Sustainable Impact and Standardization of a DC Micro Grid

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Abstract

Electric power consumption is on the rise. Electrification of transportation, houses, offices and more continues worldwide. These loads and sustainable sources have one thing in common: Direct Current. To successfully respond to this growing usage of direct current (DC) systems it is important to provoke an evolution in the provision of DC infrastructure. At present, there are doubts about the safety, efficiency, reliability and economical aspects of DC grids. Even when considering the implementation of a DC grid there is still confusion on parameters such as used voltages, converters or plugs.

In this paper, optimal parameters are defined for a DC Micro Grid design, mainly focusing on student and domestic environments. But also office spaces, industrial and agricultural environments can use the same basic parameters. The proposed parameters are evaluated on their sustainable impact and benefit. This paper proposes a 350 VDC micro grid, based on its energy efficiency, savings of raw materials and an improved reliability. Connecting electronics consuming less than 100 W is possible by the development of a smart plug close to the consumer. This plug, based on USB Power Delivery, is able to apply a variable voltage determined by the device, communicate with other connected devices and act as a smart breaker at the load.

These proposed parameters are a guide for future work and standardization of concepts for DC grids. The guidelines can be used in future DC initiatives in order to guarantee safety and efficiency.

Keywords:

Micro grid, direct current, sustainability, standardization, USB Power Delivery

1 INTRODUCTION

The constantly growing demand for electricity causes more and more problems in the old transmission and distribution grid in Belgium, the Netherlands and other densely populated areas. When we consider the trend to go all-electric in households, with heat pumps and electrical vehicles as major consumers we will have to correctly respond to this problem. At the same time we also see a trend towards more and better DC loads and sources. At this point the implementation of these DC systems in the existing grid will involve a lot of unnecessary conversions between AC and DC.

Currently DC is mainly used to transport energy over long distances between different regions, like the 500km cable connecting the Netherlands and Norway. But there is much more potential.

Considering the entire grid, one can see that DC power is already present as high voltage DC (HVDC) in the transmission grid.

Moreover, low voltage DC (LVDC) will become more important in the future [1], [2]. In student- or household residences, one can also see the evolution towards an increasing DC usage; e.g. computers, or lighting. On the other hand, renewable energy sources like solar panels produce DC voltages. In current situations those infrastructures need inefficient AC/DC converters.

As local governments aim to create more energy-efficient and sustainable areas, efforts are necessary to consume electricity as efficient as possible. The energy consumption of student residences for example is responsible for 29% of the CO_2 equivalent ($CO_{2,e}$) emission from the University of Leuven in Belgium [3]. From those 55 755 ton $CO_{2,e}$ electricity is responsible for 7160 $CO_{2,e}$ (12% of the energy part or 4% of the total amount). It is expected that the consumption of electricity will increase more and more in the future and the need for heat produced by fossil fuels will decrease caused by better infrastructure or a transfer to electrical heating. Reports assume a growth in electrical consumption with a value between 0.1 to 2.2 % p.a. [4]. For all scenarios the residential growth is expected to increase the most due to a growth of households and electrifications of our daily life. This causes the need of developing an efficient electrical grid to have a higher sustainable impact.

To start, this paper will describe the requirements needed for a successful residential DC grid. Subsequently, all arguments for the use of a DC micro grid and an appropriate DC voltage level are explained more in detail. These arguments are split into sustainable aspects and arguments based on regulation. The last part provides a solution to connect the broad range of domestic devices onto the proposed standardized voltage.

2 DC MICRO GRID

A DC micro grid is an electric DC grid in a house with a power consumption of less than 5000 kWh a year. This value represents an average consumption of a household in the Benelux over the course of a year. This consumption is expected to rise significantly in the future with the introduction of heat pumps and/or electric vehicles (EV) in households. The grids discussed in this paper are all DC micro grids.

It must be stated that a DC micro grid for households will start working at its full potential if it is connected to a DC midi grid. This midi grid can be seen as an electrical distribution grid for a residential district with an average of 50 households.

2.1 Sustainable indicators

Prior to implementing DC micro grids in domestic housing, a thorough evaluation of their safety, efficiency, reliability and economy is mandatory. On all of these requirements, DC micro grids have to level or surpass the performance of traditional AC grids. Those requirements should lead to a sustainable electric network, able to cope with the high demands.

Safety and regulation

A major concern for DC networks is safety at high voltage. They can potentially create arcs and interrupting a DC circuit requires extra attention. These phenomena occur due to the absence of natural zero crossings of the current. Although, those problems only appear when a DC grid is secured in a similar way as an AC grid, i.e. using mechanical fuses to interrupt shorts.

Currently no regulation is describing the safety criteria for DC grids; the proposed solutions should at least level and preferably surpass the available rules for AC networks. The fuse dedicated for DC circuits should detect improper or abnormal switching behavior in the circuit. The fuse should also be able to switch off the circuit significantly faster without interrupting the whole network [5]-[7]. This allows a safe interruption of the circuit and reduces the risk of arc creation significantly.

Efficiency

During the past years we notice a shift from using fossil fuels for big energy consumers to a more electrified energy usage. As a response to this trend it is important to think about more efficient ways to use and transport this growing demand of electricity.

Another way to think about efficiency and durability is to reduce the use of raw materials that become scarcer and more energy consuming to mine.

Reliable

The increasing demand of energy and the different decentralized (renewable) energy sources cause different problems involving instability in the transmission and distribution grid [8]. With the use of DC grids it becomes much easier to connect different grids with each other both on district and country level.

The total grid should be simplified by omitting unreliable electronic components. This advances the reliability due to a reduced downtime and/or an extended lifespan. In most cases this will also improve the efficiency of the grid.

Economy

It is not evident to guarantee an economically feasible model while technology is still under constant and rapid development. A DC micro grid should be able to compete with an AC grid without any financial support. The integration of different functionalities - like transmitting power, communication and security control - into a DC micro grid should create an economically viable product.

2.2 Standardization of supply voltage

The current interest in DC grids by several groups leads to a fractured approach. This results in a broad range of different voltages and performance standards across adjacent application spaces [9].

This paper aims to a DC voltage and performance standards that fit a very broad field of applications. Different studies propose networks based on a supply voltage varying between 12 and 380 VDC [10]-[16]. To obtain a breakthrough in the development of DC grids, standardization is necessary. A standardized supply voltage for DC micro grids should be compatible with the requirements formulated in section 2.1.

The required voltage should also be extendable to larger grid scales like local district networks or industrial areas. This is important for the wide acceptance and development of the standard.

3 ARGUMENTS TOWARDS DC

This paragraph shows the opportunities of working with a DC micro grid and the resulting improvements in the field of sustainability. The arguments are based on derivations of physical properties and experiments stated in literature. All calculations are made for different DC voltages and compared with the standard AC voltage. Combined experiments and simulations are planned for the near future.

The following assumptions are made for all calculations:

- A current density of 6 A/mm^2, based on the allowed insulation value of an electric wire according the regulations described in IEC 60364.
- Only the ohmic resistances are considered for AC and DC grids. This implies that for all AC cases the real value will be worse than given here.

3.1 Grid properties

Following arguments will give the sustainable significance of a DC micro grid.

Circuit interruption DC micro grid

Interrupting a current is more difficult in a DC grid than in an AC grid. When switching a DC current, an arc can appear and can cause damage to the internal parts of the switch. Therefore special care should be taken when designing switches for a DC grid.

A well-designed protection system is necessary to ensure a reliably operating low-voltage DC micro grid. The protection system consists of current interrupting devices, relays, measurement equipment, and grounding [17].

By using power-electronic switches, such as thyristors, the operation speed decreases and the inductive current interruption capability can be increased. However, the related energy losses of a power-electronic solution are much higher when compared to a mechanical switch. Therefore, a combination of a mechanical switch and a power-electronic switch is recommended [18].

Experiments are performed to compare AC and DC short circuits [19]. The test included a standard 16A ‘C class’ breaker, a fast acting 6A 1kVDC fuse and a 16A electronic fuse. The electronic fuse is developed by Direct Current BV. For these 3 breakers the short circuit was alternately applied on the beginning and the end of a 100 m cable. This cable connected a 400 VAC or 700 VDC power source to a load (a lamp) of 1000W. The results of these experiments are listed in Table 1.

Table 1: Comparison of the reaction time of a 16A ‘C class’ breaker, a fast acting 6A 1kVDC fuse and a 16A electronic fuse during a 400 VAC or 700VDC short test at the beginning and at the end of a 100 m cable.

Voltage	**Fuse type**	**Location of short**	**Reaction time fuse**
400 VAC	16 A ‘C class’	begin	< 100 ms
		end	< 100 ms
700 VDC	fast acting 6A 1kVDC fuse	begin	25 µs
		end	3 ms
700 VDC	16 A electronic fuse	begin	200 ns
		end	800 ns

The last column indicates the time when the fuse blows or the smart electronic fuse shuts down. As can be seen in Table 1, the safe shutdown times for the 700 VDC circuit are all well below the norm of 100 ms. When using the 16 A electronic fuse there was even no arc creation noticeable.

Copper conductor savings

Compared to AC, wires in a DC circuit can handle higher power for the same cross section. There are several reasons for this. Firstly AC wires are dimensioned to handle a peak voltage which is square root of 2 higher than the RMS voltage.

Table 2: Comparison of distributed power, Cu efficiency and cable length in function of different supply voltage. Safety criteria considered is 1% voltage drop [19].

Supply voltage (V)	**Power (W/mm^2)**	**Cu (mg/W)**	**Cable length (m)**
24 VDC	144	124.4	1.2
48 VDC	288	62.2	2.4
180 VDC	1080	16.6	9.0
350 VDC	2100	8.6	17.5
700 VDC	4200	4.3	35.0
230 VAC	**1380**	**13**	**11.5**

Table 2 shows the amount of power distributed per mm^2 of cross section in comparison with the supply voltage assuming an equal current density. It can be seen that the higher the supply voltage the more power is transferred per mm^2. This gives a more efficient use of the installation. This effect can be expressed more significantly by the mass of copper per Watt, at 6 A in a cable with a length of 1 meter and a cross section of 1 mm^2. The total volume of this cable is 1 cm^3. With the density of copper being 8960 mg/cm^3, a power of 350 VDC and a current density of 6 A/mm^2; one can calculate that 4.3 mg Cu is used per watt. For 2 wires this becomes 8.6 Cu/W.

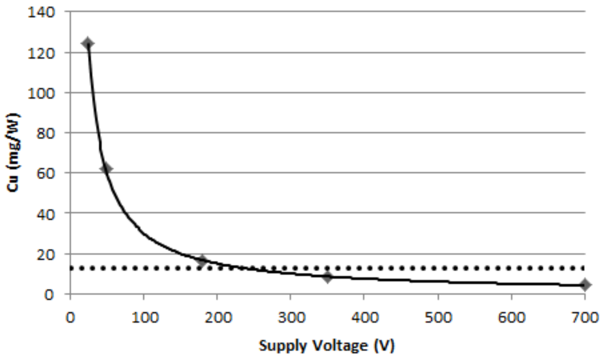

Fig. 1: Plot of the supply voltage versus the Cu material needed for each watt. The dashed line represents the mg Cu needed per watt for a 230 VAC system.

In Table 2 the calculation is done for different DC voltages and compared with a 230 VAC equivalent. Fig. 1 plots the different supply voltages versus the copper mass used per W/m. The dashed line shows the value for a 230 VAC equivalent network. An installation working on 350 VDC makes 33% more efficient use of the copper mass compared to a 230 VAC system. A direct result of copper savings is not only a saving of raw material but also cost-effective. One should also take into account that an AC cable is designed to handle the peak voltage value and not the RMS value. Hereby the real saving of Cu can be multiplied with the square root of 2.

Extension of lifespan

Both in the DC-world as in the AC-world there is still need for conversion steps, but the electronics are much simpler for DC compared to those needed for AC. It is possible to make these electronics without electrolytes that have a low lifespan [20], [21]. This causes the lifespan of loads to become much longer.

Although long life experiments hasn’t been performed so far, due to the absence of DC grids.

Conversion losses

DC circuits results in greater end-use energy efficiency and reliability when combined with energy storage or distributed generation (DG) systems, such as solar panels. Hereby the inverter stage can be eliminated. The inverter stage is relatively more energy inefficient compared to other components, as shown in Fig. 2 [22]. Eliminating the inverter of the PV system can also yield up to 25 % reduction in the capital cost. Research also demonstrates that a 3% energy efficiency improvement is possible with DC distribution integrated with a DG source such as fuel cells; otherwise DC distribution imposes a 2% energy efficiency penalty [14].

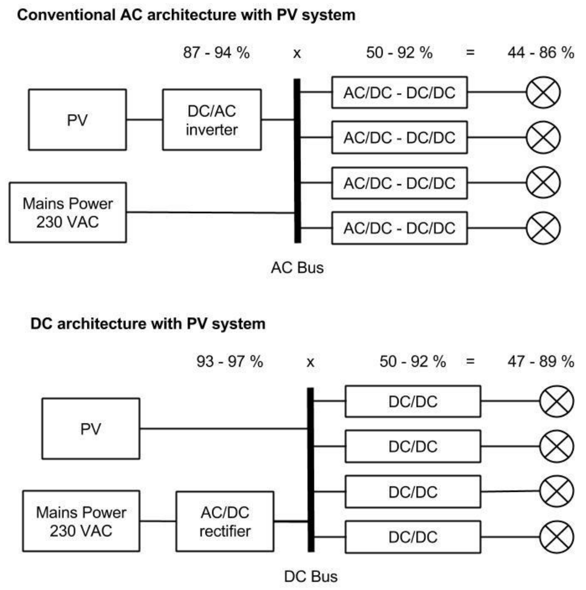

Fig. 2: AC vs. DC building distribution with distributed generation

One should notice that there is currently a big evolution in the efficiency of converters and rectifiers. Those improvements are noticeable in high-end industrial applications and less explicit at consumer level applications, such as computer power supplies. The numbers used in the example of Fig. 2 are indicators, not fixed values. As can be seen in Fig. 2, it is also a good option to connect a DC micro grid with a DC mini- or midi-grid. In this case an extra 3% or 6 % efficiency gain can be obtained compared to the DC architecture or the AC architecture respectively.

3.2 Towards a standardized DC voltage

The following arguments will be used to select a supply voltage for a DC micro grid. This voltage will be proposed as a standard.

Voltage drop in copper wires

Due to the resistance of copper, power density versus wire length is an important parameter to investigate. During a constant power demand of the load, a voltage drop results in an increase of the current. In an electrical installation a voltage drop of 1% over the length of a cable is acceptable. A drop higher than 1% can lead to current values that exceed the maximum current insulation value of the insulation material of the wire. This can result in potential safety risks such as overheating of the wire.

Low voltages (24-48V DC) are used in caravans and boats because the limited grid size and the low power demand. In houses a cable length of 15 m/mm² and a power demand of 2000 W are common.

The voltage drop for a 350 VDC 2 wire system can be calculated as follows. The resistivity of copper is $1.687 \cdot 10^{-8}$ $\Omega \cdot$m. With a current of 6 A/mm² this gives a voltage drop of 0.1 V/m or in a two wire system of 0.2 V/m. 1% voltage drop equals 3.5 V for the 350 VDC system, with a voltage drop of 0.2 V/m. This equals an acceptable distribution distance of 17.5 m/mm². Table 2 gives the acceptable cable lengths per mm² for different supply voltages, the comparison is also made with a classic AC system. The given numbers have to be multiplied by the cross section of the used wire to get the total length. It’s clear that a higher voltage allows a bigger electrical network.

Regulations

The regulations set by the IEC affects the decision for an optimal DC voltage in residential areas.

The most important criterium is the line of demarcation between low and high voltage which is set to 1500 VDC (IEC 60038). This means that selecting a voltage which is scalable towards 1500 VDC is a good choice. It is recommended to take an overshoot of the voltage into account. A 350 VDC is four times scalable towards 1500 VDC with a margin of 100 VDC while a 380 VDC grid exceeds this value after 4 steps. Currently, 380 VDC is proposed as voltage level by other consortia [6].

Secondly, the maximum allowed bus voltage in a variable frequency drive is 700 VDC.

3.3 ± 350 VDC standard voltage

With these limitations in mind it is obvious that the maximum used voltage can only be 700 VDC, which is probably a good choice in industrial grids but not suitable for residential applications. Thus, a 3 wire system of 700 VDC in extension of a 2 wire system of 350 VDC is a logical option. This 3 wire system will exist out of a +350 VDC, - 350 VDC and 0 V wires [23].

Selecting ± 350 VDC in a micro grid gives the following benefits:

- This voltage level gives an appropriate power density and an optimal usage of copper.
- Safe and efficient voltage for domestic devices using the +350 VDC line.
- High power connections possible by using a ± 350 VDC line for dedicated purposes like charging EVs.
- Easily scalable with an efficient DC mini or midi grid on ± 700 VDC with respect to the regulation for low voltage circuits.

4 CONNECTING DEVICES ONTO A ± 350 VDC GRID

This part of the paper discusses the possibilities for connecting residential appliances to a DC micro grid. In this paper domestic appliances are divided into 2 categories. The first category contains stationary domestic tools that consume more than 100 W, like a fridge, dishwasher or heat pump. The second group contains small electronic devices operating already on DC and consuming limited power; such as a laptop, mobile phone or router. The limit is set to 100 W as will be explained in section 4.2.

4.1 ± 350 VDC connection

The first category will be directly connected to the ± 350 VDC, secured with an electronic active security breaker. This means that connecting and disconnecting is only possible when there is no voltage. Abnormal switching behavior will also be detected and if necessary the circuit will be interrupted without any arcs. At this moment the favorable composition of the grid in a normal house would be that the 3 wire power connection to the grid is applied centrally in the domestic grid. Here the big consumers, like heat pumps and EVs, can be connected to 700 VDC allowing fast DC charging for EVs. The local domestic grid will exist of 2 ring structures, one with 0 and +350 VDC and one with 0 and -350 VDC.

4.2 USB Power Delivery

The second group of appliances gives 2 problems when trying to connect these to a DC micro grid.

1. It is not possible to connect these with a voltage level of 350 VDC.
2. There is already a significant range of low operating voltages.

A smart plug, able to switch from the 350 VDC to a lower and variable DC voltage, is designed as solution to these problems (Fig. 3).

The new USB standard, USB Power Delivery (USB PD), it is able to deliver a maximum of 20 VDC and 5 A, equaling 100 W [24]. The most important property of this USB PD connector is the range of possible voltages and currents. The voltage can vary from the standard 5 VDC to 20 VDC and the current limited to 5 A. The USB PD protocol provides voltage negotiation between plug and load. This allows a diversity of small electronic devices to connect with only one type of plug.

Additionally, other functions like build-in security and data communication can be integrated in this connector. This paper suggests a security communication line via the 350 VDC wire with a power line communication protocol for domotica and security. Transfer of large data blocks will be done over plastic optical fiber leads (POF).

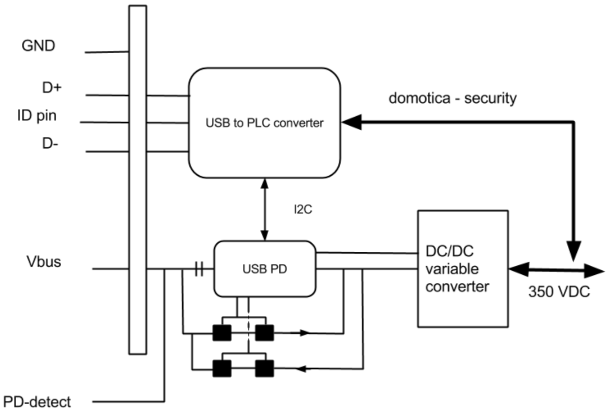

Fig. 3: Scheme of hardware for smart DC plug

This device can be mounted on a 350 VDC wall connector. This guarantees the flexibility of the micro grid by letting the user choose the location of the different plugs. But also the voltage level stays at his optimal value in the entire network, only at the load side the conversion is made.

5 CONCLUSION AND FUTURE WORK

The use of DC grids is proposed as sustainable alternative for AC grids. Different arguments like sustainability and standardization (± 350 VDC) are discussed and conceptual solutions are developed. An important argument for these voltages is the safe shutdown time when using electronic breakers. In addition, a DC voltage of 350 V allows a reduction of copper of at least 30%. The replacement or removal of inverters or rectifiers leads to a rise in efficiency. Also the feasible length of the conductors in the grid is calculated. In addition to these technical arguments, also the limitations as defined by the IEC are given and taken into account.

Furthermore, the paper proposes different ways to connect devices to this grid. In this paper a smart DC plug is described to connect low power devices up to 100 W to the grid. This connector is based on the USB PD protocol and has a voltage range of 5 to 20 VDC.

Future work is needed in the form of demonstrators showing the functionalities and assumed benefits of DC grids and DC connectors as the smart USB PD connector. Also, this paper gives arguments based on literature. In a next stadium, comparisons between AC and DC student residences will be made based on simulations and experimental data.

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