DC SUPPLY OF LOW-VOLTAGE ELECTRICITY APPLIANCES IN RESIDENTIAL BUILDINGS

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ABSTRACT

This full paper concentrates on the results of technical and economical analyses of DC supply of low-voltage electricity appliances and application of low-voltage DC (LVDC) networks in electrification of real estates. This paper illustrates possible advantage that can be achieved by using DC voltage inside the premises.

The main contribution of this paper relates to the suitability of electricity appliances for low-voltage DC and the influences of LVDC real estate distribution networks on the energy- and cost-efficiency of electricity distribution.

INTRODUCTION

Nowadays, many low-voltage electronic appliances such as computers, televisions and digital set top boxes operate internally at DC voltages and thus have built-in voltage conversion circuits. Losses can be reduced if the number of successive and parallel voltage conversions is decreased by using DC voltage directly in some parts of the internal networks in the customers' premises. The internal voltages of electronic devices are usually quite low such as 12 VDC, 5 VDC and even lower. This is why these voltages are not suitable for distribution inside premises, and therefore some DC conversions are still required. The aim is to implement these conversions more effectively than before through DC/DC conversion.

The use of DC voltages inside the premises is based on the fact that the public low-voltage grid is a bipolar ±750 V DC network. Application of LVDC networks in public distribution networks has already been introduced [1],[2]. The network interface of ordinary household customers is unipolar. Figure 1 illustrates implementation of the network interface.

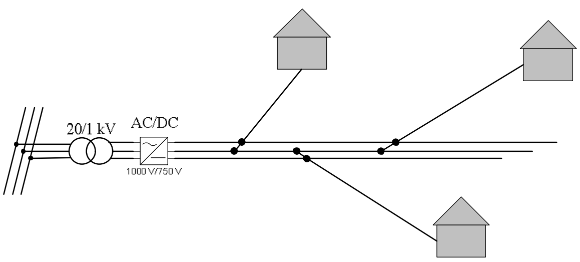

Figure 1. Unipolar interface of a building to the public bipolar LVDC distribution network. The houses are connected between 0 and 750 VDC.

There are different voltage conversions inside the building distribution board. Some appliances can be supplied with DC but there are also ones that require AC supply to work properly. Figure 2 presents a possible alternative of low-voltage supply in the future.

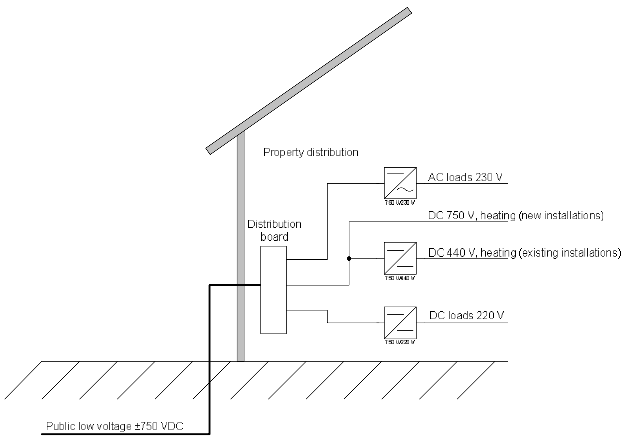

Figure 2. Solution for internal distribution network structure in real estates in the future [3].

As it can be seen in Figure 2, the DC voltage level can also be considerably higher than the level used in LVAC circuits at present. The higher voltage level provides a further opportunity to reduce losses at the customer end.

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SUITABILITY OF APPLIANCES FOR LVDC

There are various electricity appliances in common households, such as heaters, lights, different washing machines, tools and electronic devices. Nowadays, a great majority of these appliances are designed for AC use only [4]. There are exceptions such as lights, televisions and digital set top boxes, which can be used both at AC and DC. The following categories include common appliances, which are used in most households.

Electronic appliances

Electronic appliances use internally DC voltages. Power supplies of these instruments are typically switched-mode power supply units (SMPS), and ordinary transformers have not been used. SMPS works with a wide range of input voltages. Normally, this means 100-240 V/50-60 Hz, which, in practice, means 90-265 V/47-63 Hz and a DC voltage [5]. If a power supply contains an ordinary transformer, it cannot operate at DC at all. Many power supplies, which are designed for AC use only according to the signboard, still work properly with DC.

Lights

In practice, a vast majority of commonly used lights could work with DC voltage. Ordinary incandescent lamps can be modeled as a pure resistance, and hence there is no problem when using DC. On the other hand, these light bulbs are very vulnerable to overvoltages, which shorten their lifetime. Incandescent lamps are dependent on the root mean square of the supply voltage, which means that the DC voltage should be 230 V at highest [5].

Fluorescent lights could be connected to DC voltage with an electronic ballast. In fact, an electronic ballast is a switched-mode power supply, the output voltage is DC and the input voltage can be either AC or DC. Generally, the permitted DC input voltage is up to 300 V, which is slightly higher than the corresponding AC voltage. When using electronic ballasts, fluorescent lights eventually operate with DC regardless of whether the supply voltage is AC or DC.

Heaters

Purely resistive loads such as direct electric heaters work well with DC. Heaters available are still designed for AC supply, and there is no permission for DC use. Problems may arise with switches that are not designed to cut off the DC voltage [2]. If heaters were designed for DC use, it would be beneficial to use a higher voltage level than the present one. An economical voltage level could be 750 VDC, because it is the fundamental voltage of the public LVDC network, and thus no converters would be needed.

The suitability of heat pumps for DC depends on the pump's motor and the motor control circuit types. If the motor is an induction machine, it will not work with DC without an inverter. An induction stove is also a device that requires an inverter when the supply voltage is DC.

Appliances including rotating motors

Electric tools, kitchen appliances and washing machines include rotating motors. Small hand tools, hair dryers, vacuum cleaners, food mixers etc. typically have a universal motor as the power source. The universal motor in these devices is mostly like a DC motor, but it works properly with both AC and DC voltages. Washing and dish machines are usually operated with an induction motor. Induction motors require AC voltage to build up a rotating magnetic field.

As this short survey of household appliances shows, AC voltage is still needed in electrification of households. When the public network is a DC network, the required AC voltages can be produced centralized at every real estate's distribution board or within each appliance requiring AC. A large number of electrical devices could be designed to work with DC. If DC distribution inside real estates becomes common in the future, manufacturers will bring much more DC compatible appliances into markets.

INTERNAL DISTRIBUTION NETWORKS

Figure 3 presents five network topologies compared in this study. The comparison focuses only on internal networks; investments and losses in the public network have not been taken into account except for power electronics, which has a significant influence on the investments and energy efficiency. The problems in this approach are how to define the boundary between the customer and the public DC network and how energy measurement should be arranged.

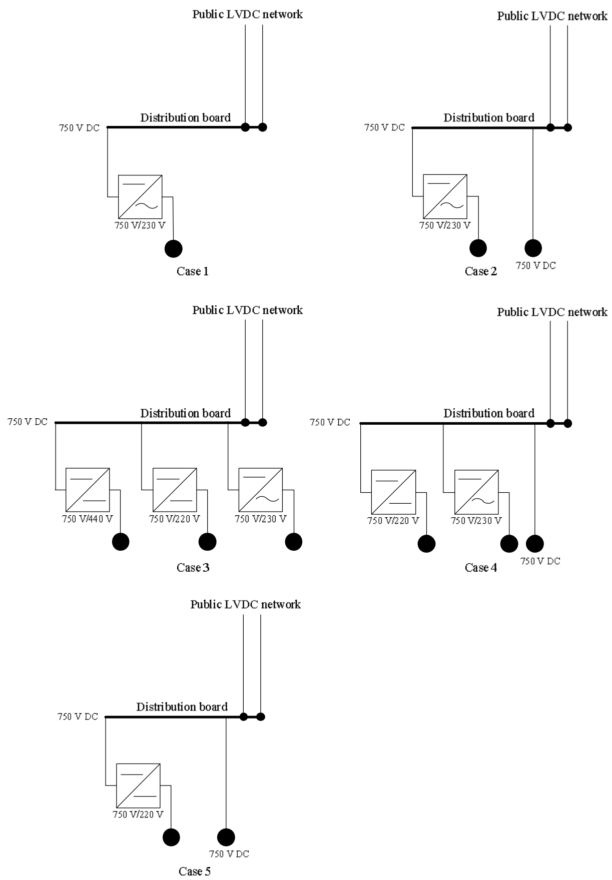

Figure 3. Network topologies which have been analyzed [3].

Case 1 has only one voltage level, 230 VAC.

Case 2 has 750 VDC for heating and 230 VAC for other appliances.

Case 3 has multiple voltage levels. 440 VDC is for heating, and in addition there are both 220 VDC and 230 VAC. Appliances including rotating motors operate with AC voltage and others with DC.

Case 4 is similar to Case 3, but there is 750 VDC instead of 440 VDC.

Case 5 offers two voltage levels, 750 VDC and 220 VDC. Heating is supplied with 750 V and other appliances operate with 220 V. This alternative does not offer AC voltage at all, and thus cannot be introduced here.

Voltage levels and transforms

All the selected DC voltage levels 220 V, 440 V and 750 V are standardized and recommended DC voltage levels. 220 V is chosen because it is the established voltage level in many countries. Using 220 V guarantees electric compatibility with the devices. 750 V is chosen because it is the voltage of the public DC network and does not need any voltage transformations. 440 V is chosen because 500 V is the limit value for low-voltage installation cables with cross-sections up to 2.5 mm^2. When using 750 V, it is assumed that the same cables can be used. Cable investments include only material costs.

The basic structure of the voltage transformer consists of a DC/DC buck converter or an inverter that inverts DC input voltage into AC voltage. Connecting different systems requires galvanic isolation. It is recommended to use non-isolated converters because of their lower price and better efficiency compared with isolated converters. A non-isolated converter between public and customer networks requires an IT system for the internal network, because the public DC network is implemented as an IT system.

Calculation parameters

All parameters are estimations, because real power electronic converters and inverters at this power rate are not widely available. Parameters used in calculations are shown in Table 1. The efficiency of the power electronic devices depends on multiple factors such as power rate, load rate and core volume and material when galvanic isolation is needed.

Table 1. Calculation parameters.

Calculation parameter	Value
Lifetime [a]	40
Discounting coefficient	17.159
Interest rate [%]	5
Converter investment [€/kW]	70
Inverter investment [€/kW]	70
Peak operating time of heating losses [h]	500
Peak operating time of lighting losses [h]	265
Energy spot price [€/kWh]	0.06
Energy customer price [€/kWh]	0.13
Converter efficiency	0.95
Inverter efficiency	0.9
Appliance DC/DC converter efficiency	0.95
Appliance AC/DC converter efficiency	0.85
Cable MMJ 1.5 mm^2 price [€/m]	0.8
Cable MMJ 2.5 mm^2 price [€/m]	1.2
Cable MMJ 1.5 mm^2 resistance [Ω/m]	0.0121
Cable MMJ 2.5 mm^2 resistance [Ω/m]	0.00741

Results

Figure 4 presents the results of the total cost analysis. Costs have been discounted to zero point for 40-year lifetime. Calculations have been made for a detached house, the estimated annual electric energy consumption of which is 20 MWh including 6.5 kW direct electric heating, 3 kW service water heating and 1.8 kW lighting. The household includes a rather typical combination of electrical devices; two desktop computers, one laptop computer, two televisions and peripherals and common present day kitchen and bathroom fittings.

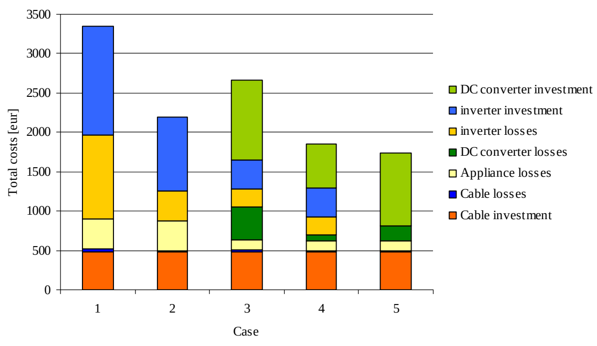

Figure 4. Results of the total cost analysis for 40-year lifetime [3].

It can be seen that the losses and investments of the power electronic devices are in a decisive role when comparing different distribution systems. In fact, both the losses and investments of the converters and the inverters are dependent on the power that has to be supplied through the device. This is why using 750 VDC straight for some application without transformation is a profitable alternative. The efficiencies of the converter and the inverter are not equal; DC/DC transformation can be implemented more efficiently than DC/AC transformation. Because of these factors, the loss components differ from each other between the cases.

When examining case 1 in Figure 4, we can see that total cost is about 3300 €. Case 1 uses only AC inside the building, and thus by comparing the other cases with Case 1 we can determine how much the modifications for DC may cost. Potential necessary modifications are lighting switches and other switches inside appliances, which are not designed to cut off DC. For example in Case 2 modifications of electric heaters should not cost over 1100 €. There are 16 direct electric heaters, a sauna stove and a service water heater in the subject house, and hence the modification should pay 60 € per device at most.

For instance in Case 4 lighting has been implemented with DC voltage. There are 30 lighting switches in the house. It is obvious that special switches for DC are needed. They should not pay over 350 € more than equivalent AC switches. DC-rated switches at 220 V are not yet available for domestic use, but there are comparable ones for industrial purposes. The prices of DC-rated switches are not considerably higher than the prices of AC switches.

LVDC distribution inside customer premises has effects on energy efficiency. Transformation losses are additional losses, and they should not be included in the customer's electricity bill. This is why transformation losses have been valued according to the energy spot price, while cable and appliance losses are valued according to the energy customer price.

When it comes to electricity distribution, the whole energy performance can be considered as energy efficiency because losses are the most dominant element. Figure 5 presents the results of the loss energy analysis. It can be seen that alternatives are in the same order as in Figure 4 so that the most expensive case has also the highest loss energy consumption. Thus there is no contradiction between the total costs and the energy efficiency.

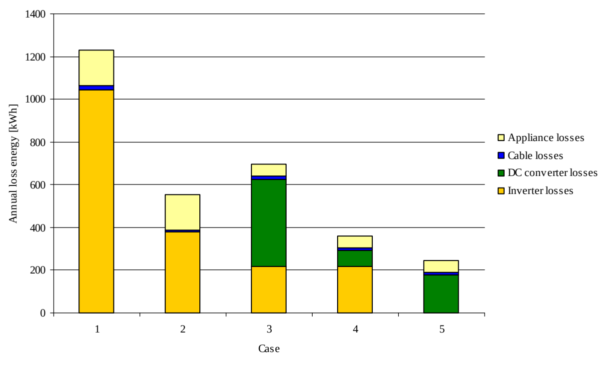

Figure 5. Annual loss energy of different internal networks [3].

When the annual energy consumption of the house is 20 MWh, the loss energy in Case 1 is about 6.1 % of the total energy. Case 2 reduces the loss energy by 55 %, Case 3 by 43 %, Case 4 by 71 % and Case 5 by 80 % compared with Case 1.

CONCLUSIONS

According to the results presented above, it has been shown that DC distribution has obvious effects on internal networks. Internal DC networks reduce the total costs of distribution and also improve energy efficiency. In fact, this holds for all the compared network alternatives utilizing DC inside the premises. Case 1 is a natural point of comparison for costs and losses, because this kind of a system has already been introduced before and the customer network is similar to an ordinary AC system.

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