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Voltage-Level Selection of Future Two-Level LVdc Distribution Grids: A Compromise Between Grid Compatibiliy, Safety, and Efficiency

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I. INTRODUCTION

Environmental concerns and new energy policies are making the energy systems to shift towards decentralization and sustainability. The electricity generation has been historically based on large-scale fossil and nuclear, even though, in the last decade the share of renewables has growth significantly. Microgrids (MGs) come as a suitable solution for the installation of distributed sources in the low voltage grid, where most of the consumers are sparsely located. Microgrids ease the integration of distributed generators (DGs), especially renewable energy sources like solar panels and small wind turbines, with energy storage systems at consumption level. By decentralizing the electricity generation, the production is moved closer to the consumer, therefore avoiding transmission and distribution losses, and increasing the efficiency of the electricity grid, as well as, higher power reliability.

In line with this, direct-current (dc) distribution systems are making their way back to electrical grid. Today's electrical system uses alternating-current (ac) worldwide; however, the technical/technological problems of dc that made it harder to transmit than ac system, over a century ago, are currently solved. Both ends of the electrical, the high voltage (HV) and low voltage (LV), have seen the proliferation of dc systems, and its implementation for transmission and distribution of electricity. For both ends dc offers significant improvement regarding simplicity, efficiency, and cost reduction. The reason why dc systems are a viable option nowadays is the development experienced in the power electronics industry, which allows to converter dc voltages to the required level for transmission, distribution and consumption.

Starting from the top end, there are over a hundred high-voltage dc (HVdc) systems already installed across the world, especially for long distance and submarine connections. HVdc transmission systems allow, higher efficiency, potentially lower costs, and enhanced environmental solutions. HVdc transmission lines are generally thinner than HVac lines, for the same power capacity; also, HVdc allows long distance transmission with underground lines, therefore the environmental impact is considerably reduced.

Moving to the bottom end, dc shows as a promising solution for modern power system, in order to improve efficiency, power quality, resiliency and reliability, despite of having no presence in grid applications, these benefits have been previously observed in several applications, such as vehicular power systems, telecommunications stations, data centers, and aerospace and marine electrical power systems; where reliability, efficiency and cost are critical.

II. POTENTIAL BENEFITS OF LVDC DISTRIBUTIONS SYSTEMS FOR BUILDING APPLICATIONS

A high penetration of installations with distributed generators (DGs) at consumption level, especially solar photovoltaic (PV) panels, energy storage systems (ESSs), and modern electronic loads, provides to dc technologies a competitive advantage when compared with ac for residential/building applications.

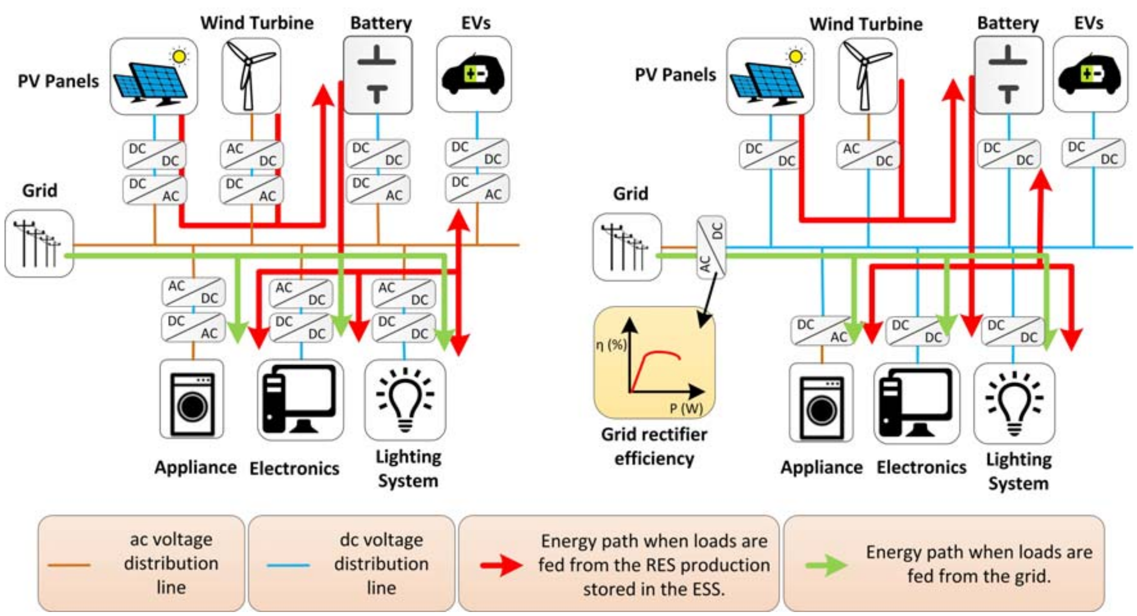

Fig 1: Make New figure showing the stages conversion reduction

Most renewable energy generators, such as PV panels and fuel cells (FCs), are dc generators, even wind turbines (WTs), although intrinsically ac generators, a dc integration can be more convenient. ESSs as batteries are dc devices as well.

Furthermore the presence of modern electronics loads (TVs, LED lights, phones, computers etc.) are all internally dc loads, and the energy consumed by these devices is increasing every day. Moreover, as happened with the WTs, even the appliances which are intrinsically ac loads (fridge, washing machine, dishwasher etc.) interface better with a dc supply, in order to avoid the ac-dc conversion. In addition, the expected future integration of electric vehicles (EVs) is going to inevitably increase the presence of dc devices in the buildings electrical system, since basically the EV is a battery that can be charged or discharged. Therefore a dc distribution system is a more natural interface between mostly dc devices, which allows a considerable power conversion stages reduction, hence achieving a significant loss reduction, as well as simplicity and potential cost reduction in the power converter units.

On top of this, there are few common benefits of dc, when compared to ac, for all applications. In dc there is not reactive power loading the lines, and there is no need for synchronization, as a consequence the system naturally becomes more efficient and simpler.

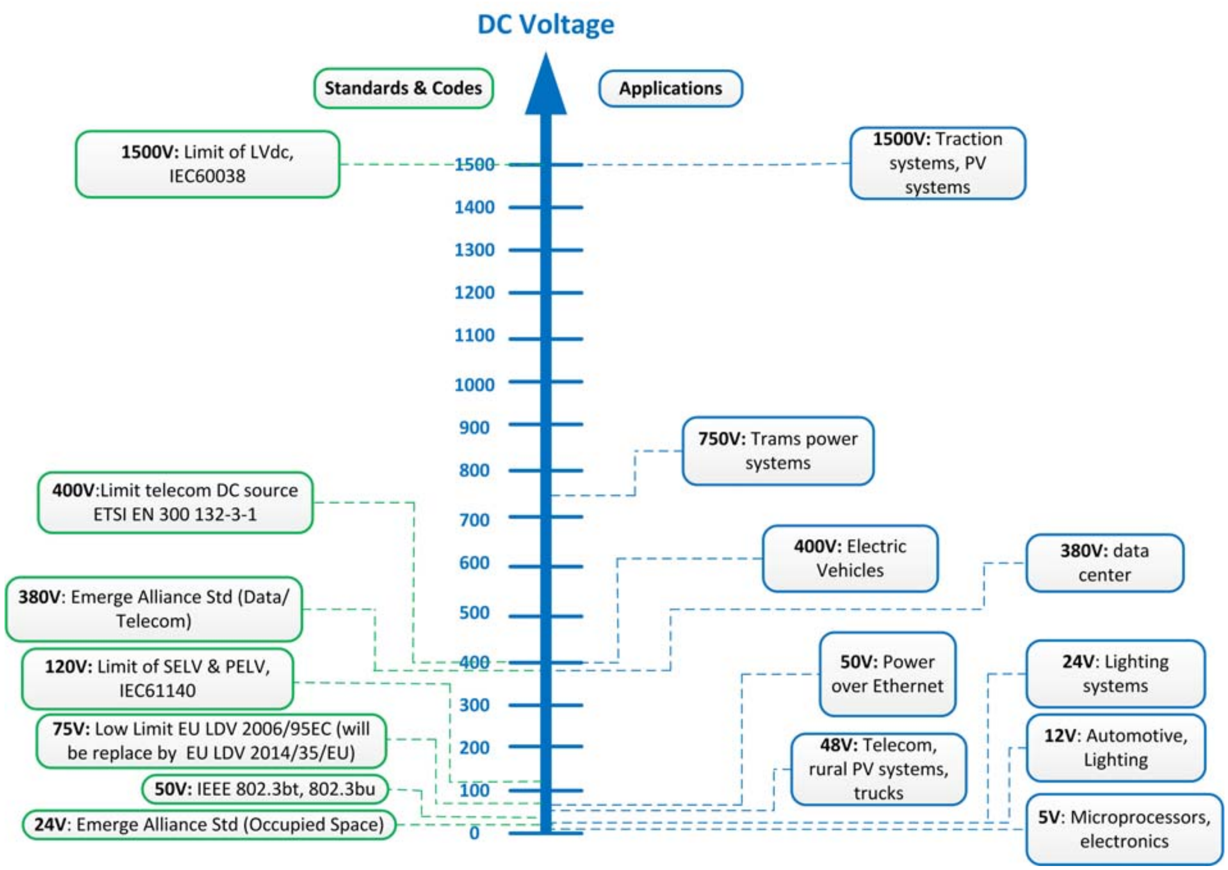

Fig. 2: A collection of standards, codes and applications using LVdc.

It is important to highlight that the efficiency or energy savings improvement, is strongly related with the presence of local RES and ESSs. When taking a look at the LVdc distribution system in Fig 1, if there is low or non-local generation, neither storage, most the energy consumed by the load would inevitably come from the grid rectifier. The grid rectifier would be rated to supply approximately the building installed power, however, the loads are normally connected at different times. Hence it is expected that the rectifier works mostly at low loads, where its efficiency is really poor, and therefore increasing the system losses considerably.

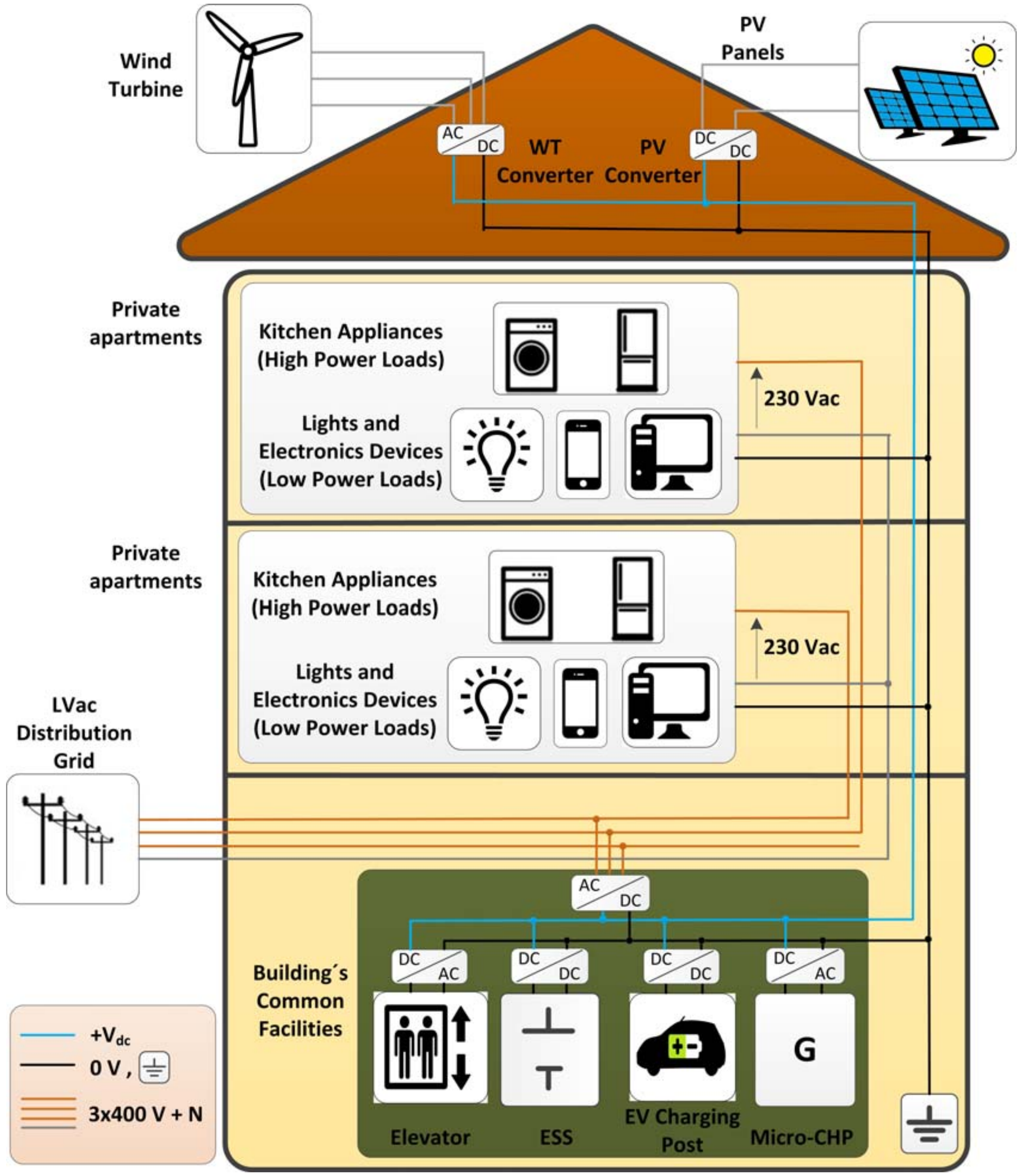

Figure 3: Schematic of a hybrid ac/dc distribution system for building/residential applications.

III. Challengues and Safety Concerns

As mentioned, LVdc distribution system for residential/building application has brought high expectations regarding simplicity, cost reduction, reliability improvement, and energy savings. The lack of commercial available products, standards, codes, regulations for dc systems, is a critical challenge holding a wider implementation of LVdc distribution systems.

The lack of commercial available products is an issue for companies implementing dc system, and users. When designing the LVdc electrical power system it would not be easy to find products (power converters, protection devices, connectors, chargers etc.) that compile with the system's requirements, especially regarding the voltage level. Also, as a consumer it would be extremely difficult to find dc compatible appliances and devices.

As for standards, several organizations as EMerge Alliance, the European Telecommunications Standard Institute (ETSI), International Electrotechnical Commission (IEC), IEEE and others, are working on developing the required regulation for the implementation of the dc system for building/residential applications. According to the IEC 60038 standard, LVdc systems are defined as those with voltage levels below 1500 V. This range gathers several applications, from computer electronics, to automotive, marine or aerospace power systems. Fig 2, shows an overview of the voltages and standards used in the different applications.

Regarding protection devices, fuses and circuit breakers (CBs) can sometimes directly be used in dc systems, however, these devices are mostly design for ac system, the current interruption mechanisms rely on the natural zero-crossing of the AC current, however in dc the current does not naturally go to zero, as a consequence, a re-design of these elements is required for a reliable protection system.

IV. ARCHITECTURES

It has been shown that LVdc distribution systems are applied in a large variety of applications, consequently different solutions and architectures have been proposed. Regardless of the power rating or voltage of the system, the system structure can be generally classified in three main categories:

- *Single-bus:* It is the simplest topology, where only two wires are used to supply the voltage. The automotive and telecommunication industries have widely used this configuration at 12 V and 48 V respectively. Proposed single-bus distribution systems often differ, depending on whether the bus voltage is tightly regulated by a power control unit, as show in Fig3, or a battery pack is directly connected to the dc bus. For the latest option the bus voltage depends on the state of charge (SOC) of the battery, and the current of battery , as a consequence this configuration is used in a reduced number of applications, since the charge of the battery needs to be coordinated by all the power converter units connected to the bus. A modified single bus topology, where the distribution is made by a three-wire (positive pole, neutral, negative pole) bipolar configuration, brings significant advantages for LVdc distribution in building/residential applications. This topology allows to reduce the distribution voltage respect to ground, and therefore improving safety, offer three different voltages levels (+Vdc, -Vdc, and 2Vdc) so the loads with different power rating can be connected to the voltage that better suits them. This topology is depicted in Fig 4 and 5.

- *Multi-bus:* This configuration is used when redundant distribution buses are needed to enhance the reliability and availability of the system, as well as, for interconnection of several MG clusters. The interconnection of MG clusters is an applicable concept for LVdc distribution between buildings, where the power exchanges between the different systems can be controlled by controlling the local voltage set points.
- *Reconfigurable:* This topology is used when the system requires higher reliability, flexibility during faults and maintenance periods. It usually consists on a mesh or ring distribution system, where intelligent electronics devices (IEDs) are able to connect and disconnect section of the mesh o ring. All the elements connected to the ring, are fed bidirectionally, however when a fault is detected the IEDs disconnect the faulty area, allowing a normal operation in the unaffected areas. Furthermore, a modified scheme is the zonal configuration, where each element is connected to different buses in a redundant system. The element can be fed by either one of the distribution buses, and when one bus gets compromised, the elements can switch to the remaining healthy bus.

V. VOLTAGE LEVELS FOR LVDC DISTRIBUTION SYSTEM FOR BUILDING APPLICATIONS

The voltage level selection for LVdc distribution systems is not a straight forward choice, and the discussion has been going back and forth for a while. The lack of standardization is palpable when observing the variety of voltage levels used for LVdc distribution systems in different application, as shown in Fig 2. The distribution voltages adopted for different solutions basically depend on what features are the main design criteria. For instance, in the automotive industry, 12 V distribution systems are used on board the cars to guarantee the safety onboard. Nevertheless, the increase of electronic devices in modern cars leads to a higher electrcity consumption, for this reason 24-48 V have been considered as an option to improve the efficiency and avoid an excessive oversizing in the conductors, since both weight and energy consumption, are critical in vehicles. In application with higher consumption, as data centers that normally use 380-400 V, the increase of the voltage level is unavoidable, if the distribution losses need to be minimize, and therefore a more effective protections system need to be developed.

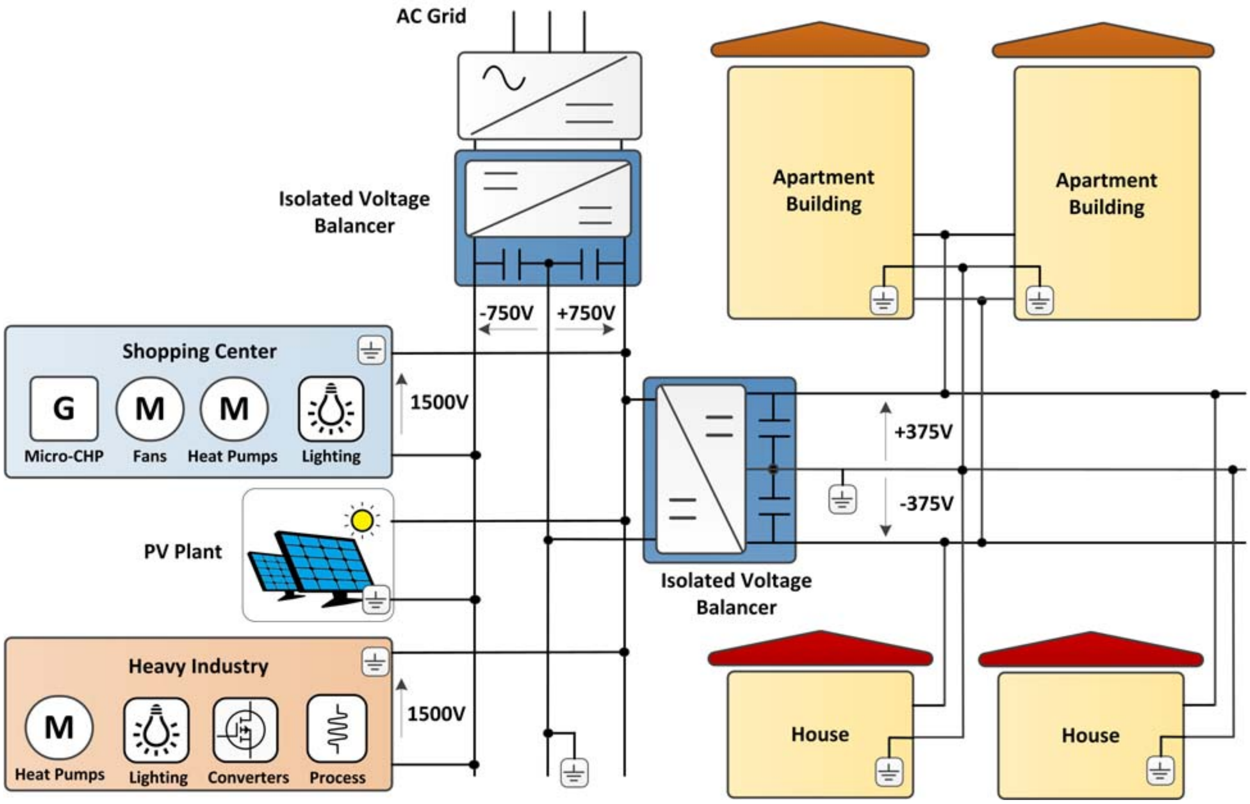

Fig 4: Schematic of a two-level bi-polar LVdc distribution grid.

Table I: Primary voltage levels for LVdc distribution for building/residential applications

Voltage Level	Advantage
≥ 565 V	Direct interconnection with the 3-phase 400V ac grid
380 - 400 V	Standard in datacenter industry
325 V	Minimum modification required for loads with input rectifier
230 V	Compatibility with pure resistive loads
120 V	Limit for extra-low-voltage definition, no need for protection system against indirect contacts.
48 V	Standard in telecommunication industry
24 V	Emerge Alliance Standard, Occupied Space
12 V	Standard in automotive industry

When analyzing LVdc distribution systems for building/residential applications, there are some voltage levels that come as a natural choices, depending on the regulation imposed by the standards, the availability of commercial solutions, or to ensure compatibility with the ac grid. A summary is shown in table I.

The selected voltage for distribution is inevitably related with the power rating of the different elements in the power system, if the same wire gauge is intended to be kept. In consequence, after an analysis of the location and power rating of the elements (DGs, ESSs, and loads) it can be noticed that the elements with similar power rating are mostly located together. Therefore, different voltages are sensitive to be used for different groups, while optimizing efficiency for each scenario, safety, and compatibility with other systems. The suitable voltage ranges would be as follows:

- *24-48V:* Low power loads (< 0.4 kW) are mostly the electronic equipment and devices (Wi-Fi routers, phone chargers, computers, TVs, DVD players, hi-fi systems etc.), and LED lights, which account for most the devices in bedrooms, living rooms, and outdoor areas, therefore the distribution in most of the spaces in a home could be performed efficiently while maximizing safety.
- *230-400 V:* Medium power elements (0.4-10 kW) usually account for the appliances in kitchens (stove, oven, dish washer etc.) and laundry room (washing machine, dryer, iron etc.). For a given power consumption, supplying the loads at 230 V would keep the same current loading in the wires as in a single-phase 230Vac system. If a high efficiency in the distribution and/or the wire gauge reduction is required, the voltage is sensitive to be increased up to 400 V. Beyond this level the efficiency improvement should is negligible, and the protection system would be highly demanding.
- *≥538 V:* High power elements (≥ 10 kW) are expected to be a part of the common facilities elements for the building, such as DGs (PV panels, WTs, FCs, µCHP etc.), ESSs and building's air conditioning system, elevators, and EV charging posts.

VI. Integration of future LVdc distribution systems

The following discussion analyzes the selection of the voltage and topology of the distribution system in building applications. The standards, guidelines and codes, that are necessary to widely implement LVdc systems to supply the electricity to homes or buildings, are not developed yet, even though several organizations, as the IEC or EMerge Alliance, are actively working on the field. In the near future, a reasonable first step for bring dc to buildings, as depict in Fig 1, is to use a LVdc system to interconnect the local renewable energy sources, energy storage systems, and common building's load such as lighting systems and elevators, while the ac distribution systems is used to connected the building to the grid and supply the apartments. The purpose of this configuration is that not a single change is required in the apartments, and therefore there is no need for the consumers to change electrical equipment in their homes.

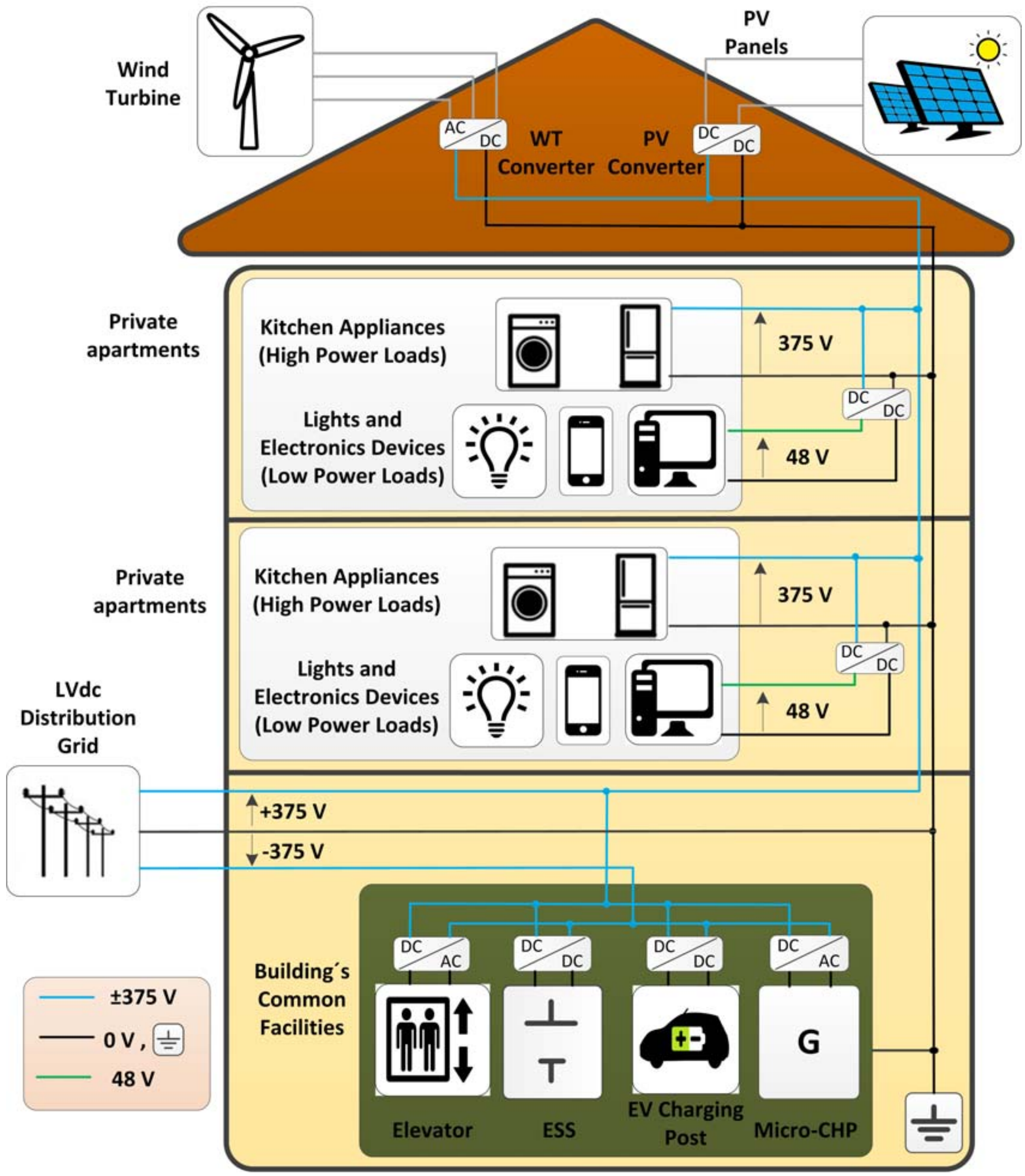

Figure 5: Schematic of a LVdc distribution system for building/residential application.

If we take a look a little bit further down the road, once the regulations and standards for dc system are developed and mature, hybrid AC/DC distribution systems for buildings, as the one proposed in Fig 3, are widely accepted and implemented, and most important, there are in the market broadly available dc compatible devices (appliances, electronics etc.) that can be used with either a ac or dc system, it would be suitable to bring LVdc distribution systems to the homes and for distribution within the buildings.

In the literature, most of the proposed architectures for dc distribution in buildings, use a unipolar bus running at 380-400V. As commented before this is the solution adopted by the data center industry, Even though it might not be the most optimized solution for buildings and homes, it is an easier step to take, rather than developing a new solution for the distribution system. This solution is simple, convenient, and more efficient than the traditional ac system. It is convenient because, it has been tested in different applications, therefore most of the solutions already developed in that field can be used for this particular systems as well. It is more efficient because, first, the voltage level is higher, hence the losses in the conductors are lower, and second, using a dc system to distribute the energy between mostly dc-based devices (PV panels, batteries, lights, motor drives etc.) allows a reduction of the conversion stages.

It seems that unipolar 400 V distribution systems are widely accepted as a suitable solution for dc distribution for building applications. However, aside from the convenience of adapting an already tested solution, are the 400V the best option for distribution in buildings? For instance, regarding the topology of the system, we have discussed before the benefits and disadvantages of unipolar, bipolar and multi-bus architectures. Bipolar configuration offer significant advantages, especially for this kind of application where there are different elements (generators, load, storage systems..) with a wide range of power ratings. Therefore the availability of different voltage levels to supply the elements in the systems, allows to achieve a better compromise between distribution efficiency and safety. As a consequence a bipolar type LVdc distribution system seems a better solution.

Then the discussion moves to which voltages levels should be used for the distribution. We have discussed that dc voltage levels within 230-400V are good compromise between, efficiency, safety, and compatibility with the existing ac system. Furthermore, once established that a bipolar configuration is a more convenient solution for distribution in building/residential applications, it seems like a good idea to apply the same topology for the distribution grid between the buildings themselves. In Fig 4 and 5, a two-level bipolar distribution grid is shown. The IEC 60038 standard sets the 1500V as the upper limit for LVdc systems, therefore, in order to maximize the efficiency in the distribution, a bipolar ±750 V is proposed, from where it is possible to extract a second level ±375 V bipolar line, which fits the suitable voltage levels for both high and medium power rating elements in buildings. It should be also noted that the use a two-level bipolar distribution system restricts the voltage level to be used in the system, therefore doubling up twice the voltage level 380-400 V would exceed the LV limit set by the standards.

The grounding and protection scheme for the proposed two-level bipolar LVdc distribution system is not trivial, and some modifications are needed in order to comply with the safety requirements. The neutral conductor of the ±375 V distribution lines is put to ground. In addition, it is required that the voltage balancer provides galvanic isolation, since the neutral in a different area may have a different voltage level.

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VII. FURTHER READING

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