PERFORMANCE OF MPPT CHARGE CONTROLLERS A STATE OF THE ART ANALYSIS

Michael Müller[1], Roland Bründlinger[2], Ortwin Arz[1], Werner Miller[1], Joachim Schulz[2], Georg Lauss[2]

1. STECA ELEKTRONIK GMBH, Mammostr. 1, D-87700 Memmingen, Germany, Tel.: +49-8331-8558530, Fax: +49-8331-8558312 E-Mail: Michael.Mueller@Steca.de, Internet: http://ww.stecasolar.com
2. AIT Austrian Institute of Technology GmbH, Giefinggasse 2, A-1210 Vienna, Austria, Tel.: +43-50550-6351, Fax: +43-50550-6390, email: Roland.Bruendlinger@ait.ac.at, Internet: http://www.ait.ac.at

ABSTRACT

Maximum Power Point Tracking (MPPT) charge controllers have recently become increasingly popular not only for off-grid PV applications.

MPPT Charge Controllers not only promise to increase the energy yield of the PV generator, they also allow to use low cost PV modules designed for grid-connected applications (between 40-70 cells) which normally could not be used in off-grid installations due to their high MPP voltage. Therefore DC-DC converters (typically step-down converters) are used to match the output voltage of the PV generator to the battery voltage. Those products commonly use MPPT-algorithm to track the maximum power point (MPP) of the PV generator. According to recent estimtations, about 30 to 50 MW of MPPT Charge Controllers are installed per year. Among the variety of products 60 A MPPT charge controllers dominate the market?

In the absence of standard testing procedure dedicated to DC battery charging MPP-trackers only part of grid connected PV-inverter tests can be applied[1]. However, due to expensive and complex test requirements it is not possible for customers to evaluate the actual performance and quality of a certain product.

This paper summarizes the results of the TESCABI[2] project which is part of the EU DERri initiative (www.der-ri.net). Within the project, a set of test procedures for performance characterization of MPPT charge controllers have been defined. Using the procedures, extensive laboratory tests were made at the AIT PV inverter laboratory with a world-wide market representative set of 9 different MPPT devices. Based on the results, recommendations for manufacturers as well as customers have been formulated to select the appropriate product for a certain application.

1. DEVELOPMENT OF TEST PROCEDURES FOR MPPT CHARGE CONTROLLERS

The developed test procedure takes into account the experience of testing PV-grid tied inverters and switching (non-MPPT) battery charge controllers. It is divided into 6 categories, which define the test procedure.

1.1 Installation and usage

The first category deals with the construction of the product and checks the most important technical data.

It evaluates the mechanical robustness of the enclosure and the ease of installation in terms of the design (e.g. if there is enough room for the cables, easy to reach terminals, etc).

1.2 Night-time and stand-by consumption

The 2nd category deals with the self consumption of the MPPT controller. In all off-grid systems it is of crucial importance to have extremely low self consumption during the night and periods of low irradiation.

1.3 DC-DC conversion efficiency

Similar to grid connected inverters, the DC-DC conversion efficiency is one of the most relevant performance parameters of MPPT charge controllers. Today, manufacturers typically show only the maximum (peak) efficiency in their datasheets which however does not reflect the real operating conditions in field. In practice a number of external factors influence the conversion efficiency: Actual battery voltage, actual input voltage, temperature and the power output of the device.

To characterize the conversion efficiency of MPPT charge controllers, the basic test procedure from the EN 50530[1] has been extended to take into account the additional aspects of the specific devices (e.g. influence of the battery voltage)

To provide a realistic picture of the efficiency in field manufacturers shall provide any efficiency rating according to the EU efficiency[3]. The definition of the weighting of the European efficiency can be seen in table 2.

Output power (% of rated)	5%	10%	20%	30%	50%	100%
Weighting factor	3%	6%	13%	10%	48%	20%

Table 2: Definition of EU efficiency

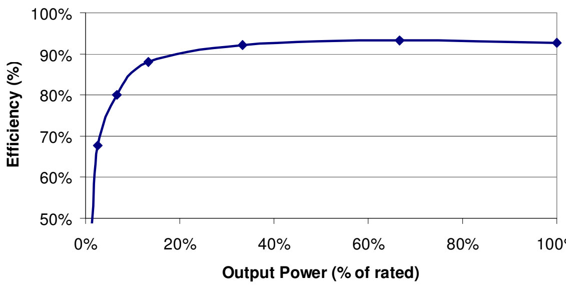
The DC-DC conversion efficiency depends mainly on the voltage difference between input and output voltage. The higher the voltage difference the lower the efficiency. It has to be measured for each nominal battery voltage individually for all possible input voltages. Table 3 shows the combinations of battery output and module input voltages for the measurements.

Battery	Measured input voltage levels				
12V	30,0V	60,0V	90,0V	120,0V	150,0V
24V	30,0V	60,0V	90,0V	120,0V	150,0V
48V	30,0V	60,0V	90,0V	120,0V	150,0V

Table 3 : Voltage table for measurements

For each test candidate those 15 measurements need to be done. Each measurement consists of 6 power set points of table 2. To characterize the efficiency 15 * 6 = 90 measurements need to be done. The EU-efficiency shall be calculated for each point. To find a representative overall efficiency the EU-weighted efficiency of all those 15 measurements have been weighted equally to provide a realistic picture of the typical field efficiency of the charger.

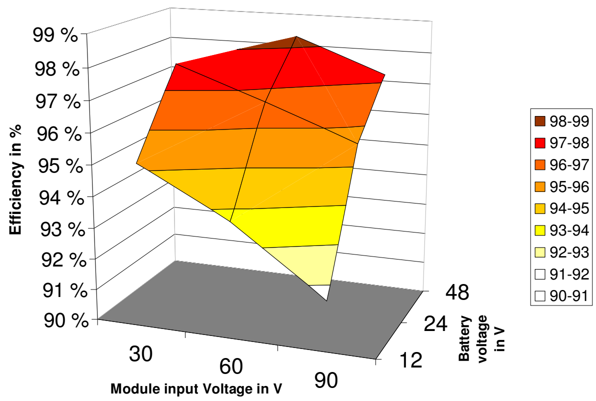
As an example, Graph 1 shows the efficiency for an input MPP voltage of 60 V and a fix battery (output) voltage of 12 V of one of the test candidates.



Graph 1: Typical dependency of the conversion efficiency on the output power

The test object reached a peak efficiency 93,3%. The European weighted efficiency is calculated to 90,9% for the given example.

In graph 2 the full picture of the efficiency surface depending on the MPP input voltage (30 V/60 V/90 V) and the battery output voltage (12 V/24 V/48 V) can be seen. Each single measurement point is the EU-weighted efficiency according to Graph 1 and table 2.



Graph 2: Weighted DC/DC conversion efficiency characteristics in dependency of the MPP and battery voltage.

The test candidate from graph 2 shows an equally weighted DC-DC conversion efficiency of 93,6%. If a configuration of 90 V module input and 12 V battery voltage is chosen, the device is operating at DC-DC conversion efficiency of 91%.

1.4 Thermal de-rating performance

The MPPT charge controller shall be able to handle its specified nominal power under the given temperature conditions for a minimum period of 10 hours. Often chargers are designed to handle the nominal power only for 30 minutes. After heating up the devices typically limit the output power (derating). This leads to a significant reduction of the possible energy yield.

1.5 Static MPPT accuracy

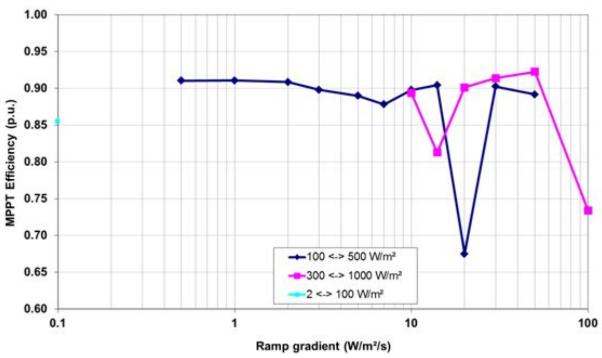
MPPT charge controllers use an MPP-tracking algorithm to ensure the maximum power output of the solar module array. Customers can not evaluate the quality of this pure software function but it has significant influence to the energy yield which the controller realizes.

Therefore the test of the algorithm according to EN 50530 has been performed. The first test is the static MPPT performance. The algorithm has been tested for all power values (see table 2) and over all input and output voltages (see table 3) with 10 sec test time. Similar to the conversion efficiency, also the measured MPPT efficiencies are weighted. An equally weighted result of all these measurements provides a realistic picture of the static MPPT accuracy. This value reflects the behavior during a full sunny day.

1.6 Dynamic MPPT accuracy

During days with changing irradiance conditions, the dynamic MPPT performance is a crucial value. It provides information on the accuracy of the MPPT algorithm to adapt to changing irradiation conditions. This has been measured according to EN 50530 (Annex B)[1] for all test candidates. Again the algorithm has been tested for all combinations of input and output voltages (see table 3) while the input power was ramped up and down from 0% to 100% with different speed ramp gradients from 0.1–100 W/(m²*sec).

All measured values where weighted according to the rules from EN 50530 resulting in a representative value η_{mpp_dyn} which describes the performance during cloudy days. An example of the results of a dynamic MPP tracking behaviour can be seen in graph 3. The unit has very low performance of about 90% while critically low values of 85%, 80% and 66% can be seen as well. Such a behaviour leads to a significantly lower energy yield under slowly as well as rapidly changing conditions. For comparison, state-of-the-art MPPTs of grid connected PV inverters reach dynamic MPPT efficiencies of more than 99%.



Graph 3 : Example of dynamic MPPT performance – EN 50530.

1.7 Efficiency Calculation

To be able to compare the realistic field efficiency of MPPT charge controllers a new efficiency performance factor called Realistic Equally Weigthed efficiency - REW is defined to:

$$\eta_{REW} = \eta_{DC\text{-}DC} \cdot \eta_{mpp\_stat} \cdot \eta_{mpp\_dyn} \qquad (1)$$

Formula 1 : Definition of REW.

with

$\eta_{DC\text{-}DC}$ Equally weighted DC-DC conversion efficiency over all possible input and output voltages according to table 3 using the European weighted efficiency according to table 2,

η_{mpp_stat} The static mpp tracking efficiency according to EN 50530 while all measured values for different irradiation conditions are equally weighted and

η_{mpp_dyn} dynamic mpp tracking efficiency according to EN 50530 with ramp gradients from 0.1 – 100 W/(m²*sec) weighted over all power levels from table 2.

The given example shows an REW-efficiency of $\eta_{REW} = \eta_{DC\text{-}DC} \cdot \eta_{mpp\_stat} \cdot \eta_{mpp\_dyn} = 0{,}9356 \cdot 0{,}9897 \cdot 0{,}8545 = 0{,}7912$.

If this number is compared with standard switching controllers like shunt or series type charge controllers which normally operate at about 85% efficiency it can be seen that the above mentioned device will bring less energy to the battery than a comparable shunt or series type charge controller.

2. LABORATORY TESTS

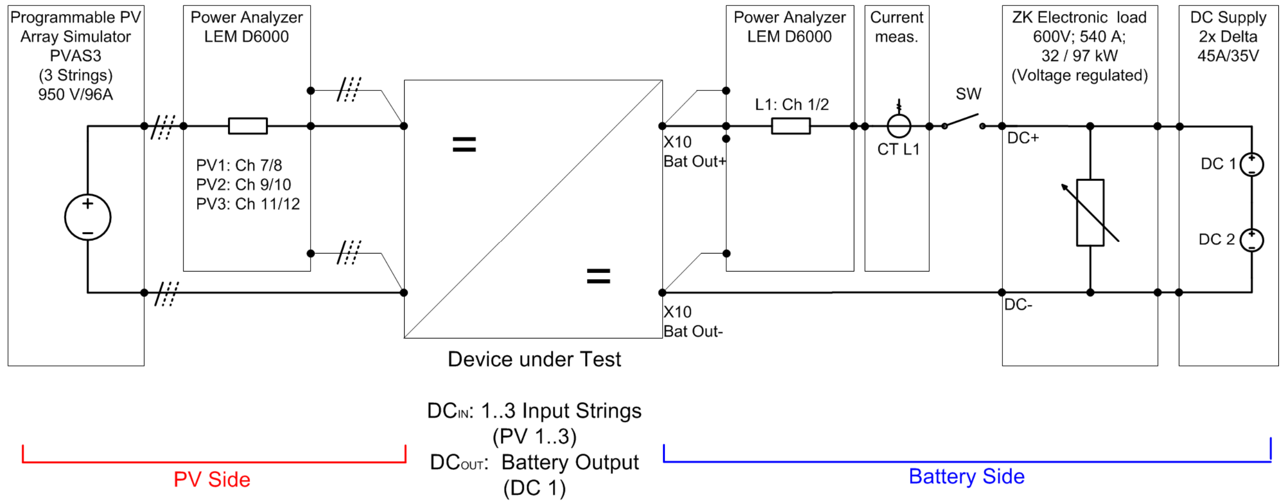
Within the European TESCABI project 9 commercially available MPPT charge controllers have been tested and measured according to the above mentioned test procedure.

Samples of all well known solar power electronic brands coming from all continents around the world have been purchased through different dealers in different countries.

The tests itself have been done with the help of the high sophisticated PV module simulator at AIT as DC power source[4].

The output of the test candidate was connected to a real battery. An electronic load was connected to the battery to stabilize the batteries voltage. Graph 4 shows the “Test Stand” which is used within the Austrian Institute of Technology (AIT) for testing PV grid-connected inverters. It was used for the tests.

All DC-input and DC-output currents and voltages have been measured with high accuracy Power Analysers available at AIT.



Graph 4 : Test setup for MPPT charge controllers at AIT[4]

3. TEST RESULTS

All 9 test candidates had to pass the tests described in chapter 1. The results can be used to compare the products and to offer customers neutral market relevant information.

3.1 Installation and usage

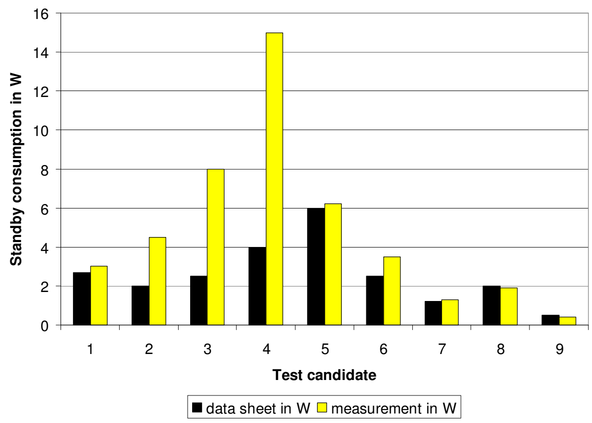
Most of the test candidates come with metal enclosure and solid construction. Concerning the connection terminal most of the samples showed rather small terminals and only limited space to connect the cables. This is not comfortable for installers.

Most of the test candidates offer an input voltage range up to $U_{oc} \leq 150$ V. Some of the products limit the input voltage in dependence of the used battery voltage. In case of a 12 V battery the maximum input voltage is significantly below 100 V, only for 48 V battery up to 150 V input is allowed. Users should be aware of this and be careful as this limits the module configuration flexibility significantly. Higher input voltage ranges offer more module configuration flexibility and is recommended as it makes the installation easier.

Most of the samples detected the battery voltage automatically and had no problem with wrong battery polarity while many of the candidates could not stand a solar module short circuit during operation.

3.2 Nighttime and standby consumption

The result of the measurement of the self consumption was compared to the given values in the data sheet of the manufacturer. Graph 5 shows the result of this comparison.



Graph 5 : Comparison of Nighttime consumption of 9 different MPPT Charge Controllers

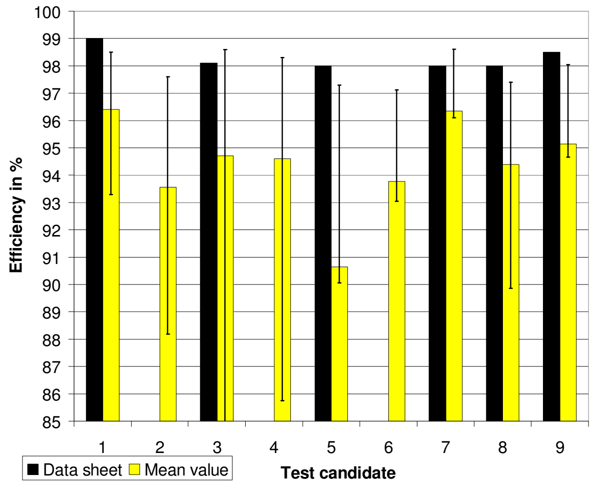
A huge difference among the test candidates can be seen in graph 5. Some samples show not only extremely high self consumption, but also perform in reality completely different than indicated by the manufacturer. An additional consumption of 12 W means 288 Wh/d. At locations of 4 kWh/(m²*d) this is an additional 80Wp solar module and 48 V@15 Ah battery more only to cover the additional consumption.
This results in significantly higher costs for the user and shows that cheap products can make the system more expensive.

3.3 DC-DC conversion efficiency

According to the defined rule a representative typical DC-DC conversion efficiency was calculated. The result of the test candidates was again compared to the information available from the manufacturers.

Graph 6 shows the comparison between the realistic DC-DC conversion efficiency. It has been weighted equally over all possible input and output voltages on the base of European efficiency values. The error bar shows the difference between the maximum and minimum measured efficiency always given as European weighted efficiency. Depending on the type of the efficiency surface (see graph 2) the conversion efficiency is closer to the maximum possible efficiency or not. The closer the conversion efficiency to the minimum of the error bar and the shorter the error bar the better the conversion efficiency.

Some of the manufacturers state that MPP trackers can bring up to 30% more energy to the battery than switching controllers. Even though such a situation can happen it must be reduced by the DC-DC conversion efficiency. If the conversion efficiency is only 90% such a controller could bring in peak times maximum 20% more but will bring most of the time less energy to the battery than a standard switching controller as it operates most of the time in low conversion efficiency. Taking the losses of MPP tracking algorithm into account the performance can even be worse.



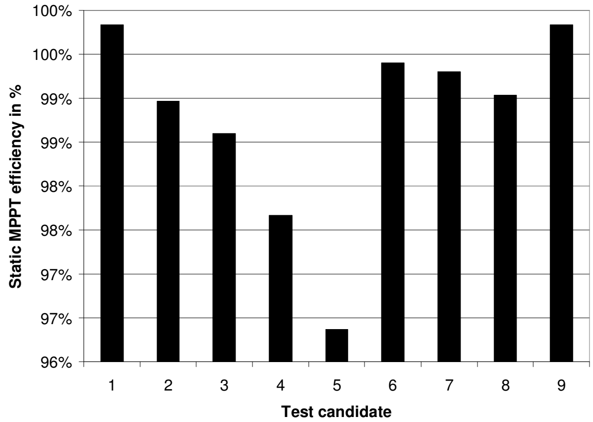
Graph 6 : DC-DC efficiency.

Customers should have a close look to the exact input-output voltage relation in the real system and select the MPP charge controller carefully according to the DC-DC conversion efficiency. Manufacturers shall provide the conversion efficiency in detail as given in graph 2.

3.4 Static MPPT efficiency

The static MPPT efficiency provides good results in order to characterize the performance of the inverter under continuous quasi-static irradiance conditions i.e.: a sunny day. . Graph 7 shows the performance of the test candidates.

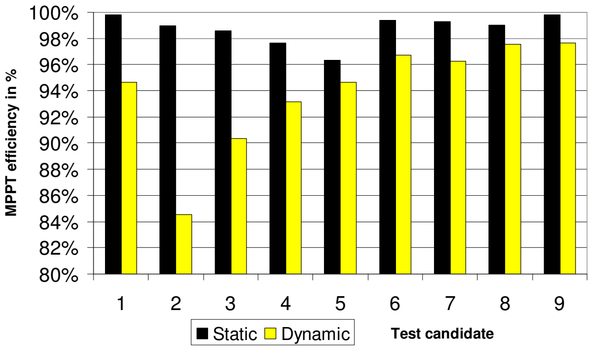
A good static MPP tracking algorithm never reaches values below 99%. Graph 7 shows that many of the test candidates show very low performance, which results in significant a loss of energy for the customer. As an example, considering a 3kWp power plant a diminished MPP efficiency of about 4% results in a direct loss of approximately 800Wh at a sunny day. This means that an additional 100Wp solar module needs to be installed in order to compensate this lack of efficiency.



Graph 7: Overview on static MPPT efficiency

3.5 Dynamic MPPT efficiency

The dynamic MPP efficiency was measured according to DIN EN 50530:2010 and provides information about the ability of the MPP tracking algorithm to adapt to both to slow an fast changing irradiation conditions. As all off-grid systems are designed to supply the connected loads during unfavourable irradiance conditions (winter season, cloudy days) the dynamic MPPT efficiency is of crucial importance. A low efficiency result of those executed dynamic ramp tests is directly proportional to an loss of efficiency for variable irradiance conditions – in practice, this can be seen as an additional loss of energy especially during cloudy days.. Graph 8 shows the comparison between the static and dynamic efficiency of the test candidates.

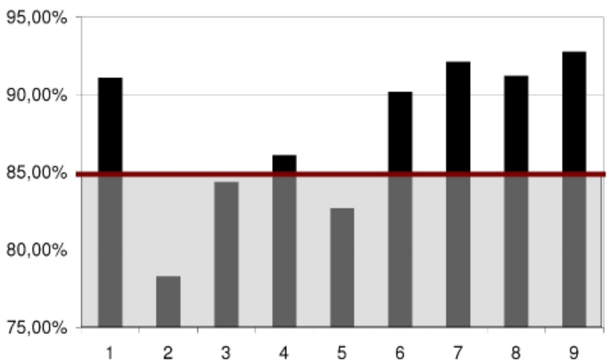


Graph 8: Comparison of average weighted static and dynamic MPPT efficiencies for the different test candidates

As it is visualized clearly, the average performance of some samples is unsatisfactory. In combination with a given low static MPPT efficiency and an additional low DC-DC conversion efficiency such devices will transfer less energy to the battery than switching shunt-type of series controllers, which feature beneficial overall performance results.

3.6 Efficiency considerations

As a result of the 5 testing categories it can be seen that there are significant differences in the test results among the all tested devices. Especially the DC-DC conversion efficiency in combination with the static and dynamic MPP tracking efficiency and the self-consumption figures represent the most important criteria.
The average performance of the test candidates according to the the Realistic Equally Weighted efficiency - REW can be seen in graph 9.



Graph 9: REW efficiency in % of all test candidates

The outcome of this test shows clearly that there is a significant difference between well designed MPPT charge controllers and low performing products. Even the best available products perform below $\eta_{REW} < 93\%$, which is a non-satisfactory figure. All well known brands are part of the test and the outcome clearly shows that there is no guaranty to buy a brand product to finally use a good performing charge controller. Five out of nine products show acceptable performance and can be effectively used in off-grid systems. Some of the test candidates reach less than 85% and will bring less energy to the battery as standard switching controllers.

All samples show a weak performance in static and especially dynamic MPPT algorithm. Taking the low DC-DC conversion efficiency under consideration none of the mentioned products is able to meet the manufacturer's specifications.

4. SUMMARY

Off-grid systems using MPPT charge controllers dominate the market more and more. Due to significant module price reduction in the last years the average off-grid system size is rising as it is now economically feasible to built off-grid systems in areas in which such systems have been too expensive up to now. Especially non off-grid modules with about 40-70 cells per module are used more and more in off-grid installations. MPPT charge controllers must be used then. The tests of this work show that variously specified products are available on the market, but it is nearly impossible for the users to find out, whether the selected MPPT charge controller shows good performance in the field or not.

4.1 Test procedure

A suitable test procedure is hereby developed and it benchmarks the performance of MPPT charge controllers into 6 categories: Installation and usage, self-consumption, an equally weighted DC-DC conversion efficiency based on the European weighted efficiencies among all input and output voltages. Furthermore derating performance, Static and dynamic MPPT efficiency.

4.2 User recommendation

For end users and system integrating companies it is not possible to perform the tests described in this paper. For each single installation it should be carefully checked, whether MPPT charge controllers are necessary and in which extent. In the case that it is possible to use standard 36-cells or 72-cells modules switching controllers can also be integrated in an efficient and effective way.

Users are definitely asked to gain detailed self consumption information from the manufacturer, as well as confirmed figures for the DC-DC conversion efficiency calculated on the base of European efficiency rules and finally MPP tracking efficiency according to DIN EN50530.

4.3 Manufacturer recommendation

Manufacturers shall provide more information in the datasheet of its charge controllers. Besides that the given values must be correct and reproducible.

Especially the DC-DC conversion efficiency shall be given as a whole surface plor depending on all relevant input and output voltage relations. As a valid alternative the newly defined REW efficiency can be used to provide a realistic figure of the conversion efficiency. All DC-DC conversion efficiencies shall not be given as peak values, but as representative European weighted values. The thermal derating performance shall be mentioned clearly.

Manufacturers should provide information on the static and dynamic MPPT algorithm according to DIN EN50530.

By designing a product manufacturers shall leave enough room to easily connect cables to the charge controllers.

4.4 System design

MPPT charge controllers offer a wide input voltage range and allow to use solar modules with more than 36/72-cells, which is similar to the input configuration of comparable grid-connected inverters. According to the system properties it is recommended to design the solar module array in an adequateway.

The maximum open circuit voltage of the module string is seen as a highly critical design criterion and must always be below the manufacturer's value given in the datasheet. This must also be valid for minimum temperature system conditions (the lower the ambient temperature gets, the higher the modules open circuit voltage is). According to the datasheet of the PV module and according to the minimum temperature specification, the maximum possible open circuit voltage must be calculated in order to fit the MPPT voltage range of the charge controller and its given figures in its datasheet.

The maximum Watt peak rating of the used module strings can exceed the nominal continuous power of the MPPT charge controller by about 15% which is a common practice for grid connected systems. This reflects the fact that the output power of solar modules is dependent on the temperature and that it is significantly reduced by increasing ambient temperature.

5. CONCLUSION

To improve the performance of MPPT charge controllers a manufacturer neutral test procedure has been developed and should be used as a benchmark during MPPT charge controller development. A new conversion efficiency rating has been defined to :

$\eta_{REW} = \eta_{DC\text{-}DC} \cdot \eta_{mpp\_stat} \cdot \eta_{mpp\_dyn}$ taking into account the European weighted DC-DC conversion efficiency as well as MPP tracking efficiencies accordin to DIN EN50530.

The test showed in an obvious way that there is especially weak MPPT tracking performance in many products.

A world wide manufacturer representative test of MPPT charge controllers shows according to graph 9 that there is still improvement of such products necessary to finally offer products suitable for sustainable and quality driven off-grid systems. The best test candidate shows typical efficiency of $\eta_{REW} < 93\%$, while the bottom quality reaches $\eta_{REW} < 78\%$.

Just by choosing an MPP tracker the customer can gain or loose a lot of energy in the system.

6. REFERENCES

[1] DIN EN 50530 VDE 0126-12:2011-04 - Overall efficiency of grid connected photovoltaic inverters, http://www.vde-verlag.de/standards/0126035/din-en-50530-vde-0126-12-2011-04.html

[2] EU Project DERRI – TA Project "TESCABI", testing scheme for MPPT charge controllers and battery inverters.

[3] EU weighted efficiency definition, H. Häberlin et al., Total Efficiency η-tot – A new Quantity for better Characterisation of Grid-Connected PV Inverters, 20th European Photovoltaic Solar Energy,Conference, Barcelona, 2005

[4] AIT inverter test laboratoy, http://www.ait.ac.at