Chapter

Assessment of the Main Requirements and Characteristics Related to the Implementation of a Residential DC Microgrid

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Abstract

A generic DC microgrid consists of a number of electric generators with static converters as interface modules, electric loads (to be connected either at DC or AC with inverter modules), as well as connection (by transformer and conversion modules) to the electric distribution network. The chapter envisages the state of the art on DC electric power distribution systems by tapping both high- and low-voltage direct current technologies and leading to the current development prospects. Moreover, a study on the existing standards applicable to DC distribution systems is achieved. The chapter leads to the establishment of the main technical requirements and characteristics suitable to the implementation of a residential DC microgrid. Also, electrical diagrams of the foreseen solutions and users' recommendations and challenges are suggested by the paper.

Keywords: microgrids, residential users, HVDC, LVDC, wiring diagram

1. Introduction

The direct current (DC) electric distribution system mainly consists of converters and DC links, as suggested by [1]. The DC distribution systems can be classified as high-voltage direct current (HVDC) or low-voltage direct current (LVDC) for which the DC-AC conversion is located near the end users.

Currently, high-voltage direct current systems are widely used for offshore and submarine electric power transport, [2], in order to interconnect non-synchronized AC grids, thus providing efficient and stable transport and control capacity. HVDC also represents the suitable technology for long-distance energy transport and large amounts of power with reduced power losses [3]. Moreover, HVDC systems stand as a key concept for overcoming the existing barriers concerning the energy generation from renewable sources (wind, solar, or hydropower), since these generating units are rarely located near urban areas or domestic energy consumption points.

The selection of a HVDC topology dedicated to the transport of large amounts of electric power over long distances in a specific case is due mostly to the following aspects:

a. Power control: HVDC is necessary from the technical point of view in order to ensure intelligent control.

b. Reduced total investments: the use of HVDC for the interconnection of two nodes within an electric power system is in many cases the more economical alternative compared to high-voltage alternative current (HVAC) systems as shown in **Figure 1**.

c. Environmental protection

Thus, HVDC systems allow the safe and stable interconnection of AC electrical grids operating at different frequency values, [5], which are otherwise incompatible. In addition, HVDC provides instant and accurate power flow control.

As far as it goes, LVDC microgrid concept has gained the scientific community attention in recent years. A direct current distribution microgrid represents a practical solution to efficiency problems of existing AC electrical grid [6]. While various papers have shown that DC microgrids can play an effective role in solving some operational

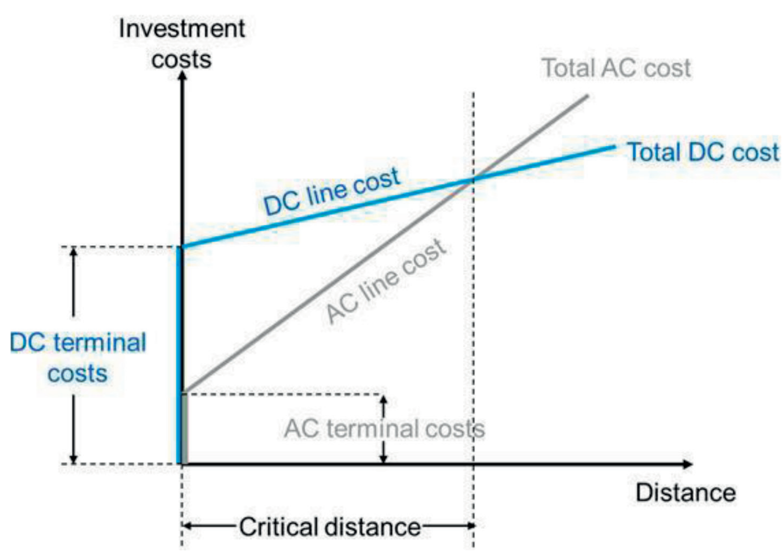

Figure 1.
Cost versus transmission distance for HVDC and HVAC systems [4].

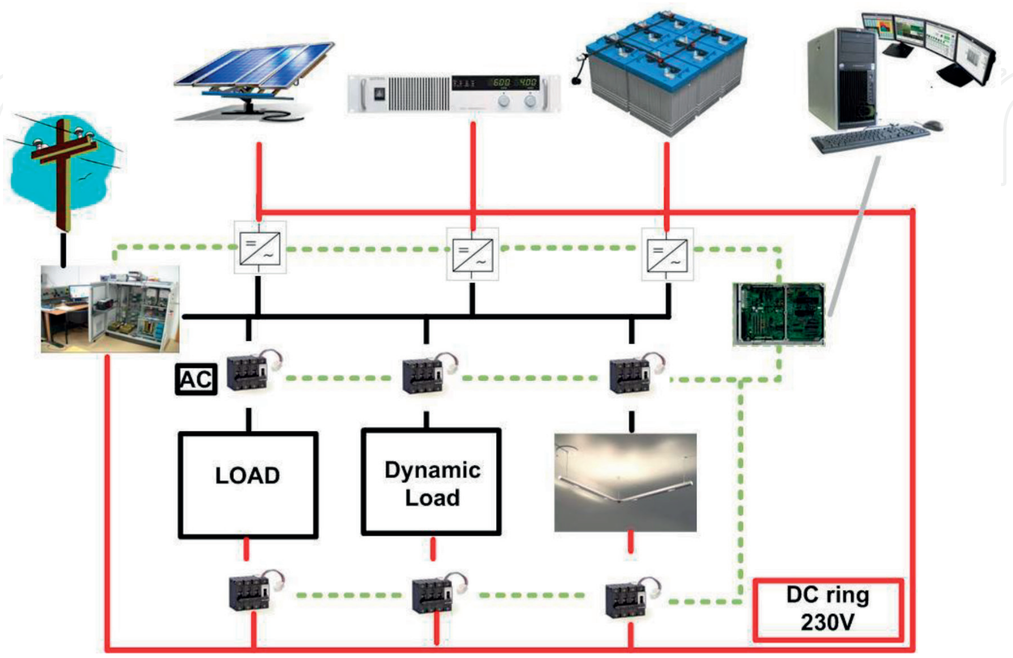

Figure 2.
The key diagram for a mixed microgrid with separate AC and DC rings.

issues on the main grid, [7, 8], one paper in particular envisages that a DC microgrid can be used for voltage support, by providing the option of injecting reactive power as an ancillary service [8, 9]. Consequently, the most important aspects regard the integration of renewable energy sources and energy storage systems dedicated to individual end users, in order to improve the quality, reliability, and energy efficiency, respectively [10]. Moreover, the increasing number of DC household appliances has brought to the attention both AC and DC distribution systems, as represented in **Figure 2**.

Thus, the chapter analyzes researches on DC distribution systems as well as their potential for residential applications. General advantages of LVDC distribution systems are envisaged, highlighting various power supply architectures and topologies. Also, there are presented demonstration facilities in which LVDC distribution systems have been implemented.

2. Analysis of existing standards applicable to DC operating power supplies

The following standards are used by the European Telecommunications Standards Institute (ETSI) for the coordination of Telekom stations equipment. These normative documents are required to be applied for DC operation:

- *IEC/EN 60947-2:2009 Low-voltage switchgear and control gear—Part 2: Circuit-breakers*

This standard applies to automated circuit breakers, of which main contacts are intended to be connected to circuits, the rated voltage of which does not exceed 1000 V AC or 1500 V DC; it also contains additional requirements for integrally fused circuit breakers [11].

- SR EN 60947-3:2009 *Low-voltage switchgear and control gear—Part 3: Switches, disconnectors, witch-disconnectors and fuse-combination units*

This standard applies to switches, disconnectors, switch-disconnectors, and fuse-combination units to be used in distribution circuits and motor circuits of which the rated voltage does not exceed 1000 V AC or 1500 V DC. The manufacturer will specify the type, ratings, and characteristics according to the relevant standard of any incorporated fuses [11].

IEC 60947-2 standardizes miniature circuit breakers (MCB) used by the industry. The aforementioned standard creates a frame for power distribution with voltage values of up to 1000 V AC and 1500 V DC for all rated current ranges starting from 0.5 and reaching 6300 A. There are three types of circuit breakers in this class:

- Air circuit breakers (ACBs)
- Molded case circuit breakers (MCCBs)
- Miniature circuit breakers (MCBs)

An alternative standard for automatic circuit breakers is represented by IEC 60898-1, which refers to the miniature circuit breakers used within the low-voltage AC grids and included in electrical panels from households, shops, or office buildings. **Table 1** synthetizes the major differences between the two standards which apply to MCBs.

Another difference is to be observed when comparing the trigger curves. If the IEC 60898-1 standard clearly describes the B, C, and D curves as depending on the rated

MCB's characteristics	IEC 60898-1	IEC60947-2
Regulated for:	**Residential domain**	**Industrial domain**
Rated current, I_n	6–125 A	0.5–160 A
Maximum current, I_{cn}	25 kA	30 kA
Rated voltage, U_e	400 V	440, 500, 690 V
Impulse voltage, U_{imp}	4 kV	6 or 8 kV
Degree of protection	2	3
Trigger curves	B, C, D	B, C, D, K, Z, MA
Operation mode	AC	AC or DC
Maximum ambient temperature	30°C	50°C
Electrical auxiliaries	No	Monitoring and control

Table 1.
Comparison between the characteristics of miniature circuit breakers (MCBs) regulated according to IEC [12].

Figure 3.
Examples of Resi9 circuit breakers for residential applications and Eazy9 for industrial use manufactured by Schneider [13].

current, IEC 60947-2 shows that instantaneous triggering may be adjustable in accordance to the user's necessities or predefined by the manufacturer with a precision of 20%. This is the reason why many manufacturers have added K, Z, and MA curves (**Figure 3**).

In conclusion, the use of MCBs which are certified according to both standards and are suitable for residential as well as industrial use is preferable.

- *IEC/EN 60269-1 Low-voltage fuses—Part 1: General requirements*

This standard is applicable to fuses incorporating enclosed current-limiting fuse links with rated breaking capacities of not less than 6 kA, intended for protecting power-frequency AC circuits of nominal voltages not exceeding 1000 V or DC circuits of nominal voltages not exceeding 1500 V.

The standard has been updated and released again as SR EN 60269-1:2008/A1:2010 and SR EN 60269-1:2008/A2:2015.

- *IEC/EN 61000-4-29 Electromagnetic compatibility (EMC)—Part 4–29: Testing and measurement techniques—Voltage dips, short interruptions and voltage variations on DC input power port immunity tests*

- *IEC/EN 61000-4-5 Electromagnetic compatibility (EMC)—Part 4–5: Testing and measurement techniques—Surge immunity test*

As mentioned by [14], in the United States, restrictions regarding electrical systems are established by the requirements of NEC (NFPA-70), Section 210.6, for branch-circuit voltage limitations. Thus, this code from the US National Electrical Code imposes the voltage in residential and similar occupancies to 120 V, while only in the case of specific loads, the limits are raised to 277 V among conductors.

Also, at the moment, an IEEE standard for DC microgrids for rural and remote electricity access applications is under development, targeting sustainable DC off-grid and remote power and relying firstly on user's safety.

3. Assessment of consumption requirements and preliminary features for the development and implementation of residential DC microgrids

3.1 Methods for adapting the electrical consumers to DC grid parameters

In order to establish the proper methods regarding the consumers' adaptability to a DC grid, it is necessary to identify the ones which are to be used and to analyze the possibilities of modifying the included power supply. The classification of electrical appliances that are usually found in a household is therefore highlighted. The main categories of electric consumers can be defined as follows:

- Heating appliances with resistive loads only (hotplates, ovens, radiators, heat exchangers) can easily be supplied from the DC grid if the same voltage level and electric power requirements are ensured as from the single-phase AC grid. If the DC voltage is different from the end users' parameters, buck (step-down) or boost (step-up) DC/DC converters can be used.

- Household appliances with inductive loads (fridge, pumps, vacuum cleaner, fans, etc.) using mainly asynchronous AC motors require DC/AC inverters in order to restore the pure or modified sine wave which drives the electric motors.

- Equipment with multiple (resistive, inductive) loads: washing machines and HVAC equipment (air conditioning, ventilation/heating) which operate by using a DC/AC inverter in order to adapt the required operating parameters. These household appliances also include elements that can be DC power supplied, but the required separation of the DC and AC paths is difficult and not justified.

- Low-power equipment using DC in the voltage range of 5–48 V. These can operate with step-down DC/DC converters. A separate 48–50 V power supply line can be used for a low installed power supply for the following end users: LED, laptop/desktop PCs, telecommunication equipment (router, mobile phone), LED TV, monitors, printers, etc.

A step-down converter with 48 V input and 5–9–12–20–24 V output operates with very good conversion efficiency. Due to the fact that it does not process significant power amounts, it has an affordable price.

Currently, the home appliance industry is mainly focused on AC power supplied products. Still, there are an increasing number of DC power devices that use switching mode power supplies (SMPS) for AC conversion and voltage level adjustment. These devices can be modified by eliminating the rectifying and power factor correction modules.

SMPS are electronic power sources which include switching regulators for the efficient energy conversion. SMPS use a transistor (or a group of pass transistors) that continuously switch between low-dissipation, full-on, and full-off states in order to remain as little as possible in high-dissipation transitions, thus minimizing the wasted energy. Ideally, switching mode power supplies do not dissipate any power. Voltage regulation is achieved by varying the time ratio between saturation and blocking. High power conversion efficiency represents an important advantage of a switching power supply. Also, SMPS can have significantly reduced dimensions and be lighter than a linear power supply due to the size and the weight of the included transformer. Switching regulators are used as replacements for the linear regulators when higher efficiency or more reduced size and weight are required. These are, however, much more complicated; if not suppressed, current can cause electrical noise problems during switching, while the simple models may have a low power factor. Ideal switching elements (e.g., transistors operating outside their active mode) have no resistance when "open" and do not carry any electrical current when "closed." Therefore, converters are able to theoretically operate with 100% efficiency (e.g., all input current is delivered to the load, and no current is wasted as dissipated heat).

The output of the switching source is adjusted by using the fill factor control; the transistors are switched in fully closed or open stages, so that the resistance losses between input and load are limited. The only amount of generated heat results from the non-ideal characteristics of the used components and from the residual currents related to the control circuits.

The losses due to transistors' switching (especially in the short part of each cycle when the device is partially activated), the switching transistors' resistance, the series resistance of both the inductor and capacitors, and the inductor's iron losses as well as the voltage drop on the rectifier diodes lead to a specific efficiency of about 60–70%. However, the optimization of the SMPS design (choosing the optimal switching frequency, avoiding inductor saturation, and active rectifying) will provide the minimization of the energy losses. Thus, an optimal switching source configuration will be characterized by 95% efficiency.

The efficiency of the DC/DC converters is comparable to that of the switching sources if considering that the operating principle is similar after the point of power factor rectifying and correction. Most currently manufactured SMPS also include power factor compensation circuits in order to reduce grid losses and disturbances and to comply with international regulations.

The unity power factor represents the objective of any power generating company, because otherwise, a higher current value has to be provided to the end users for a certain power demand. In this respect, the manufacturer sustains higher line losses. In the case of an industrial power plant, a penalty is charged if the power factor is way different from 1 (under the neutral power factor of 0.92). Mainly, motors' windings act as inductors within the public distribution grid. Opposite effect capacitors which are compensating the motors' inductive windings can be used.

SMPS do not operate as reactive loads like the electric motors but instead represent nonlinear loads for the power supply grid. Sources without power factor correction (PFC) absorb high current pulses or spikes from the AC grid (which provides sinusoidal voltage) due to the low conduction angle in the input stage that carries out the rectifying. If left uncompensated, a switching source power factor (PF) will generally be equal to 0.65 or even lower. PF can be compensated by using power factor correction circuits. These circuits smooth current pulses, improve PF, and reduce the possibility of the AC circuit breaker safety devices to act prematurely.

There are two basic types of PFCs: passive and active. Passive PFC circuits are less expensive and usually can compensate the power factor at around 0.85. The PFC active circuits are the most used ones and are even included by the power supply source, thus increasing PF over 0.98. A close to 1 PF indicates good power supply performance.

Due to the high increase of household appliances that include power supplies which add up to existing consumers, since 2001 the European Union (EU) has set harmonic currents' limits that can occur within the AC power grid and are caused by SMPS.

The most important regulation is EN61000-3-2 which relates to SMPS with input power of over 75 W while absorbing up to 16 A electric current. Severe limits regarding up to the 39th harmonic currents, measured at the power supply input, are set. For example, EU has established a 50 Hz value for the frequency of the first harmonic. The third harmonic is equal to 150 Hz, while the 39th harmonic equal to 1950 Hz. These unwanted harmonic currents have a direct connection to the SMPS power factor. PFC significantly reduces the AC harmonics, leaving mainly the "fundamental," which is in phase to the waveform. Power supplies that meet the EN61000-3-2 standard are normally characterized by a power factor higher than 0.97.

PFC increases the power supply capacity, thus determining the amount of useful energy which SMPS will use from the AC grid and then deliver it to a load. The relation showing the abovementioned is shown in Eq. (1):

$$P_{out} = V_{RMS} \cdot I_{RMS} \cdot PF \cdot Efficiency \tag{1}$$

Many technologies and topologies can be and were designed for PFC. When dealing with low installed energy (even up to 200 W), various passive PFC techniques have been used in order to increase the conduction angle of the electric current waveform [15].

It can therefore be concluded that if SMPS include the power factor correction module, the conversion efficiency will be similar to the case of DC/DC converters. In the absence of power factor correction circuits, the DC power supply will contribute to reducing losses in the power transformation chain.

Moreover, if the foreseen household DC grid is characterized by a nominal voltage that coincides with the rectified voltage of an equipment switching source, then the appliance is ought to be directly connected to the DC power grid without any further changes.

Recent developments in the field of electric drives have allowed the large-scale use of Inverter technology for most household appliances using significant power motors. The main purpose of this technology is to increase the energy efficiency by varying the motor speed which can also operate on partial loads. The Inverter technology represents the most recent technological evolution regarding the compressors' electric motors. The inverter is used in order to continuously adjust the temperature by controlling the speed of the compressor motor. The DC inverter units dispose of a variable frequency drive, comprising an adjustable electric inverter which controls the speed of the electric motor and of the compressor, respectively. The unit converts the AC current input to DC, and then by modulating it through an inverter, it produces the foreseen current frequency. A microcontroller will acquire each value of the ambient air temperature and therefore adjust the compressor speed accordingly. The inverter air conditioning systems operate more efficiently than conventional ones, providing extended lifetime of their components

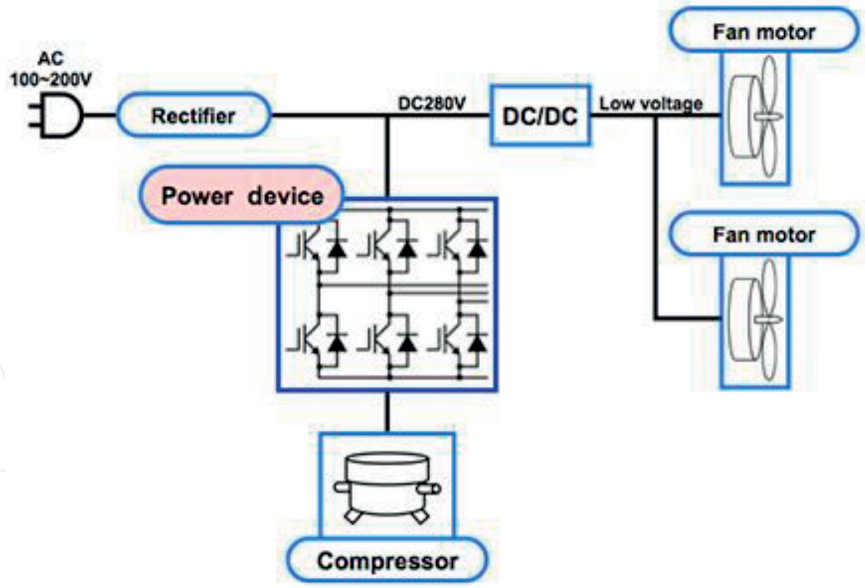

Figure 4.
Inverter technology freezer developed by Mitsubishi [16].

and not introducing disturbances to the main grid. An example of a freezer Inverter technology implemented by Mitsubishi is shown within **Figure 4**.

As shown in **Figure 4**, the system includes an AC/DC rectifying module, subsequently used in order to reshape the sinusoidal waveform along with the variable frequency required by the compressor and fan motors. It can thus be directly supplied with adequate DC voltage without any additional problems.

In the case of DC-powered equipment with low voltage levels, it has been shown previously that DC/DC converters can be used successfully.

DC/DC converters represent power supplies that convert electrical power with an unstable DC input voltage into a stabilized DC output voltage, to different values, lower value (step-down), higher value (step-up), and equal (stable level), or to inverse polarity comparing the input voltage (invert).

The more complex converters are based on microcontrollers in order to ensure high efficiency and as low as possible size, disturbances, and thermal dissipation losses. DC/DC converters are generally used in order to isolate electrical noise, for galvanic isolation, to voltage level conversion, and to provide a stable voltage level for voltage-sensitive equipment and various battery voltage values which supply portable equipment. Power density, efficiency, and reliability represent the basic characteristics which are considered for the price/performance ratio evaluation of a DC/DC converter. DC/DC converters are widely used either for fixed equipment power supplies (supplied from the AC grid) or for portable (battery powered) and IT equipment (where various voltage values are required for CPU, RAM, memory drives, and interfaces) [17].

DC/DC converters are basically SMPS with the following advantages:

- Very high efficiency comparing to the case of linear sources (typically 75–90%).
- Reduced energy transfer loss since all the components are smaller and require simple thermal management.
- The energy stored by a coil from a switching regulator can be supplied with higher voltage than the input voltage (boost) or even negative (inverted);

when using a transformer, galvanic isolation can be provided (minimum 1000 V DC), which cannot be achieved by a linear source.

The basic operating principle of a DC/DC converter regards the command of a high frequency switching element (at least 100 kHz) by variably controlling the on-time/off-time ratio ("duty ratio") in order to keep the output voltage at a certain value. Usually, the voltage is constantly controlled through the negative feedback of the output voltage. Some switching sources also solve the problem of electrical noise, with specialized controllers embedded in integrated circuits.

It is worth mentioning that about 80% of electromagnetic compatibility (EMC) problems are due to both power and I/O cables which produce an unintended "antenna structure." This structure can emit the electromagnetic energy generated by product-embedded electronic components and also receive the electromagnetic energy from the product's exterior. EMC regards electromagnetic interference (EMI) which stands as the amount of emitted energy, whether intentionally or otherwise, by electronic equipment that cause performance degradation on nearby equipment. Also, EMC addresses electromagnetic susceptibility (EMS) and the lack of immunity to internal or external interference, respectively. Emissions of radiated or conducted disturbances (within the AC grid) by IT equipment are covered by EN 55022 standard.

EN 55024 and EN 61000-4-2, 3, 4, 5, 6, and 8 standards regulate immunity to electrostatic discharges (ESD), intentional radio emissions, switching noise or electrical transitory regimes, lightning, 50–60 Hz variable magnetic fields, and power fluctuations in the AC grid [17].

The maximum efficiency of the operating switching sources is associated to a well-designed load when the equipment is power supplied similarly to the nominal regime parameters, yet considering a certain reserve of power. For example, a source works seamlessly with a load of only 10%, but energy conversion losses are higher than in the case of 80–90% load.

Therefore, manufacturers have developed switching sources suitable to a wide range of products provided with different input/output voltage values while characterized by efficiency between 70 and 96% and a few watts up to several thousand watts power.

Also, there are available various sources with a wide range of input and output voltage control according to the consumer's parameters. Thus, the same source is able to supply equipment that work at 5, 9, 12, 20, 24, and 48 V. The voltage can be adjusted before coupling, whether it is the case of a single output related to an only consumer or the case of a single source ensuring different simultaneous voltage values through dedicated terminals.

A solution for integrating these DC/DC converters in order to supply office equipment is shown in **Figure 5**.

From 24 V DC, the voltage can be reduced to the required voltage in order to power each device. A DC/DC converter can be mounted in a distribution panel for adapting the voltage from 380 to 24 V DC. Then, by using a low-power converter, the power can be transmitted to consumers through a device that integrates multiple outlets. Such a device is shown in **Figure 6**.

In order to power up electrical consumers with different voltage values such as laptops, monitors, and mobile phones that require voltage below 24 V AC, a buck converter can be integrated into a compact unit that incorporates multiple outlets. The coupling terminals for each voltage are integrated into the socket that can supply up to 100 W.

When considering only AC operating equipment, DC/AC converters (inverters) must be used. This solution is more complicated in terms of power electronics and thus more expensive. Inverters are provided with DC voltage (or current) source as input that converts it into alternating voltage (or current) for output, which can

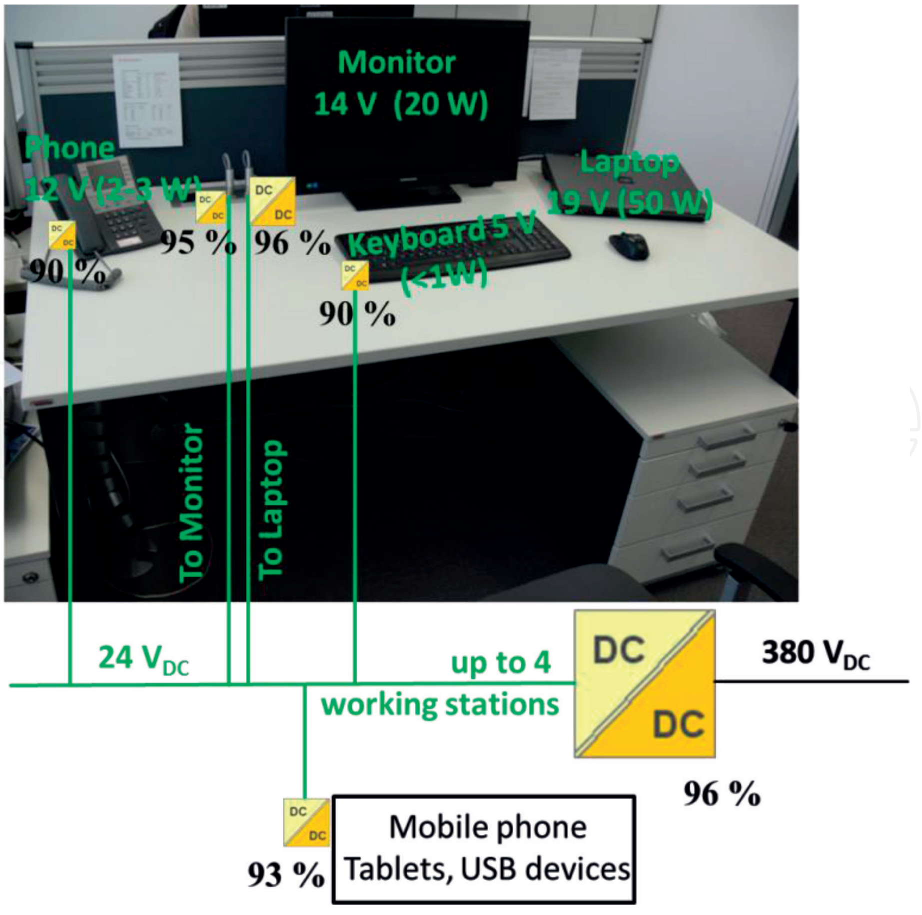

Figure 5.
Power supply infrastructure for office equipment [18].

Figure 6.
Power supply device for low-power equipment [19].

have adjustable frequency and/or voltage. Usually, inverters are used to drive AC motors with adjustable rotational speed but are also applicable to other domains, for example, the case of uninterruptible power supplies (UPS). It is therefore necessary to convert the voltage value of about 300 V DC to 220–240 V AC. The on the market wide available solutions usually convert low voltages (12/24/48 V DC) due to the fact that they are required in backup systems which use battery storage for the electric power generated by photovoltaic panels or wind/water turbines. The fact that there is no market for 300 V DC/240 V AC poses a challenge and is due to this system's high price which needs to be produced on special orders. Standard inverters that accept low voltage inputs may be used, but the considered electric grid must support higher current values for the same transferred power. It can also be used along with step-down converters, but the solution is costly and inefficient increasing the losses on the power transformation chain.

All of the aforementioned aspects show that switching home appliances to DC power configurations can be achieved without any significant problems or at significant costs.

The transition is easier when using new equipment that mainly embeds switching power supplies or *Inverter* technology to drive washing machine motors or compressors for refrigerators and air conditioning systems.

Older generation equipment that still uses transformers or AC motors requires more significant changes of the power sources or the use of DC/AC converters.

These aspects do not stand as obstacles to the development of DC grid when considering that the aging of old appliances will gradually eliminate them and lead to their replacement with newer technology that is easily adaptable to the DC grid.

3.2 Considerations regarding the assessment of a typical household required power

According to Siemens, buildings account on about 40% of global energy consumption and 21% of greenhouse gas emissions, respectively. Consequently, buildings represent the key to reduce energy consumption and support sustainable urban development. The use of modern technology in intelligent buildings can reduce emissions to 40% without affecting the comfort of residents.

Thus, the intelligent house concept is evolving in response to technological progress regarding distributed energy sources as well as information and telecommunication technology, so that through management systems, consumers can contribute to more efficient use of electric power. The use of smart home energy management systems will allow the end users to efficiently use low-cost electric or thermal power [20].

According to the 2016–2030 Romania's Energy Strategy, [21], with 2050 perspectives, the electricity consumption for 2016 by its destination is shown in **Figure 7**. The used electric power in MW by activity sectors is also indicated by **Figure 8**.

According to the 2016–2030 Romania's Energy Strategy, [21], with 2050 perspectives, the share of household consumption will not change significantly. Due to technological progress, it is still possible that the energy share is related to a household to vary between certain limits depending on the appliances within.

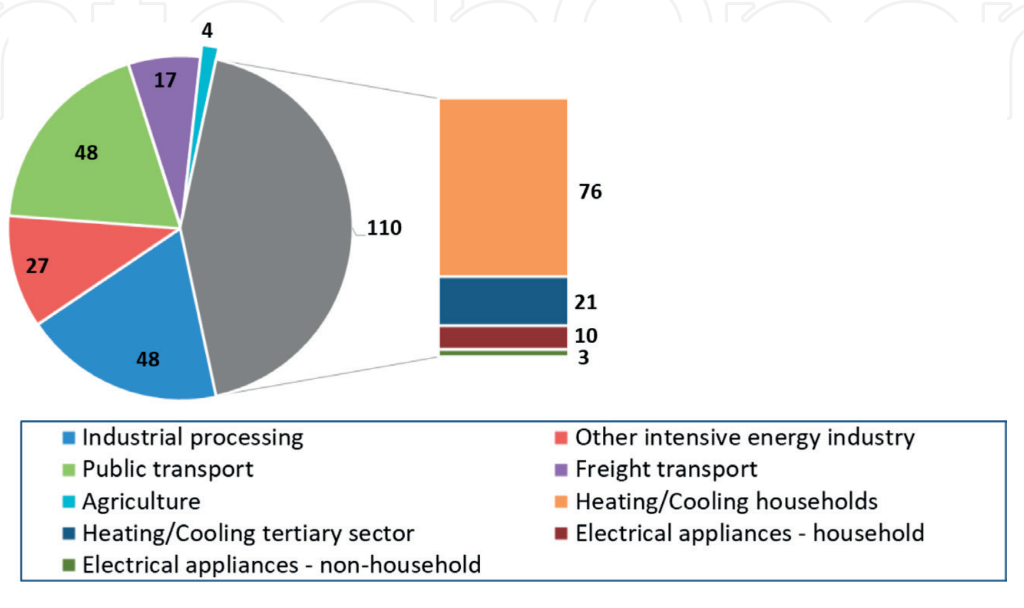

Figure 7.
Diagram regarding the final electric power consumption [MW] [21].

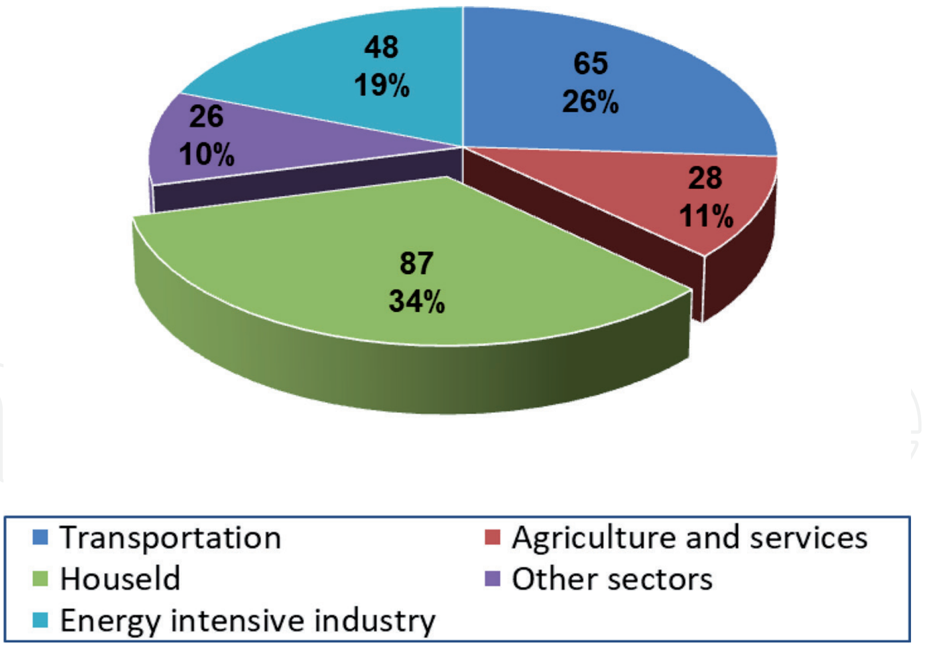

Figure 8.
Electric power [MW] by activity sectors [21].

When discussing 2016, the share of household appliance consumption is shown in **Figure 9**.

At the moment, the price cost of a new household appliance is payed off by lower operating costs (electric power, water or other forms of energy). If considering the share consumption related to household appliances beside the total electric power consumption of the residential sector as well as the life exceeded household appliances in Romania, it becomes obvious that there is a significant potential to reduce the power and water demand, and implicitly final costs, by replacing old equipment with new one, which is much more energy efficient.

Currently, when comparing to other European countries, Romania is characterized by a very low replacement rate of household appliances. In most cases, the average replacement rate exceeds the lifetime of the equipment. These aspects can also represent positive perspectives, namely, the growth potential of new energy-efficient household appliance market [21].

Hereinafter, electrical power requirement is estimated by considering various household electrical consumers and appliances generally used. The table below shows the consumers taken into account for the power estimation as well as their characteristics (**Table 2**).

Following the estimation, it is shown that 5 kW is sufficient to supply a typical household. Depending on the season, outside temperature, or time of day, actual consumption may be much lower than anticipated.

If the air conditioning is operating while at the same time an electric vehicle is charging, the consumption is higher (about 50% of the required energy). When these consumers are not connected due to the fact that there is no need for heat/cold or the electric car has enough remaining power, then the local generated energy can be stored in batteries or transferred to the public DC grid.

In order to ensure the energy needs, several power sources can be considered depending on the location's energy potential: photovoltaic panels and wind/water electric generators. A microgrid based on renewable energy sources can be technically and economically designed in order to provide 5 kW power. A 3 kW photovoltaic panel system provided with maximum power point tracking technology (MPPT) along with a 2 kW wind turbine can generate the required power. The surplus energy will be stored in batteries and used when needed. If the microgrid is designed to work on-grid and not autonomously, public AC grid access will be opted via AC/DC bidirectional converters.

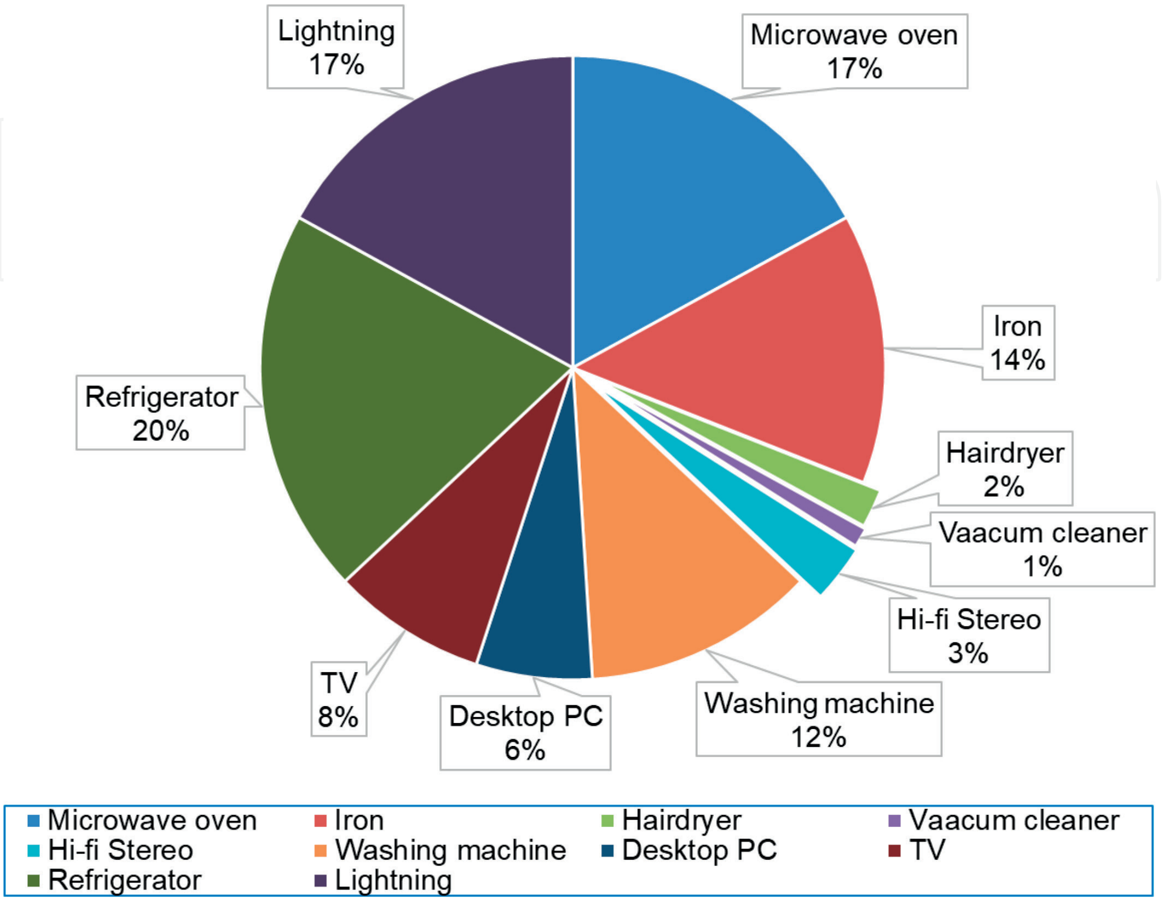

Figure 9.
The share of household appliance power consumption [21].

No.	Electric consumer	Installed power	Absorbed power	Rated voltage	Current	Using time/h	Total using time/ day	Required energy
UM		[W]	[W]	[V DC]	[A DC]	[min]	[h]	[kWh/day]
1	Heat pump	3000	750	375	8.00	15	12	9
2	Ventilation	250	83	375	0.67	20	18	1.5
3	Washing machine	2000	1000	375	5.33	30	1	1
4	Refrigerator A+	200	50	375	0.53	15	24	1.2
5	Dishes washing machine	1600	400	375	4.27	15	1	0.4
7	Lightning	300	300	48	6.25	60	4	1.2
8	TV + laptop + router	100	100	48	2.08	60	6	0.6
9	Electric vehicle charger	1500	1500	375	4.00	60	8	12
10	Power supply pump	1600	267	375	4.27	10	24	6.4
11	Total	10,550	4450	—	35.4	—	—	33.3

Table 2.
Electric consumers considered for the estimation of the necessary power.

4. Establishment of the DC microgrid layout

The previously detailed aspects demonstrate the efficiency of DC power distribution.

Although DC grids show many advantages and most home appliances are able to operate by using DC power, the development of these power distribution grids has yet to face several challenges, including:

- The necessity of using bidirectional energy conversion equipment, DC/DC and AC/DC converters, respectively.
- In-service safety and fuse protection.
- Universally accepted standard voltage regarding the operation of household appliances, as well as telecommunication equipment, electric vehicle transport, and aerospace industry.

Moreover, potential users do not yet have access to home appliances provided with DC power options. In terms of developing standards, several international organizations such as Emerge Alliance, ETSI-IEC, and IEEE are taking steps in order to establish regulations which are needed for the implementation of DC systems designed for residential applications.

According to IEC 60038 standard, distribution systems using low-voltage direct current should not exceed 1500 V. In this respect, the voltage levels' diagram which is currently used for DC power supply is shown in the following (**Figure 10**).

The transition from current distribution systems to DC grids must be gradually achieved, by ensuring parallel operation of both systems in order to ensure continuity of the power supply. DC power distribution is considered a solution

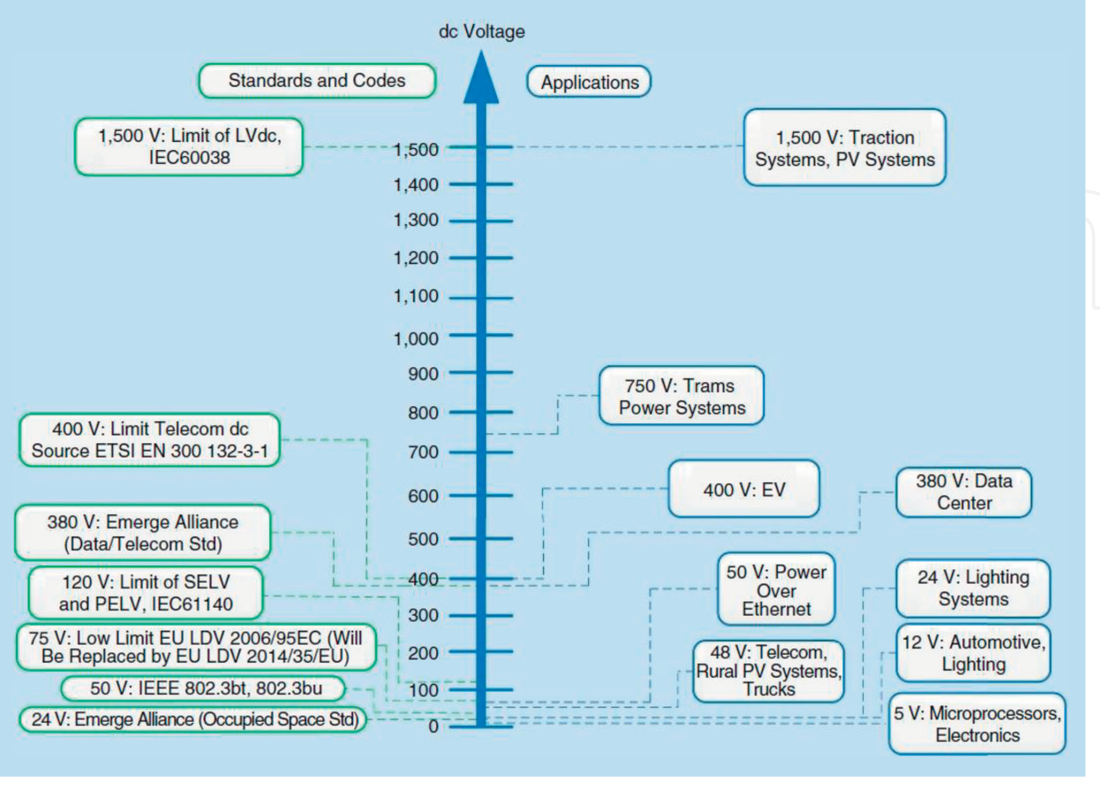

Figure 10.
Voltage levels currently adopted for DC power distribution [22].

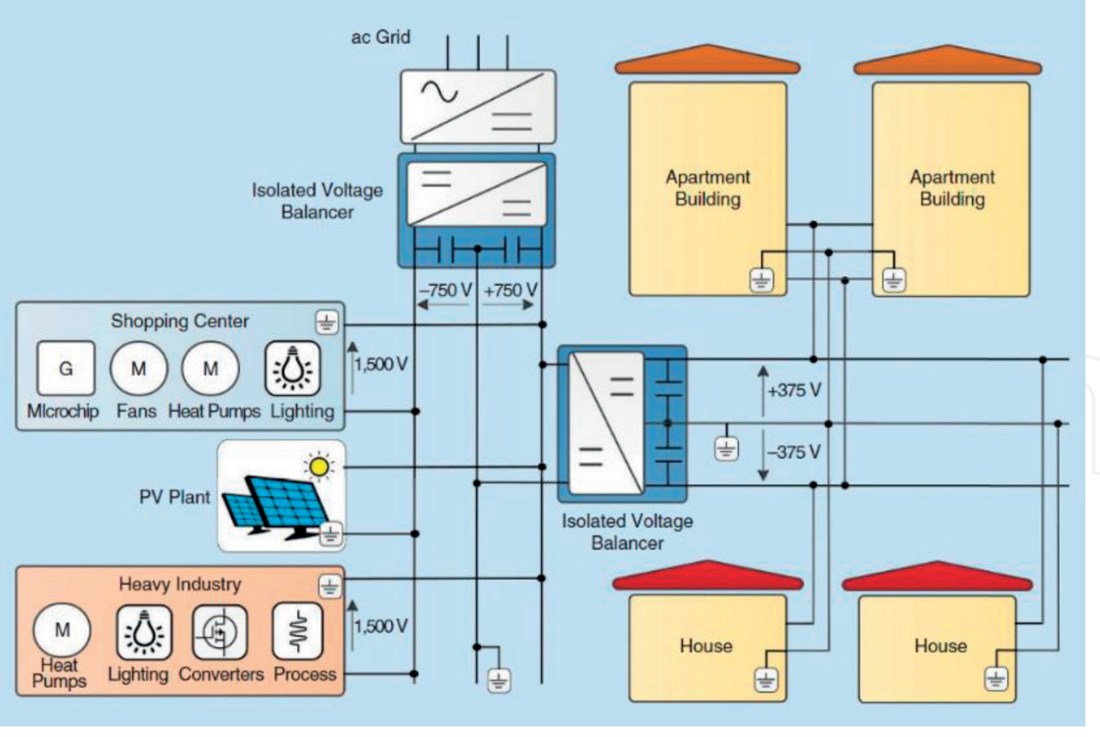

Figure 11.
DC grid provided with multiple voltage levels [22].

only if it can easily be adapted to household consumers or when it can be efficiently implemented by direct connection to renewable energy sources such as photovoltaic panels. **Figure 11** shows a DC grid structure using several voltage levels depending on the consumers' requirements.

As in the case of alternating current distribution systems, the energy flow can be transmitted through two conductors (single phase) or four conductors (three-phase). The DC grid power can also be transmitted in a similar configuration: two-wire (unipolar) and three-wire (bipolar) systems. The difference between the two grid configurations is given by the number of available voltage levels.

The need for fast integration of renewable energy sources (such as photovoltaic panels) and storage units into distribution systems has highlighted the benefits of using DC microgrids.

On the other hand, the power supply related to any distributed energy source is not time constant due to weather condition dependence. Therefore, the AC grid interface is very important in order to improve the reliability and availability of the microgrid [22].

There are several ways to connect the DC grid to an AC grid, of which there are to be mentioned:

- Radial configuration—for which the DC path starts from the AC grid through an AC/DC converter, supplying the line consumers through a single DC bus. This configuration has certain advantages such as the simple mounting and operation as well the multiple voltage level option. However, this configuration is not flexible under defective conditions. For example, a single failure in the input power end may affect all the connected consumers afterward. A radial DC grid model is shown in **Figure 12**.

Various radial DC microgrids are currently implemented and operating throughout the world. Several microgrid test beds from the United States are to be mentioned: University of Miami test bed, Florida; Sandia National Lab Test bed, Washington, DC; and UT Arlington test bed, Texas.

- Ring or loop configuration—consisting of two or more DC paths powered by converters in a single node or across multiple grid nodes. This configuration uses fast switches in order to isolate the defective circuit so that other consumers can still be supplied without any inconvenience.

- Interconnected configuration—the reliability of the DC microgrid can be further improved by providing alternative AC busses in the event of one of the AC/DC converters' failure. An example of an annular grid which is interconnected at multiple nodes with the AC grid is shown in **Figure 13**.

A complete grid structure regarding typical households which include usual appliances, consumers, battery storage units, and renewable energy sources as generation units is shown in **Figure 14**.

Some of the DC microgrids worth mentioning with ring or interconnected configurations are deployed as follows: Bosch DC Microgrid at California

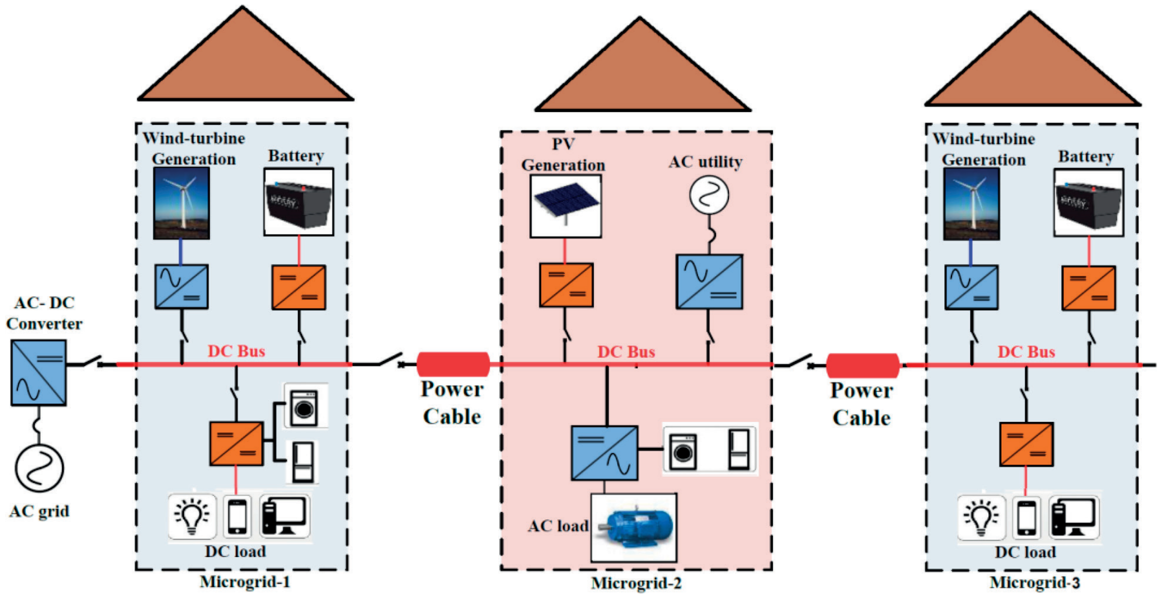

Figure 12.
Radial DC grid topology [22].

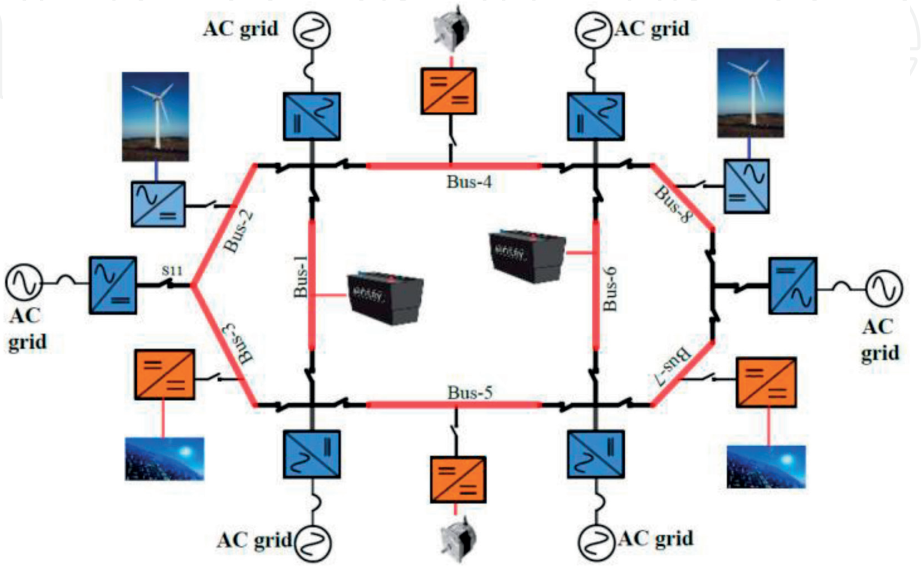

Figure 13.
Annular interconnected DC grid [22].

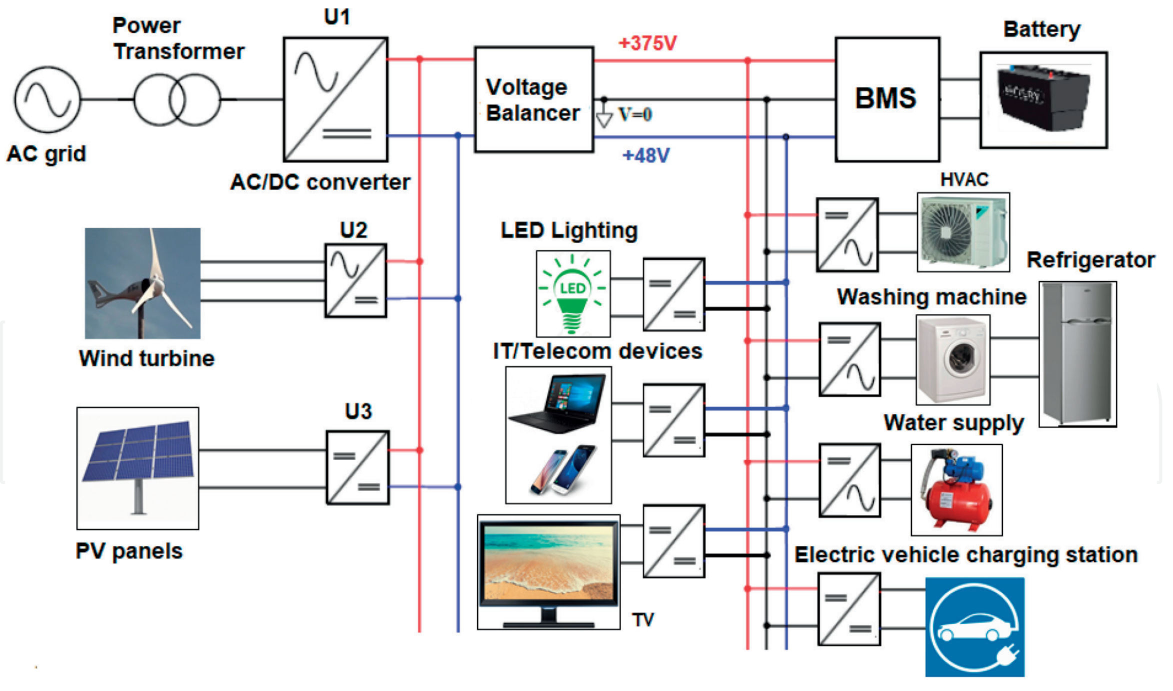

Figure 14.
Topology of a household DC power distribution system which integrates typical consumers as well as renewable energy sources.

Honda Facility; Burlington DC Microgrid Canada, North America, Ontario; Xiamen University DC Microgrid China; Intelligent DC Microgrid Living Lab Denmark.

Depending on the costs and consumer requirements, the DC layout which is outlined above may vary. When taking into account the perspective of renewable energy production, the variation along with the site's weather conditions must be considered. Moreover, the predicted power varies over time, throughout the day, or depending on the season. Thus, the connection to the public distribution grid is necessary if available. Storage systems also allow the accumulation of surplus energy when consumption is low in relation to production capacity.

5. Conclusions

The current chapter envisages and analyzes both advantages and several topologies of LVDC distribution systems for residential applications.

Various analyses regarding energy savings and voltage levels while addressing LVDC distribution systems have been presented. Studies have shown that DC grids will increase energy efficiency and power quality. There are still solutions to find to the challenges that DC grid systems have to overcome compared to existing AC systems, such as equipment safety and protection.

LVDC distribution systems provide particular advantages when integrating renewable energy sources along with storage systems. The development of DC power solutions designed for on the market household appliances may be the next step for the promotion of LVDC systems, especially when minor changes are required. Isolated areas without access to public electricity grid can opt for energy generation from renewable sources. In this case, LVDC grids are the first energy distribution options given the low deployment costs.

For the time being, the home appliance industry is mainly focused on AC power supplied products. There is an increasing number of DC-powered equipment that uses switching mode power supplies for AC conversion as well as for voltage level regulation. These devices can be easily modified by eliminating the rectifying and power factor correction stages.

Most switching mode power sources are already very efficient even with DC/AC conversion module included. Therefore, imposing a different power grid supply for households must be justified especially by the advantages related to the energy production and distribution stages and less by the aspects which regard the final consumer.

It can be concluded that modifying switching home appliances to DC power configurations can be achieved without any significant problems or at significant costs. The transition is easier when using new equipment that mainly embeds switching power supplies or *Inverter* technology to drive washing machine motors or compressors for refrigerators and air conditioning systems.

Older generation equipment that still uses transformers or AC motors require more significant changes of the power sources or the use of DC/AC converters.

The lack of both commercially available electronic devices and systems, and their required standards and regulations, is a major challenge that hinders the rapid development of this field. Currently, it is difficult to identify converters, fuses, or chargers which are necessary for the implementation of DC systems as well as to design and implement a DC microgrid, especially when operating at different voltage levels.

Moreover, potential users do not yet have access to home appliances provided with DC power options. In terms of developing standards, several international organizations such as Emerge Alliance, ETSI-IEC, and IEEE are taking steps in order to establish regulations which are needed for the implementation of DC systems designed for residential applications.

Even though the DC grid system protection is more difficult to be achieved than in the case of AC systems, a corresponding selection of a grounding configuration can be established by using adequate protection devices.

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Conflict of interest

The author declares that there is no conflict of interest. Thus, there are no conflicts of interest to disclose.

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