Comparison of low voltage AC and DC power grids

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Abstract

DC power grids offer efficient electricity distribution with less conductor material compared with AC grids. Hence DC grids offer both cost reduction and sustainability features. Properties of low voltage AC and DC power grids are compared in this paper. 380 V DC grids can transfer the same power level at equal cable loss with 63 % less cable cross section than 230 V AC grids. 2-phase DC grids operating with ± 380 V DC can transfer the same power at lower cable loss even with 71% less conductor cross section than 230 V 1-phase AC grids. Details are offered as input for the discussion of future DC power grid architectures and standards.

1. Introduction

It is a trend of the last two decades to increase energy efficiency of buildings by using electrical applications with more and more power electronic modules to control the energy usage more precisely. That trend in combination with the high amount of building constructions worldwide increase the demand of classical AC power cables that contributed already to an increase of the copper price. But it also motivates the question if electricity can be transferred with lower investments into cable conductor materials. Power electronics to control drives of heating, ventilation, air-con (HVAC), lighting and photovoltaic power systems all operate internally with DC supply voltages. It is already know from High Voltage Direct Current (HVDC) grids that DC power grids can transfer power with less conductor effort [1]. That motivates the question if DC power grids might be a general alternative to AC power grids for the distribution of electricity in buildings. This paper adds arguments by comparing properties of low voltage AC and DC power grids to distribute electricity in commercial buildings. Target applications of future DC power grids in energy efficient buildings are electricity generation by means of photovoltaic power systems as well as fixed installed electric appliances like adjustable speed drivers in HVAC, freezer compressors, lighting and more [2]. Details are offered as input for the discussion of future DC power grid architectures and standards [3]. Standardization of DC grids will become key to combine products from several manufacturers as known from AC power grids.

2. Single-Phase Power Grids

The first comparison considers electrical applications with internal 380 V DC operating voltages that are supplied from 230 V single-phase AC grids. The coupling module between the AC grid and the internal DC supply voltage is a rectifier with power factor correction (PFC) circuit. Classically that coupling module is part of computer power supplies, lamp drivers and other appliances. Electricity is supplied over an AC power cable to these applications.
Alternatively, rectifier modules can be located at the public grid access of buildings and electricity can be transferred locally by 380 V DC grids. Figure 1 compares different real currents in 230 V AC and 380 V DC grids for a load of 230 W. The DC grid is loaded only with 60 % of the current due to the higher RMS voltage. That can be used to reduce conductor cross section by 63 % or one can transfer 65% more power with original cables. The difference is even larger when the AC grid is loaded with reactive currents and a power factor lower than one.
The comparison in Table 1 considers different cable configurations and equal power loss per cable for both AC and DC grids. A further alternative for 1-phase DC grids is also a reduction of the number of cables from 5 to 3 with conductor resistances of 0.5 Ω. That offers a mix of reduced conductor cross section and reduced voltage drop.

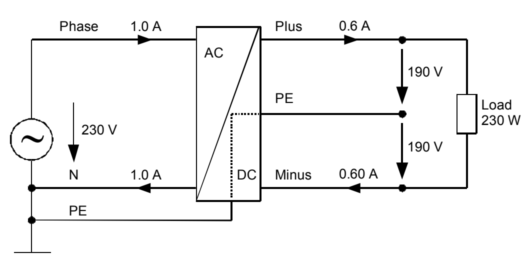

Figure 1: Real currents in a 230 V AC and a 380 V DC grids load with 230 W

3. Multi-Phase Power Grids

Symmetrical loaded 3-phase AC grids are a standard technique to increase the rated power of electricity distribution cables and to reduce hereby infrastructure and especially cable cost. This is achieved by compensating the current in the neutral conductor and by saving copper of neutral and protected earth conductors in contrast to multiple single-phase cables. That feature can be also used with 1-phase AC loads that have to be arranged in three groups each connected to a different AC phase. An example is illustrated with Figure 2.

A first example considers a 3-phase AC supplied application equipped with an internal rectifier module operating with a load of 690W. Electricity is transferred with a 5-wire 3-phase AC cable where each phase is loaded with a real current of 1 A. For simplicity a conductor resistance of 1 Ohm is considered resulting in 3 W AC cable losses. The current in the neutral conductor is also zero with 3 single-phase loads since 3 AC currents with 120° phase shift and equal amplitudes compensate each other. A current in the neutral conductor is only conducted if loads are not equally shared to all three AC phases.

A second example illustrates now the advantage of a 2-phase DC grid in contrast to a 3-phase AC grid. In that example a rectifier module is no longer integrated in applications but located again at the grid connection of a building. That rectifier is considered to generate a 2-phase DC grid with ± 380 V DC. Loads are either supplied with a line-to-line voltage of 760 V DC such as speed-variable drives of HVAC units. Or loads can be supplied with a single-phase DC voltage of 380 V e.g. power supplies of computer servers or lamp drivers. Again a symmetrical loaded DC grid is considered that requires an equal distribution of single-phase DC loads to both phases. A total DC load of 690 W in two phases generates two phase currents of 0.91A in the conductors of the plus and minus phases. The current in the neutral conductor is again zero considering symmetrical loads in both DC phases.

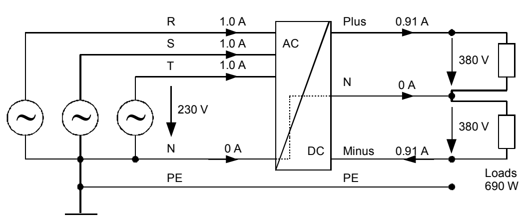

Figure 2: Real currents in a 3-phase 400 V AC and 2-phase 380 V DC grid

To operate with equal cables loss of 3 W as in the 3-phase AC grid the conductor resistance is increased to 1.8 Ohm. Thus 2-phase DC power grids have two advantages compared with 3-phase AC. First, 2-phase DC grid cables require only 4 conductors. One phase conductor or 20 % cable cross section can be saved. Second, the conductor cross section can be reduced by 44 % to increase the conductor resistance by 80 %. Both features result in a total conductor cross section reduction of 56 % for 2-phase DC grids in comparison to 3-phase AC grid cables.

A 5-conductor 3-phase AC cable could be also used for 2-phase DC power grids at an output of a central rectifier as depicted in Figure 3. That configuration is not recommended since it doubles cable power loss. Thus the transfer power of 2-phase DC grids would be even lower than in 3-phase AC grids considering equal conductor resistance and cable loss.

4. Cable Voltage Ratings

The higher power capability of the discussed low voltage DC grids comes to one part from the transition of a sinusoidal voltage to a constant DC voltage and the definition of a DC voltage level slightly above the maximum AC peak amplitude. The AC mains voltage has a practical voltage range of 220 V...240 V ± 10% in Europe. The maximum line-to-earth AC voltage is 264V_{RMS} and 373 V_{Peak}. Line-to-line voltages in 3-phase AC grids are root(3) higher 457 V_{RMS} and 646 V_{Peak}.

Cables for the proposed DC power grids fall in three standard cable voltage ratings.

First, cables for 1-phase DC grids with ± 190V DC nominal voltages with respect to protective earth requires cables with "300V/500 V" voltage rating (line-to-earth / line-to-line).

Second, cables for 1-phase DC grids connected to one phase of 2-phase DC grids with +380 V DC nominal voltage with respect to protective earth requires cables with "450V/750 V" rating.

Third, cables for 2-phase DC grids with ± 380V DC nominal voltages with respect to protective earth require cables with "600V/1kV" rating.

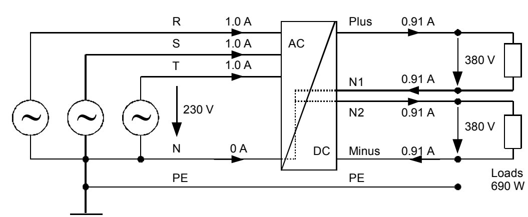

Figure 3: Not recommended architecture of a 2-phase DC grid

5. Comparison

A direct comparison of single and multi-phase AC and DC power grids is offered in Table 1. Reference case example 1 considers a real power transfer of 11.5 kW by using five single-phase AC cables in parallel with in total 15 conductors. Cable losses have been fixed for all examples to 100 W per cable to consider equal thermal stress and temperature rise of all cables that is a typical limitation [4]. A conductor resistance of 0.5 Ω has been selected to illustrate the differences in cable loss and voltage drop within the 5 % limit of IEC 60364-5-52 [4].

Example 2 illustrates the advantage of single-phase DC grids. Due to lower currents the conductor resistance can be increase by 172% to operate with equal cable loss. That results in 63 % less cable cross section to transfer the same power.

Example 3 shows the advantage of 3-phase AC compared with single-phase AC. A similar power level can be transferred with 33 % less total conductor cross section due to the avoidance of currents in neutral conductors and the lower number of protected-earth (PE) conductors that do not contribute to power transfer. Cable loss and voltage drop are reduced from 4.3 % to 1.8 %.

The comparison of examples 3 and 2 illustrates that the 3-phase AC example reduces the amount of conductors by 1/3 as well as cables loss and voltage drop from 4.3% to 1.8 %. But the 3-phase AC case has still a significant larger total conductor cross section due to the considered conductor resistance to limit the loss per cable to 100 W.

Example 4 highlights the advantage of 2-phase DC grids over 3-phase AC. The DC grid transfers with the same number of cables 35% more power at 20 % less total conductor cross section considering equal conductor resistance and loss per cable. Relative cable loss and voltage drop are also further reduced.

Example 5 uses the higher power capability of the 2-phase DC grid to minimize conductor cross sections further under the constraint of equal cable loss and voltage drop like in the 3-phase AC cables. The result is a 56 % smaller conductor cross section as in 3-phase cables! The 2-phase DC grid also requires 22 % less conductor cross section than the 1-phase DC grid cables to transfer the same power at equal cables loss due to the absence of current in the neutral conductor and 60 % less PE conductors.

These examples clearly show that DC power grids have advantages beyond 1-phase DC grids currently discussed for data centers. The authors also propose to extend earthing systems for DC grids beyond *Isole Terre* (IT) earthing discussed for data centers. TN-C and TN-S grids should be considered in the standardization of future DC power grids. Table 2 offers an overview. The option to realize DC grids without mains insulation is important to avoid cost increase since rectifiers of today's drive and lighting systems typically do not have mains insulation.

Examples	1	2	3	4	5
Parameters	5 cables of 1-phase AC	5 cables of 1-phase DC	2 cables of 3-phase AC	2 cables of 2-phase DC	2 cables of 2-phase DC
Voltages	5x 230 V	5x 380 V	2x 3x 230 V	2x 2x 380 V	2x 2x 380 V
Conductor current	10 A	6.05 A	8.16 A	10 A	7.41 A
Real Power	5x 2300 W 11500 W	5x 2299 W 11495 W	2x3x1877W 11261 W	2x2x3800W 15200 W	2x2x2815W 11260 W
Conductor resistance	0.5 Ω	**1.36 Ω**	0.5 Ω	0.5 Ω	***0.91 Ω***
Cables loss & Voltage drop	500 W 4.3 %	500 W 4.3 %	200 W 1.8 %	200 W 1.3 %	200 W 1.8 %
Number of conductors	5x 3 = 15	5x 3 = 15	2x 5 = 10	2x 4 = 8	2x 4 = 8
Relative total conductor cross section	100 %	37 %	67 % *100 %*	53 % *80 %*	29 % *44 %*
Real power per conductor	767 W 100 %	766 W 100 % Thinner conductor	1126 W 147 %	1900 W 248 %	1408 W 184 % Thinner conductor

Table 1: Comparison of different power cable systems transmitting electricity at equal loss of 100 W per cable, AC power with power factor of one

Parameter	DC power grids for data centers	DC power grids for general usage
Nominal supply voltages	±190 V DC	± 190 V DC, + 380 V, - 380 V ± 380 V DC
Application DC voltages	380 V DC	1-phase DC loads: 380 V 2-phase DC loads: ± 380 V
Earthing System	Isole Terre (IT) earthing	IT or TN-C earthing for ± 190 V TN-S earthing for + 380 V, - 380 V, ± 380 V
Mains insulation	Always to achieve IT earthing	Not required, optional
Neutral conductor	No	IT: No TN-C, TN-S: Yes
PE conductor	Yes	Yes

Table 2: Comparison of DC power grid parameters as input for standardization

6. Safety aspects

DC grids require different switches, connectors, plugs, fuses and circuit breakers than AC grids that suppress arcing when disconnecting live DC currents. These components are available for the use in DC grids e.g. in photovoltaic power systems with DC voltage ratings up to 1000 V DC.
On the other side the arcing problem can be reduced by simply avoiding plugs and switches.
A large amount of electrical applications proposed for DC power grids in commercial buildings is generally fixed connected to grids that do not require plugs and connectors. These applications include heating with heat pumps, ventilation, air-conditioning, lighting, photovoltaic power systems and large freezer stations in supermarkets. The all-electric supermarket in [2] is a reference for that using a classical AC grid.
The need of power switches for DC grids is also reduced if electric appliances have control interfaces for the connection to a building management system. Switching of appliances is simply realized by means of controls.
AC switches at rectifier inputs can be used to turn-off DC power grids in the case if maintenance work must be performed. Only physical DC sources such as photovoltaic or batteries still requires DC power switches that are state-of-the-art today. The consideration of the "Five safety rules" is strongly recommended - if not mandatory as in German - to maximize safety when performing construction or maintenance work in AC and DC power grids [5].

7. Conclusion

Both 1-phase 380 V and 2-phase ± 380 V DC power grids offers significant reduction of cable conductor cross sections in comparison to classical 1-phase 230 V and 3-phase 400 V AC power grids. Especially the 2-phase ±380V DC power grid is proposed to extend the advantages of low voltage DC power grids beyond actual discussed 1-phase DC grids of data centers. The proposal also includes the realization of DC power grids with TN-C and TN-S earthing to realize similar benefits already used in AC power grids.

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8. Appendix

8.1 References

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