White Paper

Efficiency Advantages of ±380 V DC Grids in Comparison with 230 V/400 V AC Grids

Authors

Ulrich Boeke, Philips Electronics Nederland B.V., Philips Research Eindhoven
Dr. Roland Weiß, Siemens AG, Corporate Technology Erlangen
Anton Mauder, Infineon Technologies AG, Neubiberg
Luc Hamilton, Micro Turbine Technologies B.V., Eindhoven
Leopold Ott, Fraunhofer Institut IISB, Erlangen

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1 Introduction

This white paper explains the efficiency advantages of the new 2-phase DC power grid architecture in Figure 1 that is proposed to replace the state-of-the art 400 V 3-phase AC grids by the partners of the European ENIAC project "Direct Current Components +Grid" (DCC+G) [1].

The European Community has defined that new buildings must become much more energy efficient [2]. To reach the requested net-zero-energy status future buildings have to combine energy saving construction designs, energy saving applications with renewable power sources. Today photovoltaic solar power systems are the most prominent renewable power source for these buildings [3]. The solar cells of solar power systems generate DC current and interestingly lighting, energy efficient building heating, ventilation, air-condition and cooling as well as computer of information technology are all operating with an internal DC supply voltage already today. Thus it would be just consequent to connect DC power sources with DC loads by means of an even more energy efficient DC power grid.

The DC power grid architecture in Figure 1 has energy efficiency advantages in three areas that are explained in this white paper.

- A central AC/DC rectifier of 10 kW rated power or higher can save about 3 % power compared with rectifiers and power factor correction circuits up to 50 W used e.g. in lamp drivers and many other applications.
- Power cables operating with the proposed DC voltages can save up to 2 % of power compared with a power cable for a 3-phase AC grid. Alternative, 56 % of the copper in power cable can be saved when operating a power cable with DC and same efficiency as with 3-phase AC.
- The transfer of solar DC power via a DC/DC MPP converter in local DC loads saves 5 % of solar power compared to a solar system connected to a 3-phase AC grid.

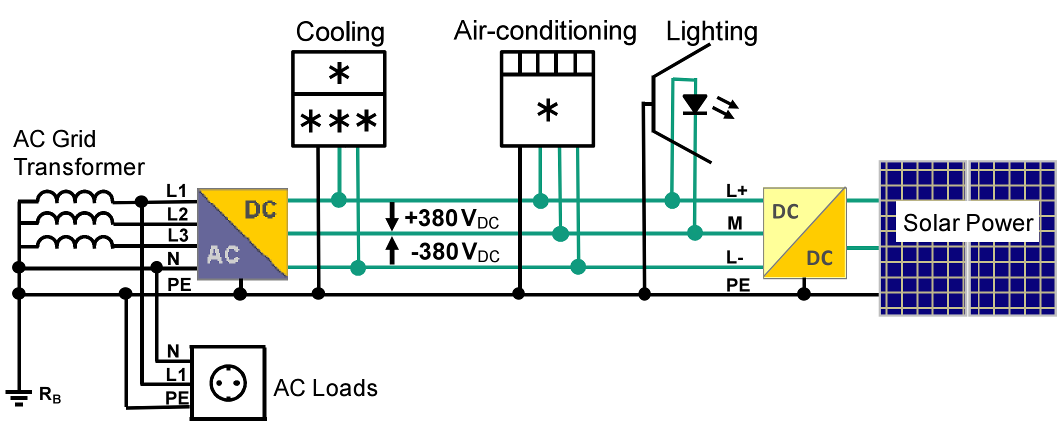

Figure 1: DC power grid architecture and applications

2 Rectifier

AC/DC rectifiers and power factor correction circuits are part of billions of electrical applications today. The efficiency of such circuits drops with the rated power of applications. The efficiency of this circuit part in electronic lamp drivers with power levels of up to 50 W is in the order of 95 % [4].

On the other side starting at 300 W rectifiers and power factor correction circuits without mains isolation can reach efficiencies of 98 % [5]. Also solar inverters can be taken as an example for that [6] since its hardware can also work as rectifier.

As result the partners of the DCC+G project expect an efficiency improvement of 3 % by changing from low power application integrated rectifiers with power levels below 50 W to central rectifiers with a power level of 300 W and above.

3 Power Cables

The energy efficiency advantage of DC electricity distribution in power cables is illustrated with two examples considering AC loads without and with reactive currents.

3.1 Power Cables with Resistive Load

Figure 2 depicts power loss in a 400 V 3-phase AC power cable that supplies three load groups with together 6600 W real power (cos phi = 1). A conductor current of 10 A generates at the considered conductor resistance of 1 Ohm[1] a voltage drop of 10 V and 300 W loss in the cable equivalent to 4.3 % of the power that is feed in the cable. There is no current in the AC neutral conductor N since the three AC phase currents with equal amplitude and a phase displacement of 120° add up to zero.

Figure 3 illustrates for comparison the same power transfer in now two DC load groups. This example considers the same total cable conductor cross section as in the AC cable. The considered conductor cross section in the DC case is 25 % larger since there is one conductor less. That reduces the conductor resistance by 20 % to 0.8 Ohm. Two DC phase currents of 8.85 A are required to supply the two load groups with 6600 W. These two phase currents generate power loss of 125 W in the cable that is 1.9 % of the cable input power. Thus the cable power losses are 58 % lower in the DC case as in the AC case.

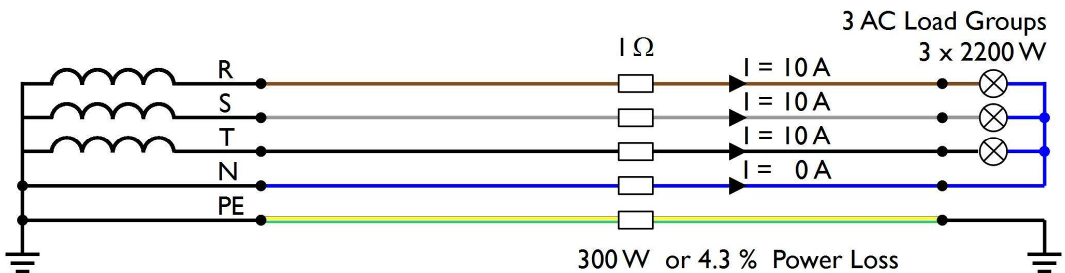

Figure 2: AC power cable loss example supplying a 3-phase resistive AC load of 6600 W

[1] A 135 m conductor with 2.5 mm² copper cross section has a resistance of 1 Ohm.

On system level DC power cable can save about 2 % of a system rated power compared with a highly loaded AC cable. This is due to a higher RMS voltage in the DC grid on a level slightly above the amplitude of the maximum AC mains voltage.

Alternative one can dimension a 2-phase DC power cable such that it has the same cable loss of 300 W as in the AC case. In that case the conductor resistance could increase from 0.8 Ohm to 1.8 Ohm. That is a cost and sustainability feature due to a reduced conductor cross section of 56 %.

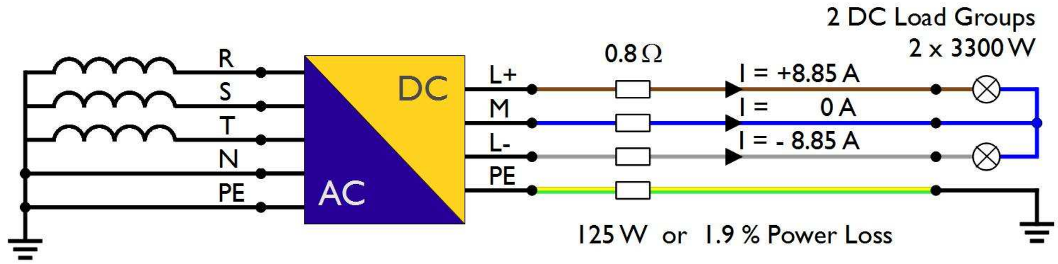

Figure 3: DC power cable loss example supplying a 2-phase DC load of 6600 W

3.2 Power Cables with Non-linear Load

In a second example a power cable is loaded in an AC grid case with additional reactive current that is not present in a DC grid case. Figure 4 shows an AC mains powered variable speed drive unit including rectifier, inverter and motor. An inverter input power of 6534 W is considered as well as a B6-type diode bridge rectifier front-end to supply the inverter from AC mains. This rectifier front-end is considered to operate with an efficiency of 99 %. These losses occur in the rectifier diodes and an EMC filter. The rectifier AC mains input current has a rectangular wave-shape with 67% duty cycle per halve-wave. This results in a cos phi = 0.95 that increases the cable current stress by 5 % [7]. As a result the AC cable losses are with 331 W about 10 % higher than in the previous chapter with pure resistive load.

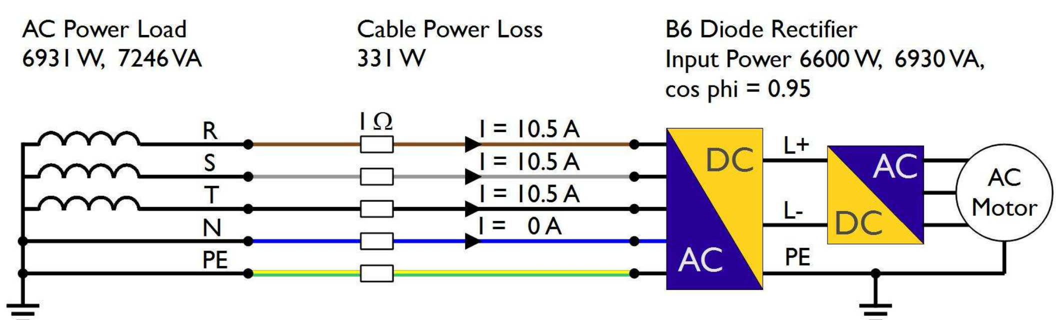

Figure 4: AC power cable loss example supplying a 3-phase rectifier of a drive system with 6600 W_{AC}, 6900 VA, cos phi = 0.95

Figure 5 depicts the supply of the same inverter & motor unit from the proposed DC grid and central rectifier using a DC power cable. The inverter input power of 6534 W is the same as in the AC grid case in Figure 4. This power is provided by a ±380 V DC grid with two phase currents of 8.76 A. The resistance of a DC cable conductor is again 20 % lower as in the AC cable due to the saving of one conductor in a DC cable as discussed in the previous chapter. This results in only 123 W DC cable loss. The DC cable is powered by a central rectifier with a different circuit topology as for the rectifier in Figure 4. The central rectifier in Figure 5 is considered to be a rectifier with IGBT semiconductors operating with pulse-width-modulation (PWM), sinusoidal AC input current, cos phi = 1 and an average efficiency of 98 % as discussed in Chapter 2. This results in slightly higher loss in a rectifier of 136 W. However, on system level the input real power of the central rectifier is still 138 W or 2.0 % lower due to the significant lower cable loss as in the AC grid case in Figure 4. Additionally the AC input current of the central rectifier is even 6 % lower as in the AC grid case because of lower mains current harmonics compared with a B6-type diode bridge rectifier.

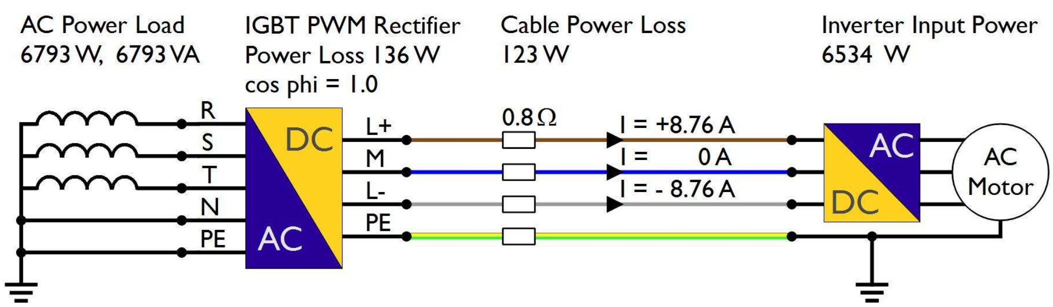

Figure 5: DC power cable loss example supplying a drive system with 6534 W_{DC} including central rectifier loss

4 Solar Power Systems

A key motivation for DC power grids is the transfer of electricity from DC power sources into DC operated applications. Figure 6 depicts the situation today if one transfers solar DC power via a 3-phase AC grid in DC operated loads. This will result in about 9 % power loss of the locally generated solar electricity.

- A very efficient solar inverter generates 2 % loss [6],
- The electricity distribution in a 3-phase AC grid is considered to generate 2 % loss. That considers a shorter power cable with about half the conductor resistance as in the examples of Chapter 3.
- The rectifiers and power factor correction circuits inside applications are considered to generate 5 % power loss [4].

Figure 7 illustrates the electricity distribution by means of the proposed DC power grid. It is the target to transfer electricity from solar modules into DC operated loads by generating only 4 % power loss.

- A solar maximum power point tracking (MPPT) DC/DC converter with galvanic isolation is considered to generate 3 % power loss. Future DC/DC converters without galvanic isolation for solar MPPT applications are expected to generate even only 1 % power loss [8].
- The electricity distribution in a DC power grid is considered to generate 1 % power loss that is the half of the AC case as discussed in the chapter above.

- Power losses in an application integrated rectifier are no longer generated by the electricity that is provided by a DC power source.

In that way 5 % more solar power is transferred in applications and hereby the cost of solar power is reduced by the same amount. This DC solar electricity value advantage is illustrated with Figure 8 in comparison with the value of AC solar power and AC power utility rates for commercial customers in Germany.

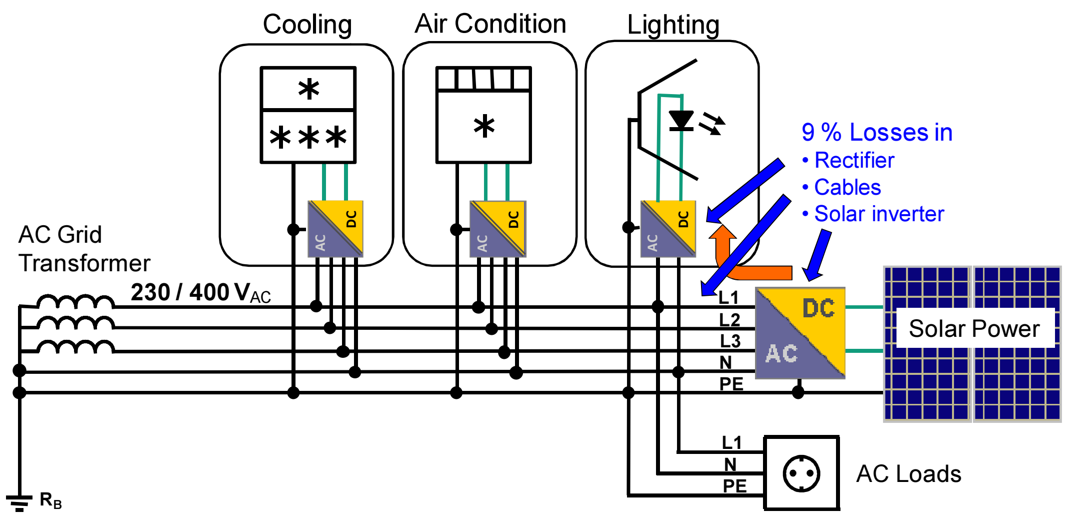

Figure 6: Illustration of 9 % solar power loss in solar inverters, AC power cables and rectifiers of applications

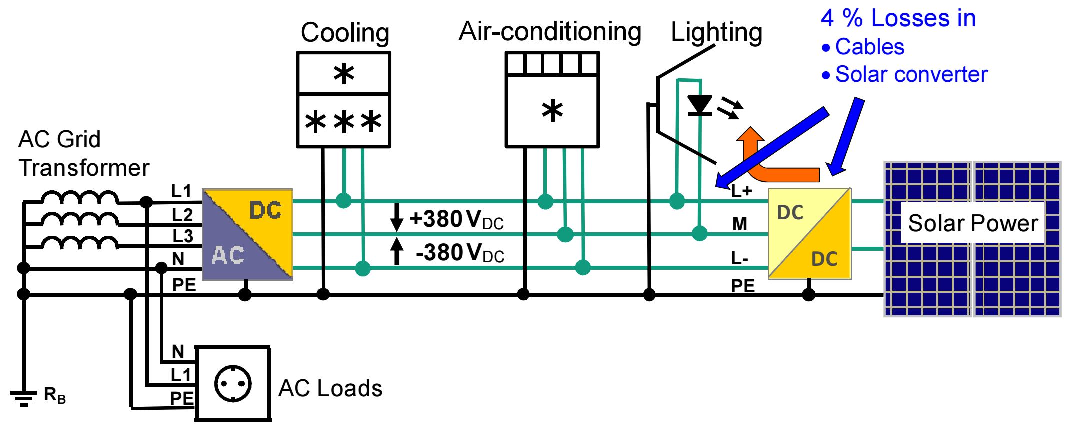

Figure 7: Illustration of 4 % solar power loss in a DC/DC solar power MPP converter and DC power cables

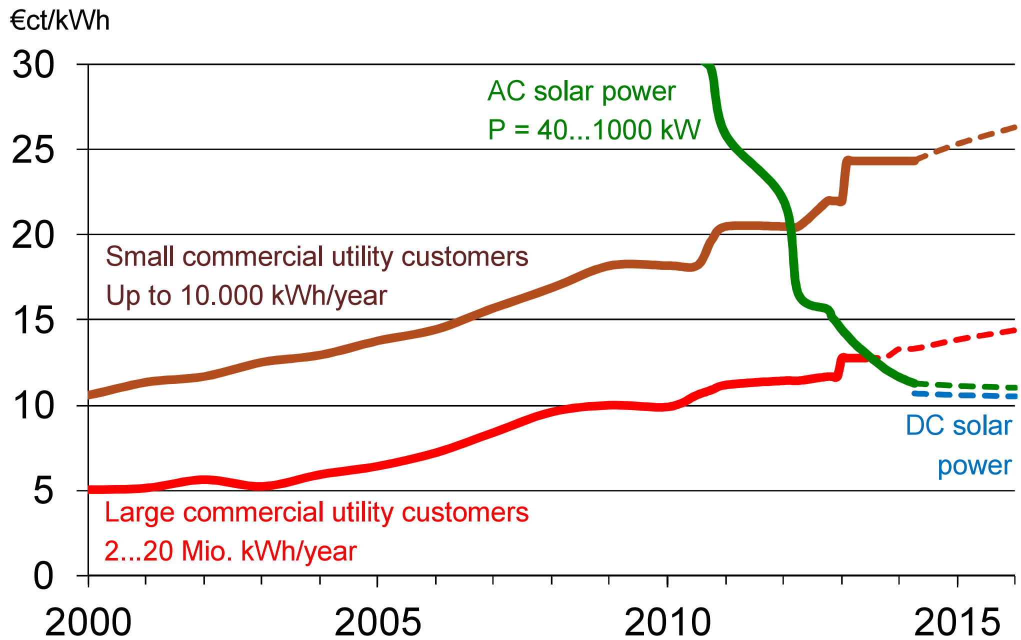

Figure 8: Trend of utility electricity rates for commercial customers in Germany (brown, red) in comparison with the artificial value of AC solar power according to the EEG law in Germany (green, plant size 40 kW...1 MW) and the target value of DC solar power (blue)
Brown: RWE utility rates for small commercial customers
Red: rates for large utility customers in Germany according to DESTAIS [9]

5 Micro CHP Systems

Similar to Solar Systems, Micro CHP systems produce heat and electricity in buildings, more effectively when they are connected to a DC power grid and DC operated applications. 6 % energy saving is expected on system level when Micro CHP units are connected to a DC grid. Typical electric power levels of Micro CHP units are 3-5 kW.

In AC grids, generated micro CHP power is first converted from DC to AC, then transported to the application via AC and converted again to DC in the application. This results in about 10 % power loss of the Micro CHP generated electricity:

- A very efficient micro CHP inverter (DC/AC) generates around 3 % loss,
- The electricity distribution in a 3-phase AC grid is considered to generate 2 % loss. That considers a shorter power cable with about half the conductor resistance as in the examples of Chapter 3.
- The rectifiers and power factor correction circuits inside applications are considered to generate 5 % power loss.

It is the target to transfer electricity from the Micro CHP systems into DC operated loads by generating only 4% power loss.

- The DC/DC converter is considered to generate 3 % power loss.
- The electricity distribution in a DC power grid is considered to generate 1 % power loss that is the half of the AC case as discussed in the chapter above.
- Power losses in an application integrated rectifier are no longer generated by the electricity that is provided by a DC power source.

Figure 9 depicts the configuration for a Micro CHP system connected to an AC grid, while figure 10 shows the configuration for the DC grid.

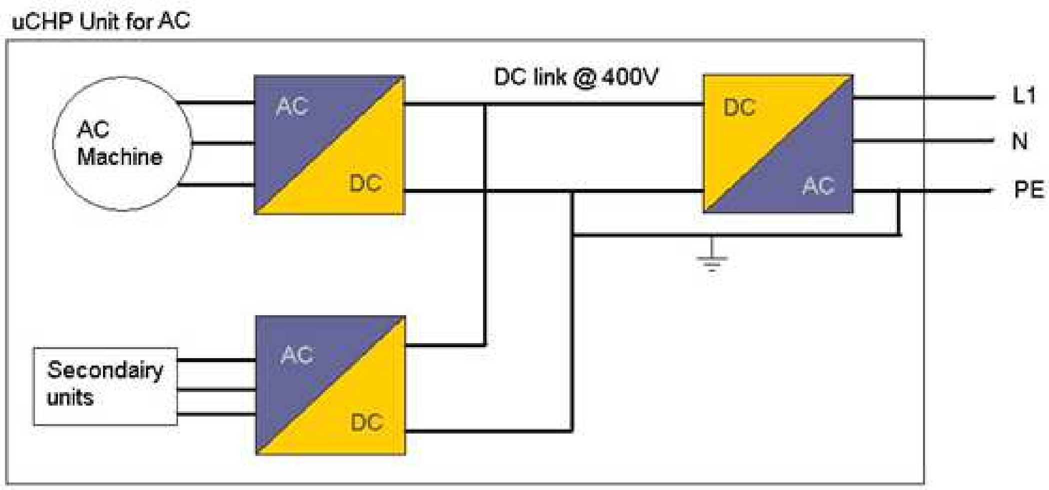

Figure 9: uCHP feeding electricity into an AC Grid

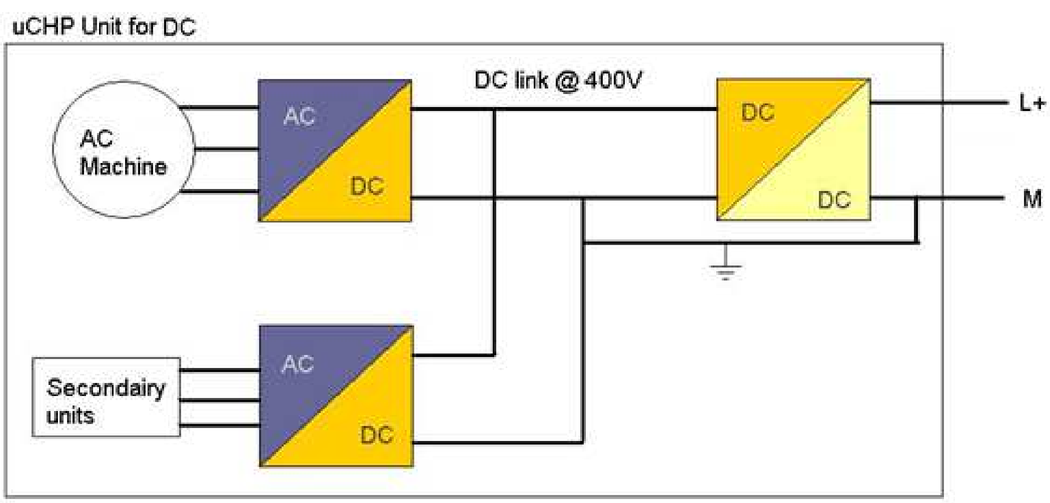

Figure 10: uCHP feeding electricity into a DC Grid

6 Battery Energy Storage

Figures 11 & 12 are comparing best-in-class electricity conversion efficiencies when transferring electricity in electric installations using AC or DC grid into a DC load. Here the case is of special interest to transfer DC solar power first into a battery, e.g. at noon, and to transfer the energy from the battery into a DC load at a different time, e.g. at night, when solar power is not available.

Figure 11 illustrates the case for the use of an AC grid. A solar inverter with 98% efficiency is considered to convert solar power into the AC grid [6]. A battery inverter with a mains frequency isolation transformer is considered that can transfer electricity with an efficiency of 95 % from the AC grid into a 48 V lead acid battery and with the same efficiency back into the AC grid [10]. A 48 V lead acid battery is considered since it is still the most cost effective battery component for stationary applications [11]. During battery discharge the transfer of electric energy through the AC grid, an AC/DC rectifier and power-factor-corrector converter into a DC load is considered with 98 % and 95 % efficiency respectively. The complete electricity transfer from a solar system via battery into a DC load has an efficiency of 82 % excluding the loss in the battery.

Figure 12 illustrates the case for a DC grid connected battery. A DC/DC solar MPP converter with isolation transformer from Emerson Network Power is considered that has an efficiency of 97 % and that feeds the DC power of a solar system in a DC grid. A bidirectional DC/DC converter with high frequency transformer is considered with an efficiency of 95 % to transfer electricity from the DC grid into the battery or back into the DC grid. The reference for this efficiency figure is the unidirectional DC/DC converter in [12] that can operate bidirectional with additional control functions. The same battery is considered as in the AC case above. The transfer of electric energy through the DC grid into a DC load is considered with 99 % efficiency. The complete electricity transfer from a solar system via battery into a DC load has an efficiency of 87 % excluding the loss in the battery.

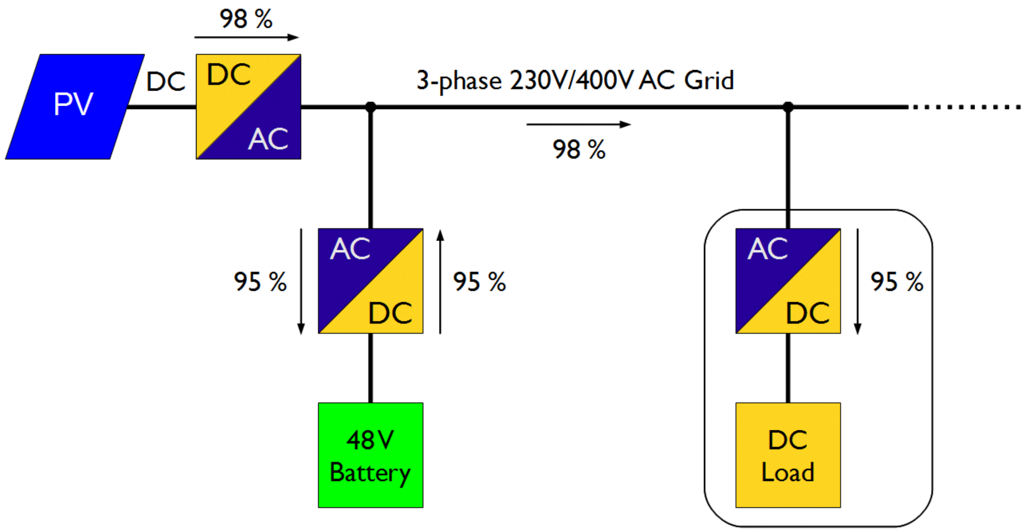

Figure 11: AC Grid connected battery energy storage unit

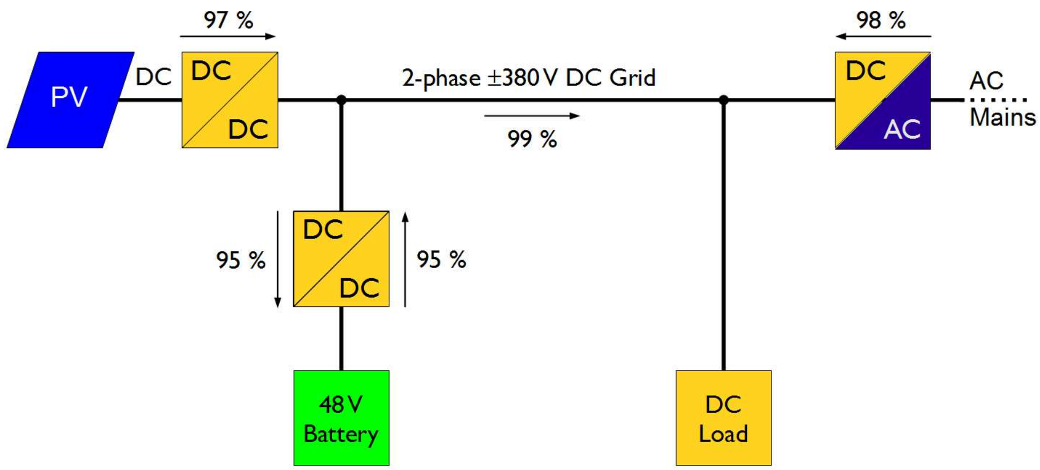

Figure 12: DC Grid connected 48 V battery energy storage unit

To conclude DC power grids have an energy efficiency advantage of 5 % when DC power from a building integrated solar system is stored in a battery module for the later use in a local DC load. This 5 % efficiency advantage is due to the avoided rectifier module in front of the DC load.

In future, higher conversion efficiency of bidirectional DC/DC battery converters can be achieved if battery converters will become available without an isolation transformer. This can result in a further efficiency advantage of DC grids of up to 4 % considering as non-isolated battery converter e.g. the power converter module in [8].

7 Appendix

7.1 Abbreviations

AC	Alternating current
CHP	Combined Heat and Power unit
DC	Direct Current
DCC+G	Direct Current Components +Grid
DESTATIS	Deutsches Statistisches Bundesamt
EEG	„Gesetz für den Vorrang Erneuerbarer Energien“ in Germany, short form „ Erneuerbare-Energien-Gesetz“
ENIAC	European Nanoelectronics Initiative Advisory Council
IGBT	Insulated Gate Bipolar Transostor
M	Mid point of a 2-phase DC grid
MPP	Maximum power point (of a solar cell or solar module)
RWE	Rheinisch Westfaelische Elektrizitaetzwerke AG
N	Neutral conductor of a 3-phase AC grid
V	Volt
W	Watt
kW	Kilo Watt (1000 W)

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