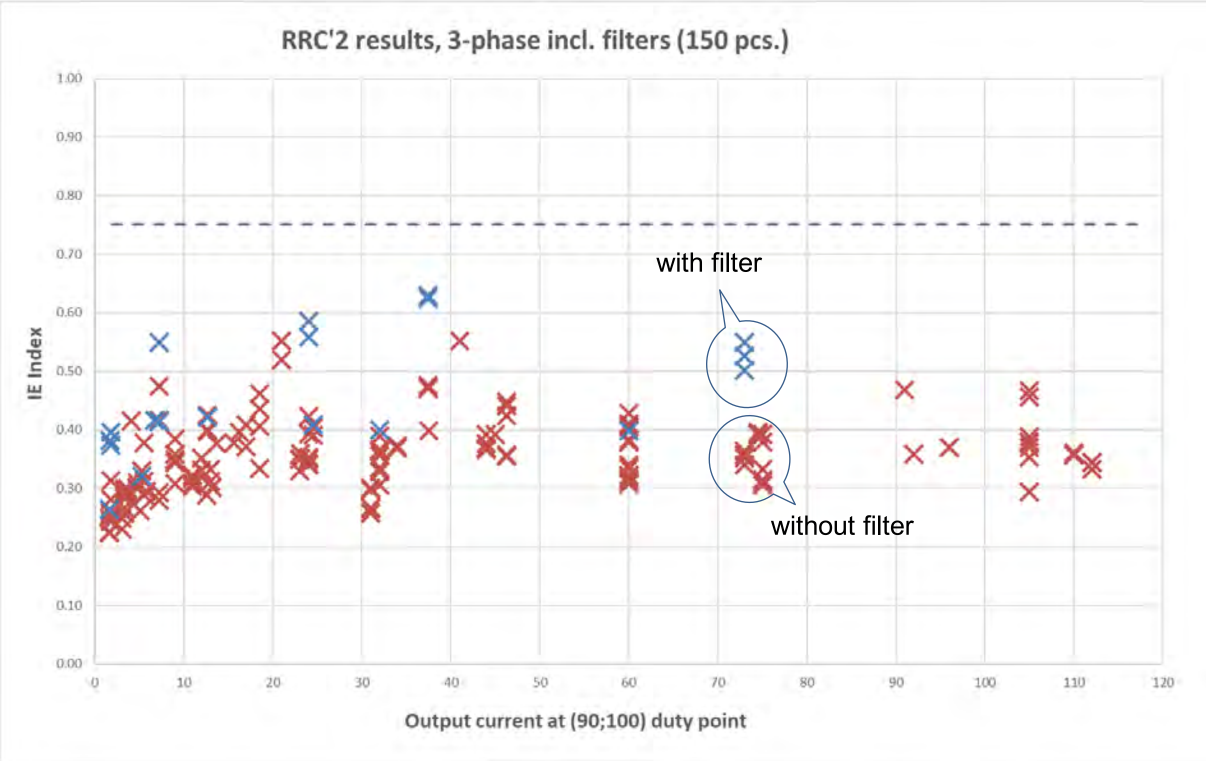


Figure 9: IE-index for 3-phase Basic Drive Modules over nominal output current at (90:100) duty point. Dotted line is the threshold between IE2 and IE1

4.2 Results for single phase converters

In the RR'C phase 2, five single-phase converters were also tested, ranging between 0.12kW and 1.1kW output power and with input currents up to 6 Amps.

As with three phase converters, Figure 10 shows that there is a linear increase in absolute losses with the output current. All values are taken at the 90% speed 100% torque current point required for the IE classification.

Figure 11 shows that the efficiencies in general are slightly lower (~96%) compared to the three-phase converters (>97%). However, as the reference losses take this into account, all the single-phase converters tested are classified as IE2 as indicated in Figure 12, since the gap between the IE1 and IE2 index levels is quite large.

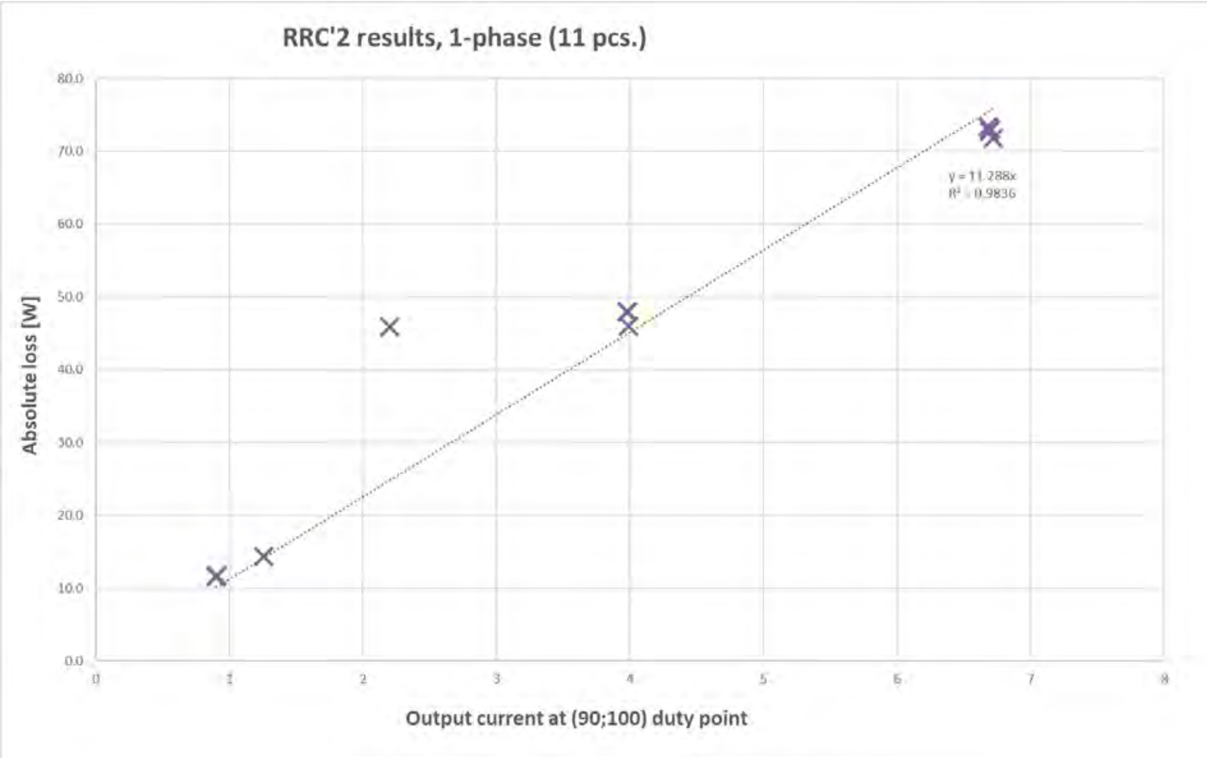


Figure 10: Absolute losses for single phase Basic Drive Modules (BDM) over nominal output current at (90:100) duty point

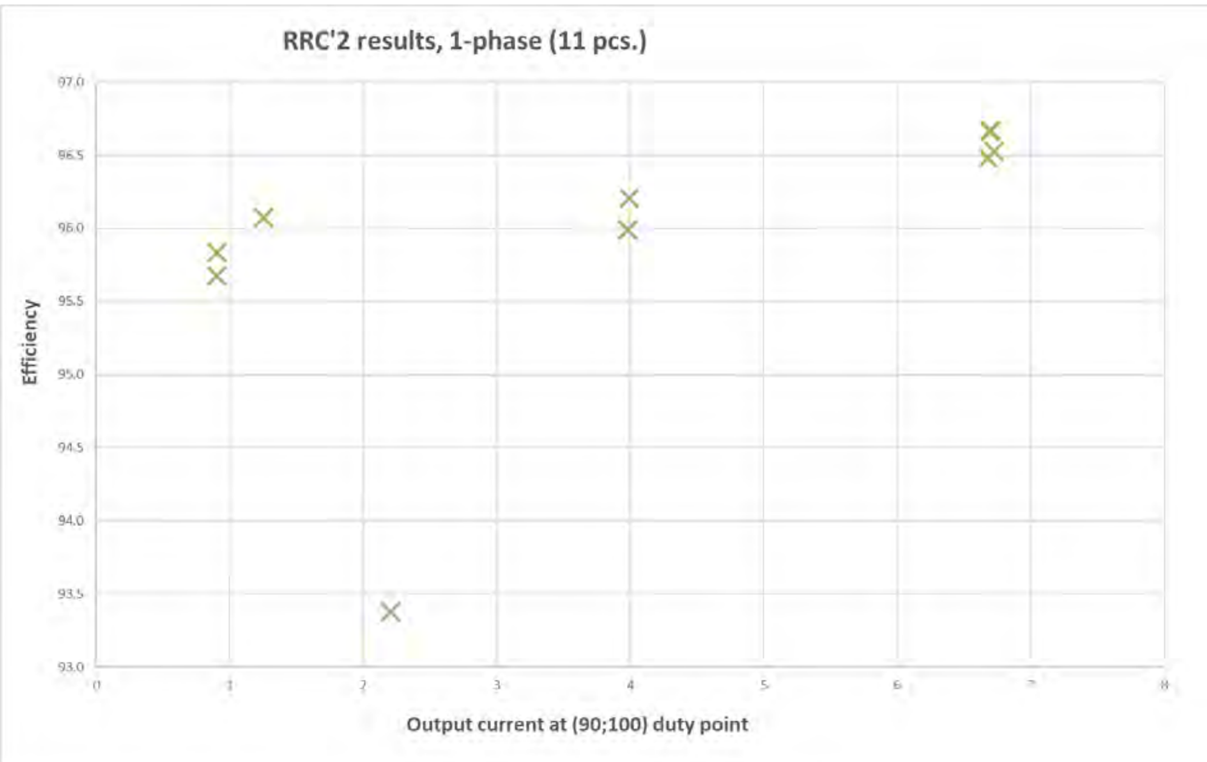


Figure 11: Efficiency for single phase Basic Drive Modules over nominal output current at (90:100) duty point

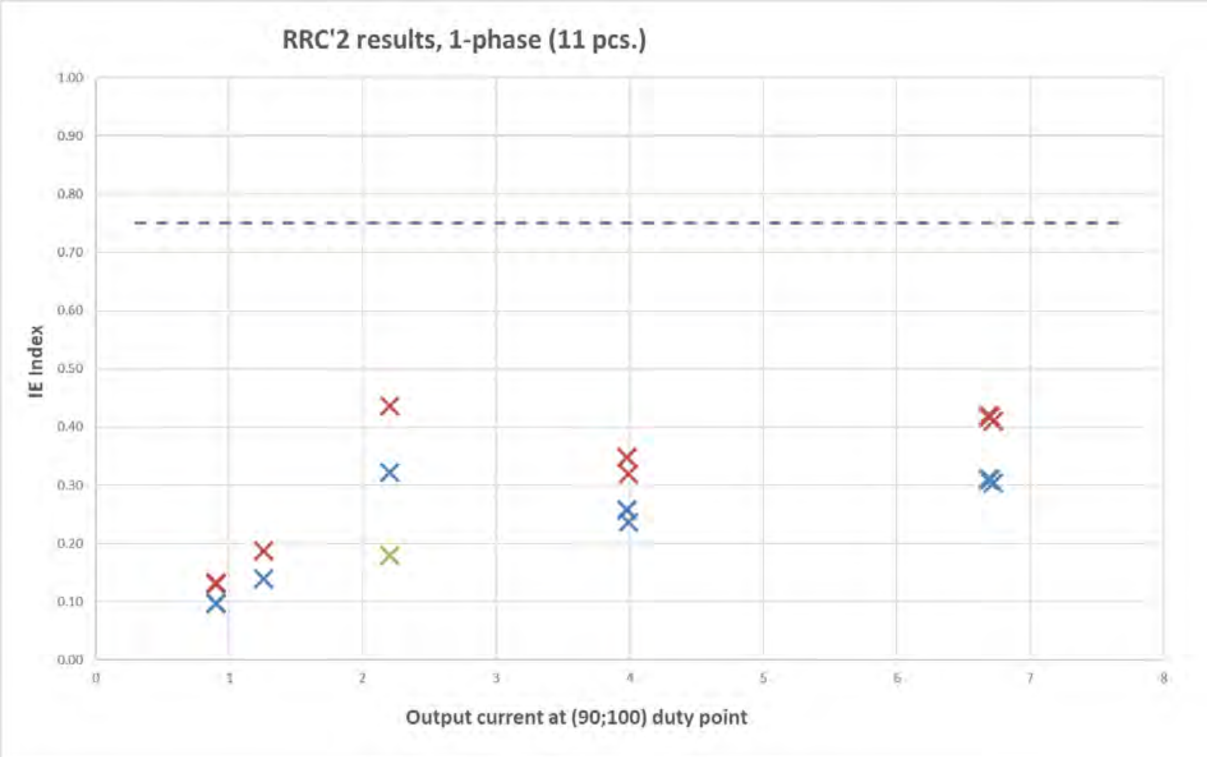


Figure 12: IE-index for single phase Basic Drive Modules over nominal output current at (90:100) duty point. Dotted line is the threshold between IE2 and IE1

4.3 Correction Factors for Advanced Converters

As the number (4) and tests (11) of 11kW converters were higher than for converters of other power rating, the RR'C undertook a comparison of the performance of this size of converter with each other (standard converters) as well as with two converters tested with output filters and one matrix converter.

From the results, the following three observations can be made:

- The IE indexes of all 11kW converters are in a very small window between 0.34 up to 0.41 (Figure 13). The efficiencies of these converters were even closer (97.4% up to 98%). When comparing the results from different laboratories for each of the individual converters, the variation in IE index is between 0.01 and 0.02 and between 0.04% and 0.2% in efficiency. This demonstrates a very uniform distribution of the results from different laboratories. As a result they all have the same IE.
- The impact of the sinewave output filters for the two tested converters is not sufficiently large that it takes these outside the IE class. If the correction factor of 1.8 is included the IE class would be even lower than with the unfiltered converter.
- Finally, the matrix converter is also well inside the IE class IE2. If the correction factor for the CDM with REGEN capability from table 8 of IEC 61800-9-2 Ed.2 is applied, this unit has the lowest IE Index of all this size of converters.

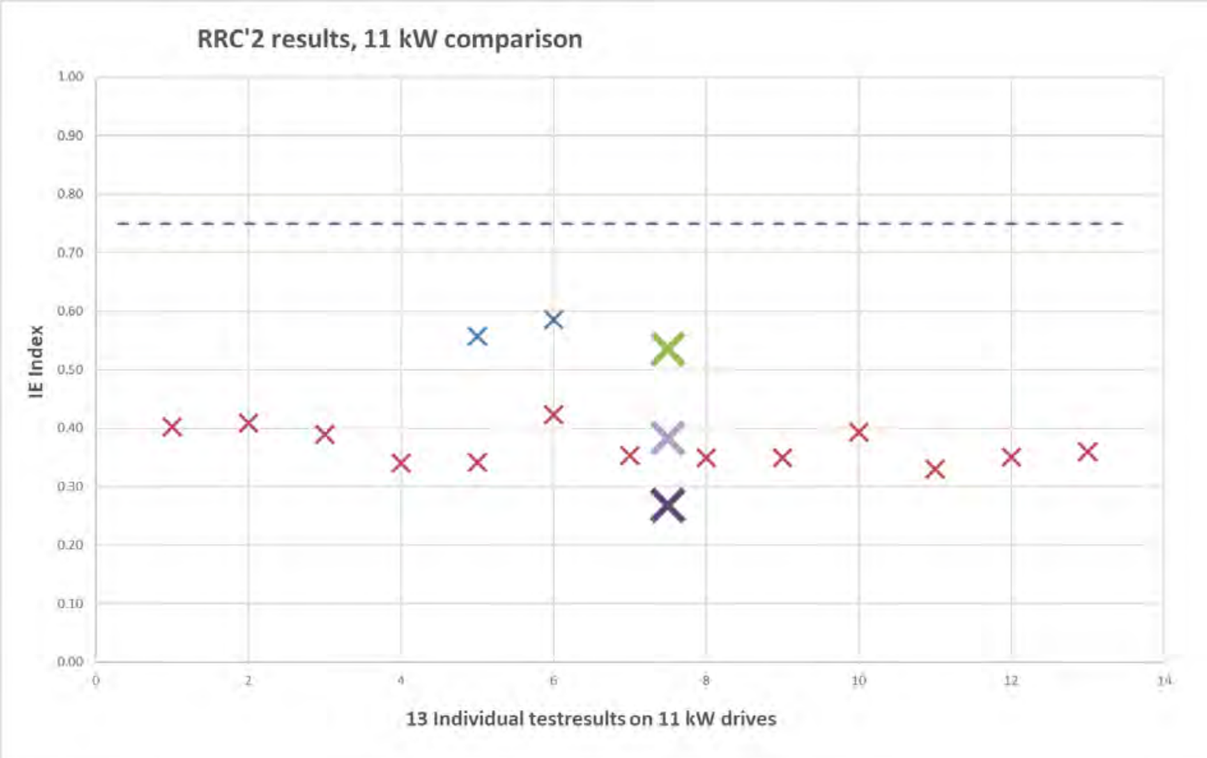


Figure 13: *IE classification for 11kW converters. Dotted line is the* threshold *between IE2 and IE1*

- *Red* *IE for thirteen standard 11 kW drives*
- Blue IE for two converters with SineWave filter, not corrected
- Green Averaged IE for matrix converter
- Purple Matrix converter corrected by 1.4 & 2.0 (for comparison as Table 8 proposes two values depending on the THD of the input current)
- Dotted line is IE2 level

4.4 Impact of Filters on Losses

To evaluate the impact of filters on losses, a comparison between converters with and without filters was undertaken for a range of converters with output currents from 1.8A up to 73A.

The outcome in Figure 14 shows that all the converters fall within the IE2 class even when using a SineWave filter.

Furthermore, the application of the correction factor (1.8) moves the IE class well below the value of the converter without modified functionality. In Figure 14 the green (corrected) points are all well below the IE index of converters without sine filters. The compensation factors therefore clearly overcompensate the losses of the sine filters.

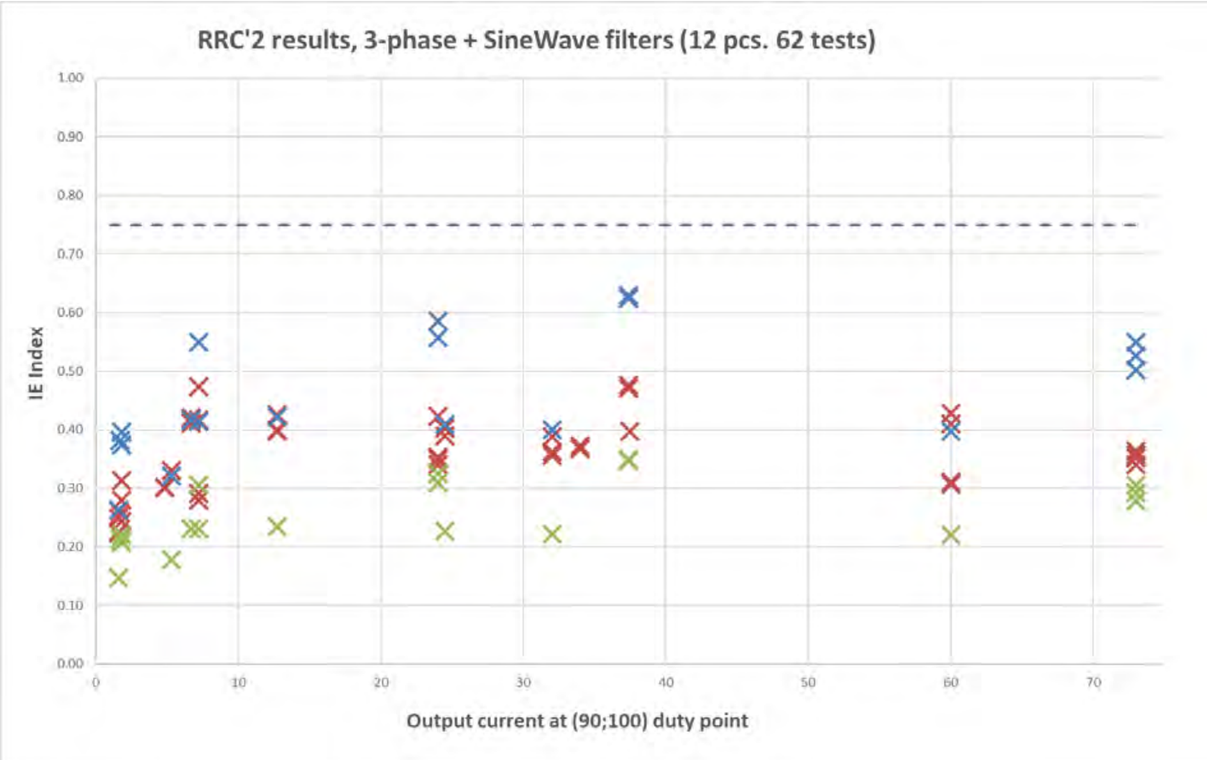


Figure 14: IE classes for complete range of converters including output filters. IE classes with (green) and without (blue) applied correction factor according to table 8 of IEC 61800-9-2 Ed.2. Dotted line is the threshold between IE2 and IE1

- Red Standard drives
- Blue Drives with SineWave filter, not corrected
- Green Drives with SineWave filter, corrected by 1.4 & 2.0 (for comparison as Table 8 proposes two values depending on the THD of the input current)

4.5 Impact of Cable Losses on Losses

Shielded cables are often necessary to meet EMC requirements. However, since the coupling capacitances of the cable increase the turn-on energy of an IGBT more than it decrease turn-off energy, an increase in the switching energy results. The degree of the increase depends on the cable length. A simple but good approach to determining cable losses is to take measurements in idle mode at zero current and then add the losses as a constant offset for the complete current range. It should be noted that the additional losses get less important at higher current ratings because the semiconductor induced switching losses scale almost linear with the nominal chip current (10A IGBT --> 100A IGBT: factor 10) while the cable capacitances rising by less than factor 3 for the same increase of nominal cable current capability.[10]

[10] Semikron Application Note AN 17-002 Influence of capacitive cable load on switching losses

To verify this, Berner Fachhochschule measured a 1.5kW converter (ABB ACS150-03E-03A3-4) with the following 2 setups:

- A 10m shielded cable, grounded on converter and motor side
- Single wires for three phases only (not twisted, only capacitances from motor and converter to earth)

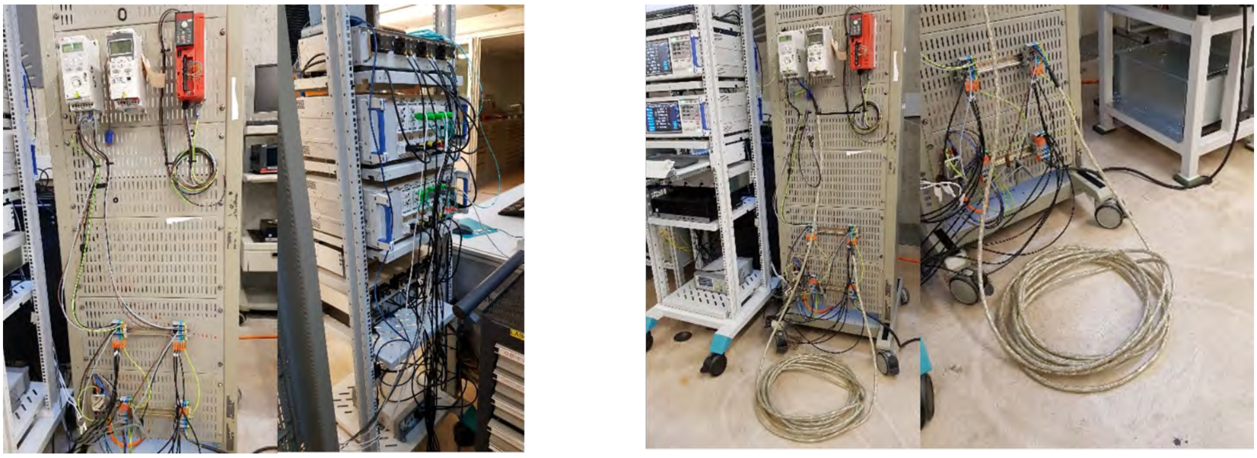


Figure 15: Setup of a small converter (ABB ACS150-03E-03A3-4) connected to the motor using 2m unshielded cables (left) and adding a 15m shielded cable with both sides grounded (right)

According to [10], the load current level has an important influence on the turn-on losses and on the voltage rise time during turn-off. The losses are linear proportional to the load producing current.

Figure 16 shows that the additional losses due to the shielded cables are typically around 10-12% higher compared to the losses without shielded cables, over the entire speed and torque current range.

Also, according to [10] for shielded cable it does not matter how the cables are installed (straight line or on a coil). This is because outside of the cable there is no capacitive coupling from shield to shield and at least no changing electrical potential.

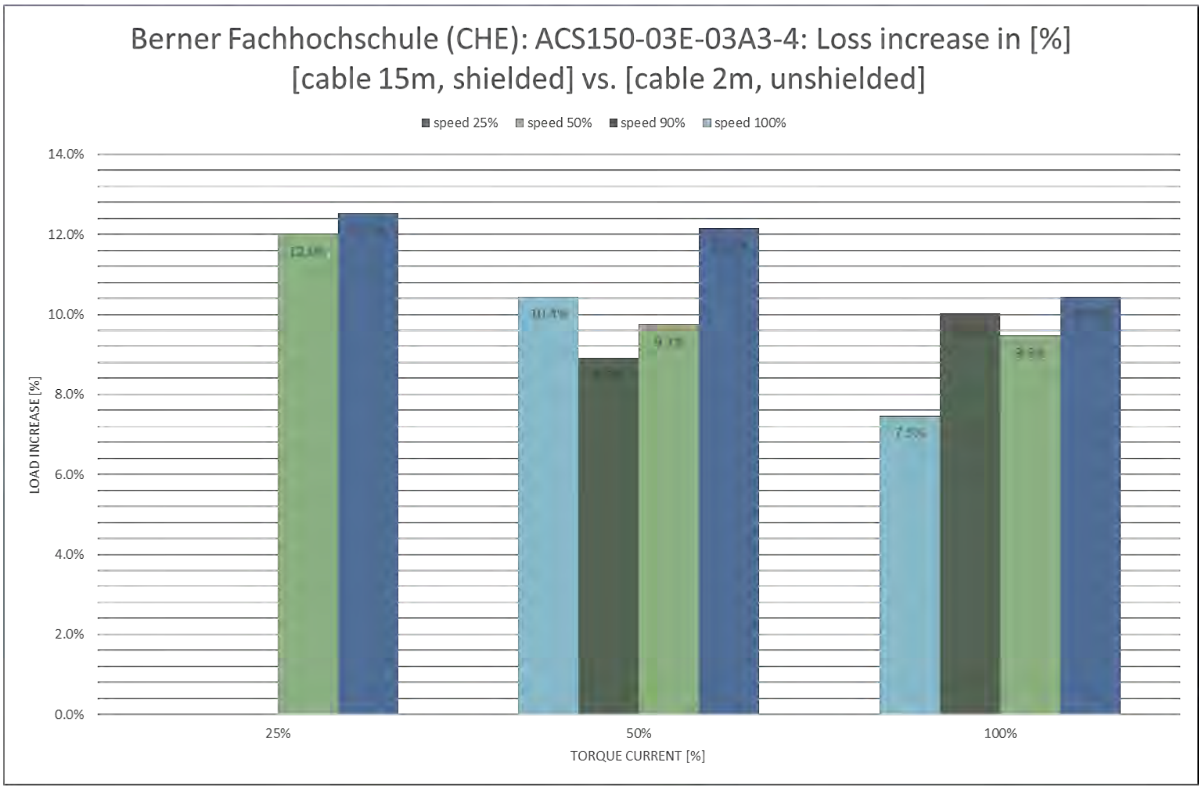


Figure 16: Additional losses due to the shielded cables normalized to the losses without shielded cables for different torque current levels and speeds here for the example of an ACS150-03E-03A3-4 converter

Based on these measurements the following additional setting conditions have been specified in the IEC 68100-9-2 Second Edition (chapter 7.5.2.2).

"Unless otherwise specified, CDMs or SDOMs having a rated apparent output power below 8 kVA should be measured with a minimum of 15 m shielded cable. If the manufacturer specifies less than 15 m maximum cable length, the highest admissible cable length should be used."

5 Validation and market survey

To compare the results from the RR’C with market data, the IE index data from two different manufacturers (X and Y) have been collected and plotted in the same way as the IE index from the RR’C (see Figure 17).

The manufacturer results cover a large power range for the same converter type (3-phase supply, 400 VAC). According to the manufacturer representatives in SC22 WG18, the manufacturers often use the ‘alternative’ calculation method as given in the IEC 61800-9-2:2017 if they must qualify converters of the same family with different power rating.

Comparing the values from the RR’C with the catalogue data it can be said that the IE index within a range of 0.3 to 0.5 is where most manufacturers today have positioned their drives. As a result of the small variation in the IE Index, the IE classification is always IE2.

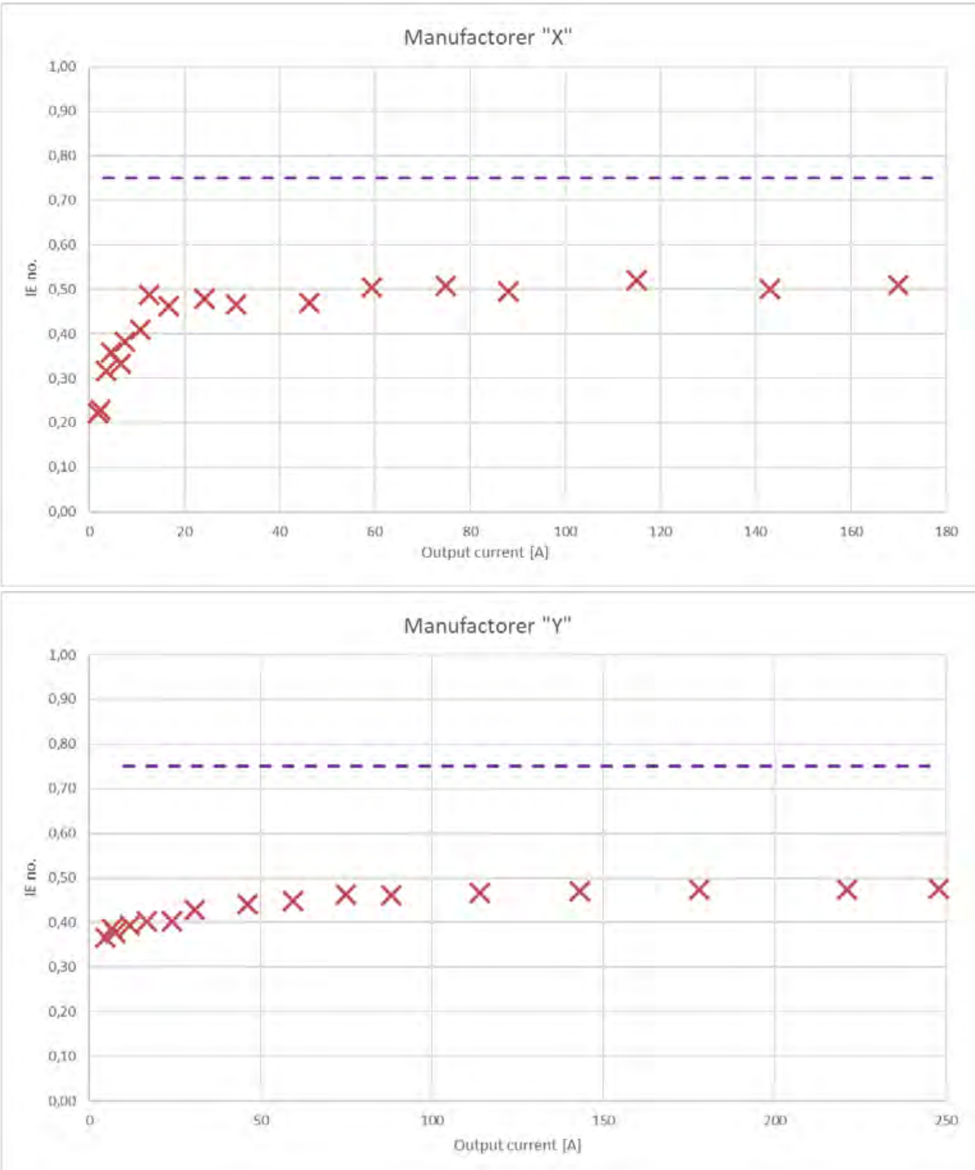


Figure 17 Catalogue data showing the IE Index for 3-phase Basic Drive Modules over nominal output current at (90:100) duty point for two manufacturers. Dotted line is the threshold between IE2 and IE1

6 Conclusions

The RR'C has so far provided the following results:

1. The Universal Testing Protocol developed by the RR'C has proven to be a valuable test method that returns highly repeatable results from converter tests in different laboratories. As a result, IEC SC22G/WG18 included the proposed modifications to eliminate ambiguities in the second revision of IEC 61800-9-2.

2. The measured converter losses were all less than 30% to 50% of the reference losses of IE1 and therefore well below the margin for the highest IE class for converters (IE2). Therefore, almost all converters on the market are within the IE2 class. Although the absolute losses can differ for the same nominal output current up to a factor of two, this does not change the IE class.

3. The correction factors introduced for CDMs with modified functionality tend to slightly overcompensate the additional losses. In extremis this means, that adding the correction factor for a unit using a sinusoidal current output filter could change its classification from IE1 class to IE2 class.

4. Finally, the test results show a very good match between manufacturer catalogue data and measured data using the input-output method. Assuming that most manufacturer data are calculated and not measured such an alignment is a positive sign. Nevertheless, most manufacturers will not completely disclose the assumptions and parameters for their calculations, so that an independent third-party recalculation is not possible. The standard IEC 61800-9-2 only gives a calculation model template with some standard parameters.

The authors would like to thank all the participating laboratories, the IEA 4E EMSA Annex for sponsoring and the IEC SC22G/WG18 for the intensive but always very constructive discussion within the second revision of IEC 61800-9-2.

7 References

[1] IEC 61800-9-2:2017: "*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*"

[2] IEC TS 60034-2-3:2013: "*Rotating electrical machines - Part 2-3: Specific test methods for determining losses and efficiency of converter-fed AC induction motors*"*;* Replaced by IEC 60034-2-3:2020 during the Round Robin Converters (RR'C)

[3] "IEC 61800-9-1: Adjustable speed electrical power drive systems - Ecodesign for power drive systems, motor starters, power electronics and their driven applications - General requirements for setting energy efficiency standards for power driven equipment," International Eletromechanical Commission (IEC), nº 1.0, p. 66, 2017

[4] Sandie B. Nielsen, Andrea Vezzini: "*RR'C PHASE 2 – UTP version 4.0: Converter loss measurement Uniform Testing Protocol (UTP), including step-by-step measurement procedure*"*;* (UTP, edition 4, 20181001)

[5] Sandie B. Nielsen, Andrea Vezzini: "*Standard Reporting Format*" ; (SRF 20180927)

[6] Sandie B. Nielsen, Andrea Vezzini: "*Round Robin Converter Losses (RR'C): Phase 2 Guidelines, version 6.0*"; RR'C Phase 2 V6_20190911

[7] Andrea Vezzini, Sandie B. Nielsen: "*Preliminary results from RR'C 2 Round Robin for Converter losses, phase 2*"; EEMODS'19 Tokyo, 42

[8] Benno Weis, Chair CEMEP Technical Board: "*CEMEP position on future energy efficiency regulation of motor systems and applications*"; EEMODS 2019, Tokyo, Japan

[9] Conrad U. Brunner, Impact Energy, Zurich; Sandie B. Nielsen, DTI Denmark; Andrea Vezzini, BFH, Switzerland; Emmanuel Agamloh, AE, USA; Andrew Baghurst, CalTest, Australia: "*Round Robin tests for converter losses (RR'C): Results from phase 1*"; EEMODS'19, 18 September 2019, Tokyo, Japan

[10] Semikron Application Note AN 17-002 *Influence of capacitive cable load on switching losses*

8 Table of Figures

ANNEX 1: Glossary and abbreviations

4E	IEA Technical Cooperation Programme: Energy Efficient End-use Equipment
BFH	Berner Fachhochschule (Bern University of Applied Sciences)
CDM	Complete drive module (defined in IEC 61800-9-2) (here used as synonym for VFD)
DTI	Danish Technological Institute
EEMODS	International Conference on Energy Efficiency in Motor Driven Systems
EMSA	Electric Motor Systems Annex of 4E, www.motorsystems.org
IEA	International Energy Agency, Paris, France, www.iea.org
IEC	International Electrotechnical Commission, Geneva, Switzerland, www.iec.ch
MEPS	Minimum Energy Performance Standard
PDS	Power drive system (defined in IEC 61800-9-2)
PLC	Programmable logic controller
PWM	Pulse width modulation
rms	root mean square
RR'C	Round Robin program for converter losses
SC22G	IEC Subcommittee 22G responsible for "Adjustable speed electric drive systems incorporating semiconductor power converters"
UTP	Uniform Test Protocol
VFD	Variable frequency drive
VSD	Variable speed drive (here used as synonym for VFD)
WG18	Working Group 18 of IEC TC22 SC22G, responsible for "Energy efficiency of adjustable speed electric power drive systems"
BDM	Basic Drive Module
CDM	Complete Drive Module
4Q	Four Quadrant (Converter)
A	Ampere
EMC	Electromagnetic compatibility
IGBT	insulated-gate bipolar transistor (IGBT)

ANNEX 2: Contact Addresses of participating labs

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ANNEX 3: Example Description of Testing laboratories

Bern University of Applied Sciences, Switzerland

The laboratory for power electronics and electric machines at Bern University of Applied Sciences in Biel/Bienne, Switzerland offers a wide range of testing facilities. The test benches are located in a large open basement on campus. Temperatures range from a minimum of 21°C during winter to a maximum temperature of approximately 25°C during summer. Currently, there is no possibility for climate control.

Ranging from 0-6 Nm and 2500 rpm for the smallest bench, up to 0-50 Nm and 9000 rpm for the largest bench, motors and electric drive systems with a maximal mechanical power output of 11 kW and 50 Nm can currently be tested. During the course of 2019, an additional 50 kW test bench has been completed, allowing an even wider range of testing capabilities. This latest upgrade also includes a 60 kVA Chroma grid simulator and a 60 kW Chroma battery simulator, allowing better control of testing environment variables.

Figure 18 Available Test Benches at Bern University of Applied Sciences in Biel (smallest to largest)

For testing VFDs, several IE3, four pole induction machines are readily available in the lab. The available machines offer mechanical power output of 0.75 kW, 1.1 kW, 1.75 kW, 2.2 kW, 5.5 kW (2 different machines available for this size – IE1 and IE3) as well as 11, 22 and 30 kW. Apart from the 1.75 kW and one of the 5.5 kW machines, all motors are from the same supplier and the same product line.

Measurements are performed using two Hioki PW6001 in master-slave mode, offering a total of 8 high resolution measurement channels. This allows full three-phase input-output measurement of grid connected VFDs or similar applications. Current measurements up to 50 A are performed using high bandwidth current shunt boxes (Hioki PW9001, 8 channels in total) whereas higher currents up to 200 A are measured using hall-type sensors (Hioki CT6863). Example: The following table shows the theoretical accuracy testing of an 11 kW VFD using the PW9001 50 A current shunt boxes:

Frequency	**DC**	**10 Hz**	**50/60 Hz**	**100 Hz**	**1 kHz**	**10 kHz**	**100 kHz**	**1 MHz**
Error	0.16 %	0.6 %	0.12 %	0.15 %	0.21 %	0.43 %	1.70 %	32.43 %

Table 1 Table illustrating measurement accuracy of three phase measurement (11 kW VFD test)

More detailed information regarding power analyser accuracy and specifications is given in the Table 2 Power analyser accuracy and specifications.

Unit	**PW6001**	**PW9001**	**CT6863**
S.N.	Unit 1: 151026458 Unit 2: 151028246	Unit 1:180430518 Unit 2: 180430517	Unit 1: 150613622 Unit 2: 150900323 Unit 3: 150900324 Unit 4: 150900325
Specs	Master-Slave (23μs sync) Quad Channel 18 Bit ADCs U: $\pm$2 % rdg. $\pm$ 0.02 % fs. I: $\pm$2 % rdg. $\pm$ 0.02 % fs.	$\pm$ 50 A 3.5 MHz $\pm$ 0.04 % (@ 2 MHZ)	$\pm$ 200 A 500 kHz $\pm$ 0.05 % rdg. $\pm$0.01 % fs.

Table 2 Power analyser accuracy and specifications

Advanced Energy, USA

Advanced Energy motors testing is carried out in its motor test laboratory in Raleigh, North Carolina, USA. The laboratory has maintained an ISO/IEC 17025 accreditation since 1997 through NIST/NVLAP. The lab has also maintained a NOM designation through ANCE, the first laboratory outside Mexico to gain such designation. From 2010 to 2014 the laboratory participated in UL's data acceptance program and has worked closely with UL to test motors intended for certification for UL clients. The laboratory has also in the past assisted CSA to certify motors for its clients, following a witness by CSA staff. The lab is currently the sole source in the US for testing converters to the AHRI standard 1210.

Advanced Energy has a number of dynamometers ranging from below 0.75 kW up to 225 kW. The 225 kW Eddy current dynamometer is shown on the left and the mid-range dynamometer where the round robin tests were conducted is shown on the right.

The laboratory is equipped with high precision instrumentation including a Yokogawa WT 3000 and Lebow torque instruments and torque transducers of various sizes, matched to the motor size under test. More information on the test lab and instrumentation can be found at: [www.advancedenergy.org/markets/motorsanddrives/.](www.advancedenergy.org/markets/motorsanddrives/)


Figure 19 Advanced Energy Test benches, left: 225 kW Eddy current dynamometer, right: mid-range dynamometer where the round robin tests were conducted

CalTest Laboratory, Australia

Main testing fields of the CalTest lab in St, Port Elliot, South Australia 5212 (www.caltestlab.com.au) are rotating electrical machines, with dynamometers providing loading facilities for machines rated up to 185 kW, and no-load tests and measurements on motors with output power ratings up to 1'500 kW, and voltage ratings up to 11 kV.

CalTest is accredited by Australia's laboratory accreditation organization, NATA, to the requirements of ISO 17025: 2017; accreditation no. 15303

The equipment used for the RR'C:

- Power supply: Mecc Alte 220 kVA motor-driven 3-phase alternator, providing either 50 or 60 Hz, depending on prime-mover speed and with voltage control by means of adjustment of alternator excitation
- Power analyser: Yokogawa WT3000 – Motor version - with 4 input modules: 2 modules for input, and 2 for output, each connected '3P3W'
- Dynamometer: Purpose built for the project, consisting of two in-line connected induction machines, one of which loaded the converter. The system included an HBM model T12 'torque flange' torque meter, but that equipment was used for monitoring purposes only: no torque or shaft speed readings were recorded.
- Motor loading: Mechanical loading of the converter-driven motor was by means of appropriately rated ABB model ACS800 variable frequency drive units operating in torque control ('DTC') mode, returning electrical power to the DC link of a similar type of VFD which supplied the (55 kW 4-poleole) motor driving the main power supply alternator, as above.
- Temperature measurement: T-type thermocouples connected to a Fluke model 54 II digital thermometer, uncontrolled laboratory ambient air temperature.

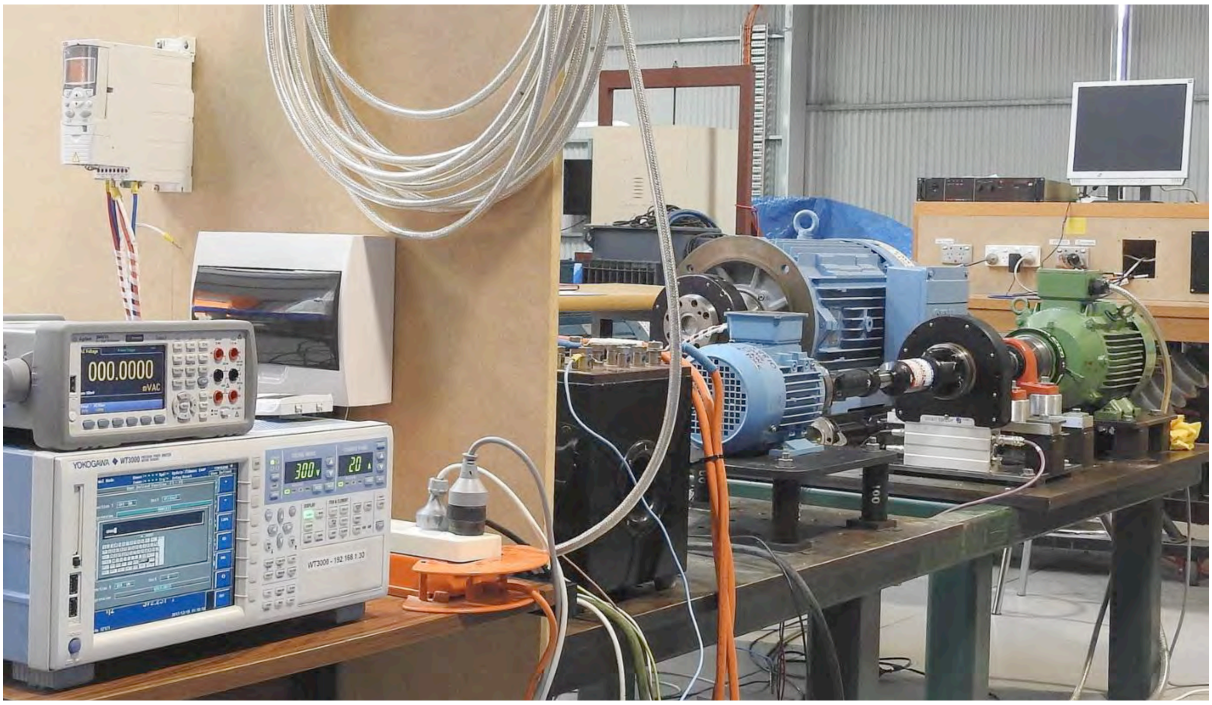

Figure 20 General view of the measurement system at CalTest

Top left: the converter under test, with coiled shielded output cable to the right Bottom left: Instrumentation – Yokogawa WT3000 power analyser with flux voltmeter above Centre: (Blue) 1.1 kW 4-poleole IE2 motor for loading the converter Right: (Green) dynamometer machine for loading the above motor (Torque transducer not used).

Danish Technological Institute – DTI Drives-Lab, Denmark

Danish Technological Institute is a leading research and technology Institute located in Denmark. DTI employ 1041 specialists and help more than 10.000 customers a year – representing 65 different countries. DTI are organizational divided into 8 divisions (Production, Materials, Life Science, Business and Society, Energy and Climate, Agro technology, Building and Construction and Meat research) – The motor test facilities are a part of Energy and Climate division.

DTI Electric motor test facilities, Drives-Lab, are as most of DTI labs, a part of the ISO/IEC 17025 accreditation and have been so since 2011 annually assessed by Danish accreditation body: DANAK which is a member of ILAC.

DTI Drives-Lab offers testing of both power electronics, electric machines, gear boxes etc. and are equipped with a wide range of testing facilities. It is physically divided into two locations in eastern and western part of Denmark which both offers climate control.

DTI Drives-Lab have been an important part of the European MEPS program on electric motors since the launch in 2011 and have today more than 150 accredited compliancy tests on motors on record performed on behalf of several European countries.

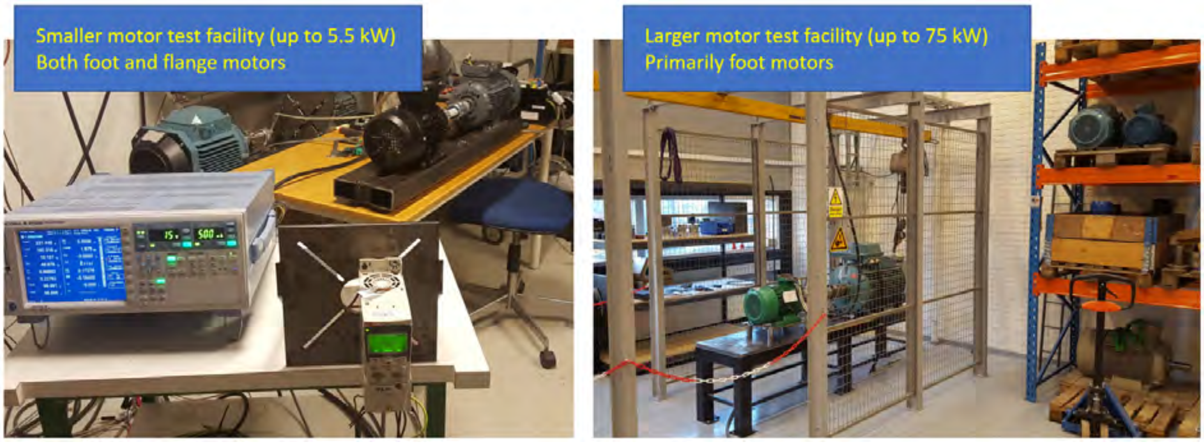

Figure 21 DTI Drives-Labs

DTI Drives-Lab is equipped with high precision instrumentation including Yokogawa WT3000E, ZES Zimmer power analysers, DANISENSE current transducers and a selection of Lorentz torque transducers of various sizes. All testing is fully automated and DAQ collected through self-developed LabVIEW software.

For more information on DTI Drives-Lab please see:
https://www.dti.dk/testing/electric-motors-and-drives/38003