A comparative study on AC/DC analysis of an operational low voltage distribution system

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Article Info

Article history:

Received Sep 11, 2020
Revised Dec 16, 2020
Accepted Feb 22, 2021

Keywords:

Low voltage DC systems
Power distribution
Power management

ABSTRACT

In the near future, the digitalizing world will continue to improve and the need for DC based devices will be increased beyond doubt. Today's electrical grid is strictly dependent on AC-DC rectifiers. Each conversion process means additional power losses and signal quality deteriorations for the network. In addition, networks which are fed by batteries and renewable sources such as solar panels, and wind turbines are suffering from conversion-based power losses. In this respect, the idea of switching to DC on the low voltage side of the networks has become an intriguing subject. In this study, the applicability and efficiency of the low voltage direct current (LVDC) concept for low voltage distribution systems is discussed and a sample LVDC distribution system is analyzed. In this operational residential application electrical transient analyzer program (ETAP) is employed for comparison of different voltage levels such as 110 V_{DC}, 250 V_{DC}, 320 V_{DC} and conventional 220/380 V_{AC}. As a novel approach different DC voltage levels are compared with typical AC system in detail. Comparative analysis is conducted for safety regulations, voltage drops, current carrying capacities, power consumption and harmonic calculation of the proposed system. In this respect applicability, possible drawbacks and future aspects of LVDC systems are interpreted.

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1. INTRODUCTION

A big debate was presented a century ago by Edison and Tesla, which was based on the discussion about the idea of Edison's direct current (DC) and the idea of Tesla's alternating current (AC) for transmission of electrical energy [1], [2]. At the time, the AC-DC discussion resulted in superiority of AC, since electrical energy conversion in terms of high voltage (HV) and low voltage (LV) can be easily adjusted by the aid of transformers in the AC system brilliantly. As a result of advantages such as voltage drop and optimum cable cross-sectional area, the electrical grid is dominantly dependent on the AC system [3]. So, AC-based distribution systems have been installed and used for a century efficiently. With the increased improvements in power electronics, AC-DC debate in the power transmission of electricity networks has been reissued due to increasing need for batteries, the expansion of electric vehicles and the advancements of renewable energy sources [4]-[6].

Many advantages of DC systems compared to AC systems can be underlined where the idea of DC distribution draws attention. Since the AC causes excessive muscle contraction when electrical contact is established with living beings, it is much more dangerous than the DC which has the same electrical stress with AC [7]. Electrical installation malfunctions may result in death or severe injury, which are observed frequently in AC networks. A more secure installation can be fulfilled by reducing the voltage level with the DC system [8]. Many equipment that requires an energy storage system need additional converters to be connected to the grid where each converter has its own additional power loss and cost [9]-[11]. Renewable sources such as photovoltaic solar panels are much more coherent to integrate into the LVDC distribution network, which only requires direct connection to the systems. The need for converters in power systems are reduced by help of DC installments where energy savings of the system is about 2-3% [12].

AC networks are faced with problems such as harmonic distortion caused by unwanted oscillations, skin effect and reactive power losses [13], [14]. The integration of electrical transportation vehicles is easier than AC networks. Network integration of technologies such as uninterrupted power supply (UPS), central battery system (CBS), will reduce losses in the DC system [15]. The power calculations of the DC networks are mathematically simple in contrast to conventional AC systems. The demand for renewable energy sources can be increased by growing the number of DC networks, which lead to reduced carbon emissions [16]. In addition to advantages, a number of disadvantages of DC systems are noted such as the lack of standardizations for LVDC distribution networks, all the electrical equipment has been designed for the AC system for a century. Besides integration of LVDC networks to the medium voltage (MV) AC distribution requires converters where harmonics and other signal quality related issues are available. Although DC transmission in HV transmission lines is a growing trend, there are still hesitations about LVDC distribution.

In this study, an ordinary house is modelled for low voltage alternating current (LVAC) with the level of 220/380V and various LVDC (110 V, 250 V and 320 V) voltages as a practical example. Different DC voltage levels are investigated for various performance and applicability metrics by ETAP program [17]. A typical house and loads such as washing machine, electrical oven, dryer. are employed to verify system comparisons. Based on the discussion mentioned above, the power losses in LVDC networks, voltage drops up to end users, variations of cable cross-sectional areas, efficiency and applicability of proposed LVDC system is analyzed.

2. DC SYSTEM PREFERENCE TO AC SYSTEM

Since the electricity is transported over long distances, it is a very economical solution to use lesser cross-sectional cables as much as possible. Increased voltage levels in transmission lines means decreased currents (constant power) and hence small cross-sectional cables with lesser current carrying capacity can be used in the network efficiently and economically. In the AC system this concept is efficiently applied by the aid of transformers in which varying magnetic fields are employed to voltage transformation according to the Faraday law. The alternating current produces a variable magnetic field, which allows transformers to operate on alternating current.

Nowadays, it is clearly presented that there are many advantages to switching the power transmission lines to DC lines on the HV and MV side in many respects. Studies have revealed that AC power losses are increased in contrast to DC power losses when line lengths exceed 100 km [18], [19]. Furthermore, in three phase transmission three per cable is needed to AC distribution networks, while on the other hand two per cable is enough for DC distribution networks. On the LV side, the energy efficiency achieved by the DC distribution network, which is fed by an energy storage system, has been increased by 15% - 30% [20], [21]. The wind turbine and photovoltaic panels are connected to the grid as shown in Figure 1 in the conventional AC distribution network. In order to store energy in the batteries, initially AC/DC conversion is conducted and then it is reconverted to the AC again for the bus bar connection. In the conventional AC system, loading is fulfilled according to the energy requirements of the equipment which will be energized, where DC conversion is needed again.

The energy stored in the batteries can be transmitted directly to the bus bar without additional converters. Afterwards, only DC/DC converters are employed for DC based equipment power demand which are the majority of domestic use. In Figure 2, a number of optimizations can be made for equipment to reduce DC/AC conversion. When the network's distribution structure is modelled as a DC distribution system as in Figure 2, the need for converters is reduced. For instance, devices such as washing machines, dryers and dishwashers can operate in both current types when universal motors are used. Refrigerators can be produced with DC motors. The microwave induction heaters have to convert the DC to AC for the AC based magnetic field generated heat, however, resistance-based heaters can be operated in both DC and AC. In summary, we can reduce the need for DC/AC conversion if the DC ready devices are employed in the system as much as possible.

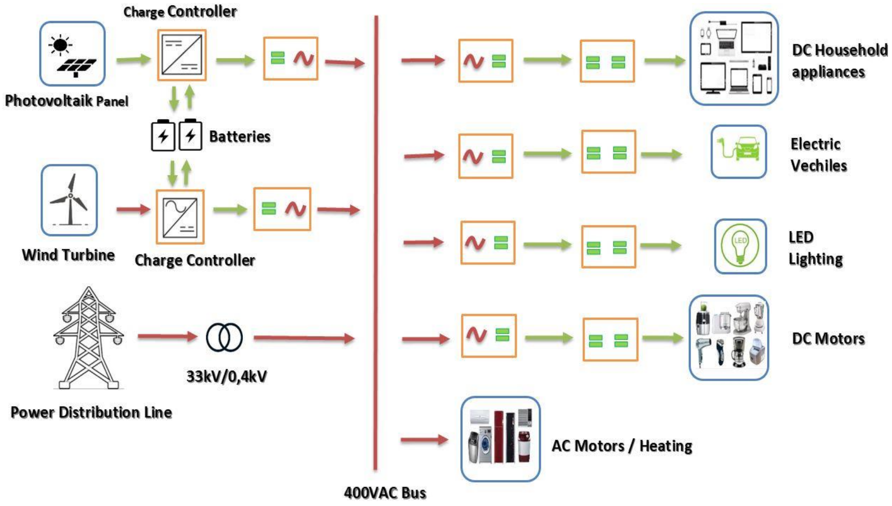

Figure 1. LVAC distribution network structure

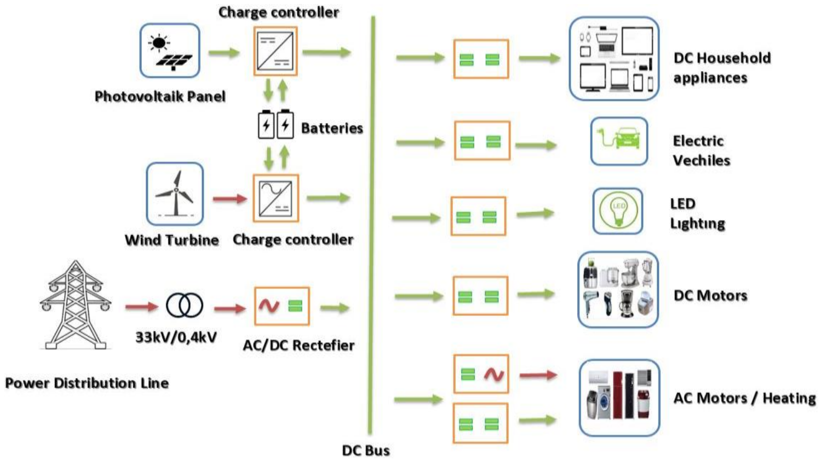

Figure 2. LVDC distribution system structure

3. INTRODUCING LVDC DISTRIBUTION FOR RESIDENTAL APPLICATION

Although there is no standardization, two basic distribution structures are introduced for DC transmission lines. The first one is the unipolar and the second one is the bipolar system. In unipolar systems, energy is carried over a single cable pair with the potential difference of +2 V_{DC} [22], [23]. The unipolar distribution structure is given in Figure 3.

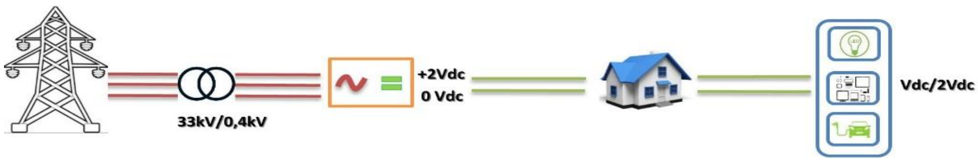

Figure 3. LVDC Unipolar distribution structure

In bipolar systems, energy is transferred to the positive and negative end with a neutral reference. By this way, the voltage level is reduced and two different voltage levels as + V_{DC} and – V_{DC} (2 V_{DC}) are given in the system [24]. The bipolar distribution structure is given in Figure 4. In addition, bipolar systems are able to overcome power outages since the system is designed to be energized on a single side of the bipolar system which will prevent system failure.

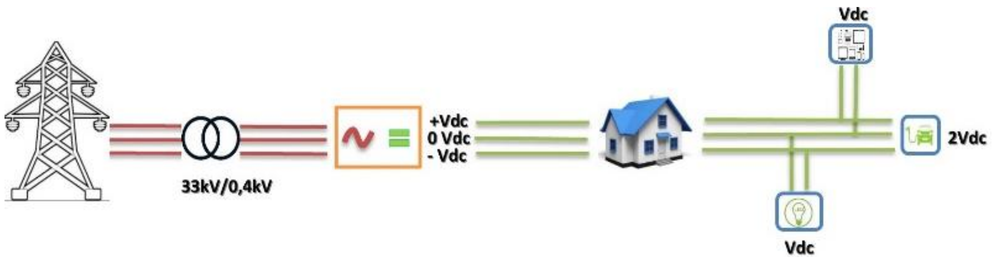

Figure 4. Bipolar distribution structure

3.1. Feasibility and efficiency of voltage level on LVDC distribution system

Determining the voltage level in the planned LVDC network is the most important parameter for the network analysis. The proposed voltage level should provide an optimal solution for both economic and safety issues since voltage drops and current demand by the loads are determined by voltage level. According to the calculated current value, the cable cross sectional areas are optimized and hence voltage drop of the system is calculated [25]. In addition, sizes of circuit protection elements are changed by the current ratings of the system. Furthermore, the short-circuit currents that may occur in the installation are directly dependent on the cable length and voltage level.

In case of any contact with electricity, which endangers human life is characterized by the rated voltage level according to safety issues. The effects of different voltage levels for the human body are shown in Table 1. AC causes muscle contractions due to oscillations of AC signals and which should be prevented. Therefore, the threshold of hazardous voltage level of AC is lower than DC. As shown in Table 1, while the muscle control is lost at 15 milliampere (mA) levels in the AC, muscle control is lost at level of 75 mA in the DC [26].

Table 1. Physical effects of electricity in various currents

Physical effects of electricity	DC	AC (50-60hz)
Sensation and perception	1 mA	0.4-0.5 mA
Slight shock	5 mA	1-1.5 mA
Painful shock, muscle control maintained	55 mA	10 mA
Pain with loss muscle control	75 mA	15 mA
Severe pain difficulty breathing	90 mA	25 mA
Hearth fibrillation	500 mA	100 mA

In contact with electricity, the current through the body is largely dependent on body resistance. Body resistance can be divided into two main groups, which are skin resistance and internal body resistance. During the electrical shock, current passes through the skin and continues through the internal organs and then comes back out of the skin and completes its path. Total resistance is determined by path of current since it contains skin resistance and internal resistance together.

The skin resistance is determined by various factors. While the resistance of a dry skin is at 100 kΩ levels, a moist skin is about 1 kΩ [27]. In addition to the skin resistance, the average internal resistance which is related to internal organs is about 300-500 kΩ. During the electrical contact higher skin resistance is broken down due to the accelerated voltage stress and excessive currents observed throughout the body. With the increased voltage levels, breakdown of the related resistances could be much easier. This phenomenon reduces the effect of skin resistance and hence total resistance. Based on the average values, body resistances vary depending on the voltage level and the fault current value resulting from hand-to-foot measurements, which are shown in Table 2.

Table 2. Hazardous hand-to-foot currents and related resistances for AC and DC voltages

Current source	Voltage (V)	Hand to foot current (mA)	Total body resistant (ohm)
	110	82.1	1340
DC	250	263.2	950
	320	381.0	840
AC	220	220.0	1000

As shown in Table 1, the muscle control is lost at 80-90 mA in DC voltage [28]. This value gives us the maximum possible voltage value which is noted as a safety threshold. The error currents calculated with the body resistance are at the most reliable level for 110 V_{DC} as shown in Table 2. Since the alternating current exceeds 30 mA levels, an operational safety issue is emerged and some measures should be taken. For this purpose, the residual current relays, which are manufactured to compare phase current and neutral current for detecting possible leakage currents are used [29]. In a DC system need for residual current relays is decreased in which DC system is said to be much more economical. Although the 110 V_{DC} system is the most non-hazardous distribution in the proposed scenarios, different DC levels (250 V_{DC} and 320 V_{DC}) are investigated for proper comparison.

3.2. A practical residential building model

ETAP power flow analysis is conducted for typical house models and calculations are investigated. AC analysis of 380 / 220V house distribution model, where single line diagram (SLD) is given in Figure 5. The 33 kV MV network is converted to a LV of 0.4 kV with a 500 kVA transformer and then converted to DC with a rectifier. The distance between the transformer and the building is considered as 200m. In addition to regular loads, light-emitting diode (LED) luminaires of 11 units, each has 25 W power and 1500 lumen are used for lighting. The luminaires are energized by two lines, where the first line has five armatures and the second line has six armature connections. Total illumination power for both lines is 330 W.

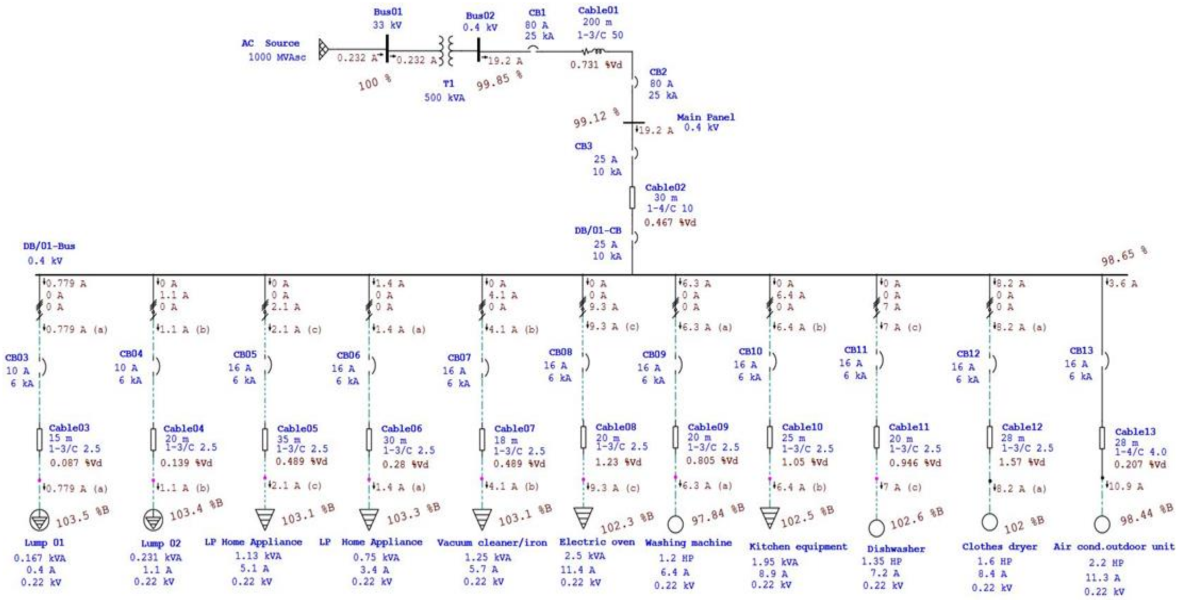

Figure 5. ETAP SLD of 380/220 V_{AC} distribution

Small power distribution has been noted for the use of general socket and kitchen equipment. With small power distribution, electronic devices such as computers, televisions and telephones can be energized. The small power distribution model assumes an average power consumption of 150-300 watts per socket. Two lines are given for general use, where one of them is intended to be used for the kitchen equipment. Besides a total of 1.5 kW power consumption is estimated for two-line common sockets and consequently total power consumption is predicted as 1.56 kW for kitchen equipment.

The remaining equipment demands high-power and each of this equipment is energized with separate lines. Briefly both models (AC and DC) contain multiple connections for small power consumption, lighting consumption and high-power consumptions as well. The main problem is the compatibility of the equipment to the DC connection (DC ready or not). SLD analysis of 110 V_{DC} distribution model is given in Figure 6. SLD analysis of 250 V_{DC} distribution model and 320 V_{DC} distribution model are given in Figure 7 and Figure 8 respectively.

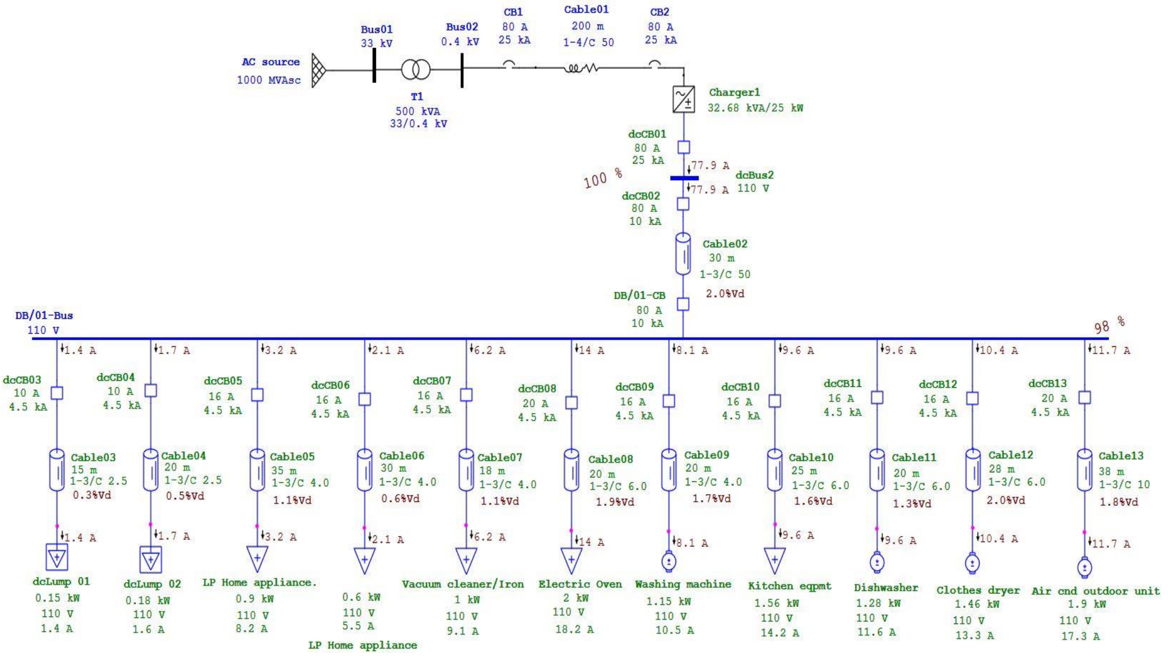

Figure 6. ETAP SLD of 110 V_{DC} distribution

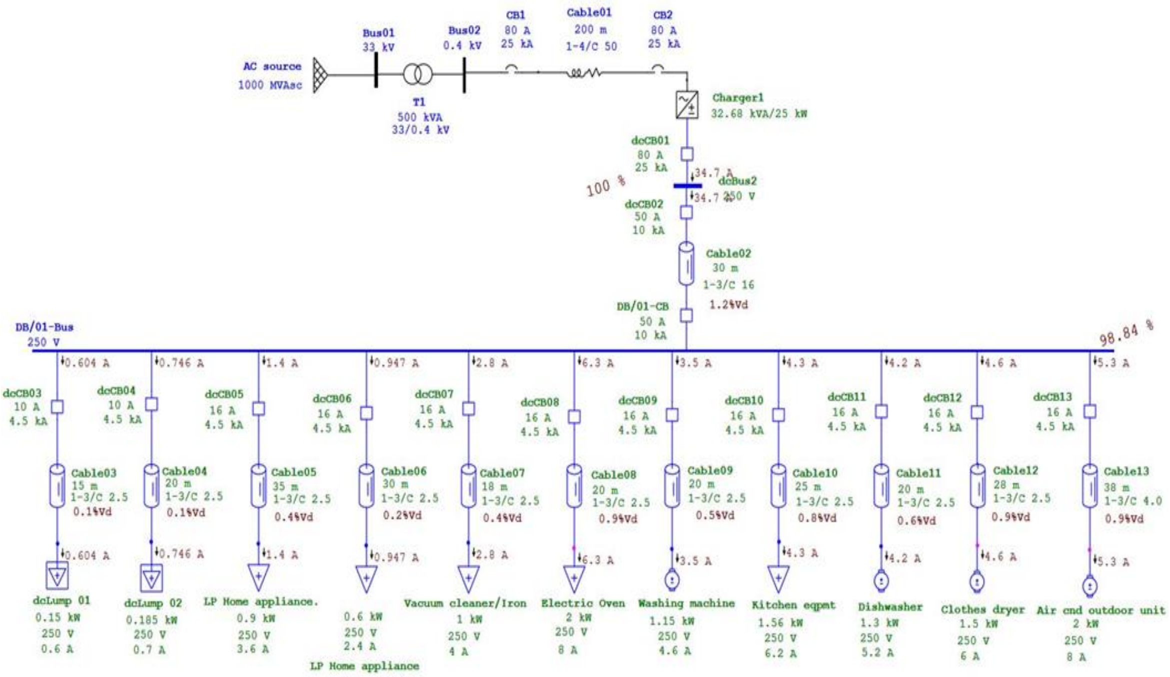

Figure 7. ETAP SLD of 250 V_{DC} distribution

All cables and equipment must be protected from short-circuit and overcurrent faults. In order to protect the lighting circuits in DC networks, miniature circuit breakers with 10A overload protection and 4.5 kA short circuit protection are used. Miniature circuit breaker with 16 A overload and 4.5 kA short circuit current are used for protection of 250 V_{DC} and 320 V_{DC} networks. The typical protection values for the 110 V_{DC} network are similar to 250 V_{DC} and 320 V_{DC} networks in the ETAP model, however only two feeder lines with approximately 2 kW power ratings are protected by miniature circuit breakers with the overload capacity of 20 A in the 110 V_{DC} network when compared to other networks.

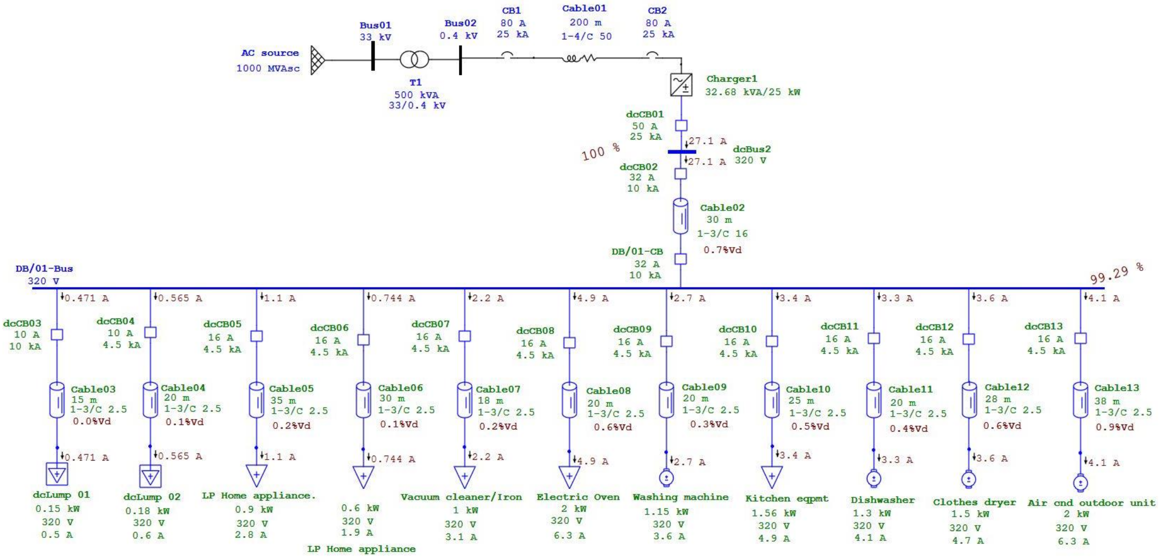

Figure 8. ETAP SLD of 320 V_{DC} distribution

The required total current can be drawn from the main board to the secondary board by a cable with 50 mm^2 cross sectional area, which is suitable for voltage drop and current carrying capacity. After cable optimization, it is necessary to determine the parameters of the circuit protection elements to protect the network from overload and short circuit fault currents. In addition, thermal protection and magnetic protection are required to prevent overload and short circuits respectively. For this reason, compact circuit breakers, which contain both mentioned protections are chosen as circuit protective elements.

For the 50mm^2 cable protection in 110 V_{DC} system, compact switches with 80 A overcurrent and 10 kA short circuit characteristics are installed to the main distribution board output and the last distribution board input Figure 6. In the 250 V_{DC} system for the 16mm^2 cable protection, compact switches with 50 A overcurrent and 10 kA short circuit characteristics are installed to the main distribution board output and the last distribution board input Figure 7. Finally, for the 10mm^2 cable protection in 320 V_{DC} system, compact switches with 32 A overcurrent and 10 kA short circuit characteristics are installed to the main distribution board output and the last distribution board input Figure 8.

4. RESULTS AND DISCUSSION

In order to investigate the proposed house distribution model, various analyses have been conducted. Power analysis, current carrying capacity analysis, voltage drop analysis and harmonic analysis are conducted which are accepted as key parameters for distribution system planning. Analyses are given in detail for AC and DC comparison.

4.1. Model parameters

The LVDC SLD of an ordinary house is modelled in the ETAP program. The responses of the network to different voltage levels are analyzed and corresponding results for 110 V_{DC}, 250 V_{DC} and 320 V_{DC} networks are interpreted respectively. The parameters required for ETAP simulation are calculated and given as follows.

4.1.1. AC source parameters:

The parameters used in AC networks are given as follows, respectively. S_K=MVA which denotes AC source short-circuit power, V_{AC}=33 kV, C is the voltage coefficient, which can be considered 1,1 for medium voltage system. Z=1.1979 Ω, X=1.1919 Ω (X=Z x 0,995), R=0.11919 Ω (R=Z x 0,1) which Z, X, and R denote impedance reactance and resistance respectively. By approximation of the proposed model, the ratio of X/R is given as 10. The impedance is calculated by the expression:

$$Zq = \frac{CV_{AC}^{\ 2}}{Sk} \tag{1}$$

4.1.2. Transformer parameters:

In the network 33 kV/0.4 kV, 500 kVA transformer with the transformer impedance of 4 % is used. The ratio of X/R is selected as 1.5.

4.1.3. Cable parameters:

In the LVDC and LVAC networks, cables with the cross-linked polyethylene (XLPE) insulation and polyvinyl chloride (PVC) jackets are used. DC resistances (per length) of cables are given as 7555.6 μ Ω /m, 4700.6 μ Ω /m, 3140.5 μ Ω /m and 394.6 μ Ω /m for the cross-sectional areas of 2.5 mm^2, 4 mm^2, 6 mm^2 and 50 mm^2 respectively. The short circuit (1 second) current (50 mm^2 cable) is 7,05 kA. After the equipment and parameters are determined, the voltage drop and the current carrying capacity of the cables should be determined for the cable optimization and power analysis.

4.2. Current carrying capacity

The current drawn conductor is prone to face with increased temperature due to its resistance. As the cable heats up, its efficiency decreases. Furthermore, if the temperature exceeds the permissible threshold, it may erode the insulation material and may cause fire. Thermal limits determine the maximum current limit that cables can carry. Nominal current carrying capacities of halogen-free and XLPE insulated cables are given in Table 3. Some repeating cables which have the same properties are not given in Table 3.

Table 3. Nominal current carrying capacities of halogen-free and XLPE insulated cables

ID	kV	Cond./ Cable	Size (mm²)	Length (m)	Phase	Base Amp.	Installation	Allowable Amp. (IEC 60364)	µOhms (25°C) / Unit Length (m)
Cable01	1	4/C	50	200	AC - 3P	209	Embedded Direct	200	394,6
Cable02	1	3/C	50	30	DC	175	A/G Conduit	168	394.6
Cable03	1	3/C	2.5	15	DC	30	Building Voids	28.8	7555.6
Cable05	1	3/C	4.0	35	DC	40	Building Voids	38.4	4700.6
Cable08	1	3/C	6.0	20	DC	51	Building Voids	49	3140.5
Cable13	1	3/C	10	38	DC	69	Building Voids	66.2	1866

Current carrying capacities are affected by the installation method of cables. The correction factor must be applied to the current carrying capacity in accordance with the installation type. Table 3 shows the maximum permissible current carrying capacities of the installation cables according to the installation type. While the current carrying capacity of 2,5 mm^2 cable is 30 A, this capacity decreases to 28.8 A when it is installed inside the building. Maximum current carrying capacity is calculated by using correction factor, where all current values are calculated according to IEC60364 standard [30]. For instance, when the maximum power of the equipment is assumed as 2 kW, the total current demand is approximately 18 A, which is verified by the (2). For 2, mm^2 cable, the maximum current allowed is 28 A. All the equipment can be energized with 2,5 mm^2 cable in the 110 V_{DC} network.

$$P_{(W)} = V_{(DC)} I_{(DC)} \tag{2}$$

4.3. Voltage droop

In the previous section, the installation is examined for current carrying capacities with regard to the correction factors. Due to the resistance of the cable, voltage drop occurs from the secondary output of the transformers to the end user. If the voltage drop is above the limits, it may damage or interrupt the operation of electronic equipment. According to regulations, 0.4 kV voltage at the secondary of the transformer should have a maximum drop of 10 % throughout the line. The voltage drop from the last panel to the lighting and socket load is determined as 3%. Additionally, voltage drop is determined as 1.5% for the motor circuits. The percentage of voltage drop is calculated as in the following expressions. In (3) differences between input and output voltages are calculated and in (4) percentage of the voltage drop is calculated.

$$\Delta U_{DC} = U_{DC2} - U_{DC1} \tag{3}$$

$$U[\%] = \frac{\Delta U_{DC}}{U_{DC}} 100 \tag{4}$$

The potential difference in the network can be computed by cable resistance.

$$\Delta U_{DC} = IR_{cable} \tag{5}$$

Cable resistance for both unipolar and bipolar systems are given in (6) where ρ denotes resistivity, l is the length and S represents the cross-sectional area of the cable. Voltage drop of the DC system is given in (7).

$$R_{cable} = 2\frac{\rho l}{S} \tag{6}$$

$$U[\%] = \frac{P_{(w)}\rho l}{U_{DC}{}^{2}S}200 \tag{7}$$

According to power flow analysis of the ETAP program, cable cross sections of the 110 V_{DC} network shown in Figure 6 are increased when compared to AC or other DC systems due to the voltage drop limits. The voltage drop in the electrical panel feeder cable is 2% where maximum voltage drop from the electrical panel to the equipment is calculated as 2%.

In the 250 V_{DC} network, the voltage drop in the electrical panel feeder cable is 1.2% and maximum value of voltage drop from the electrical panel to the equipment is computed as 0.9% as is shown Figure 7 and finally for the 320 V_{DC} network voltage drop in the electrical panel feeder cable is 1.1% and maximum value of voltage drop from the electrical panel to the equipment is computed as 0.9% Figure 8.

It is important to determine the demand factor of the loads since calculating cable cross section and total demand power on the busbar is strictly related with demand factor [31]. The probabilities of simultaneous operation of each load with the others are given in the Table 4 as demand factor. Since more than one socket is connected to lines 3 and 4 in the system, the demand factor is selected lower than the other demand factors. After the demand factor is chosen, currents are calculated according to demand powers. Table 5 shows cross sections, currents and voltage drops for DC networks.

The demand factor of the busbar at the electrical panel is calculated as 0.72. As a result, by the optimization of the installed power with the demand factor, the demand power in the electrical panel is calculated as 8.88 kW. The total demand current in the bus bar is calculated as 77.9 A, 35.54 A, 27.7 A for the 250 V_{DC}, 250 V_{DC} and 320 V_{DC} networks respectively and 18.9 A for the AC network.

Table 4. Comparison of home appliances for power values, demand factors and lengths

Home Appliances	Power (kW)	Demand factor	Length (m)
Electrical Panel	8.88	0.72	30
LED Lighting	0.15	1.00	15
LED Lighting	0.18	1.00	20
Low Power Home App.	0.90	0.40	35
Low Power Home App.	0.60	0.40	30
Vacuum cleaner / iron	1.00	0.70	18
Electric oven	2.00	0.80	20
Washing machine	1.15	0.75	20
Kitchen equipment	1.56	0.70	25
Dishwasher	1.30	0.80	20
Clothes dryer	1.50	0.75	28
Air cond. outdoor unit	2.00	0.65	38

Table 5. Comparison of dc networks (different voltage levels) for cross sections, currents and voltage drops

Home Appliances	110 V_{DC}			250 V_{DC}			320 V_{DC}		
	Cross section (mm^2)	Current (A)	Voltage drops	Cross section (mm^2)	Current (A)	Voltage drops	Cross section (mm^2)	Current (A)	Voltage drops
Electrical Panel	50	77.9	2.00%	16	35.54	1.20%	10	27.765	1,1%
LED Lighting	2.5	1.4	0.30%	2.5	0.605	0.10%	2.5	0.472	0.09%
LED Lighting	2.5	1.7	0.50%	2.5	0.746	0.12%	2.5	0.566	0.10%
Low Power Home App.	4	3.2	1.10%	2.5	1.4	0.40%	2.5	1.1	0.20%
Low Power Home App.	4	2.1	0.60%	2.5	0.945	0.20%	2.5	0.742	0.10%
Vacuum cleaner / iron	4	6.2	1.10%	2.5	2.8	0.45%	2.5	2.2	0.20%
Electric oven	6	14	1.90%	2.5	6.3	0.90%	2.5	4.9	0.60%
Washing machine	6	8.1	1.70%	2.5	3.5	0.50%	2.5	2.7	0.30%
Kitchen equipment	6	9.6	1.58%	2.5	4.3	0.80%	2.5	3.4	0.55%
Dishwasher	6	9.8	1.30%	2.5	4.2	0.60%	2.5	3.4	0.40%
Clothes dryer	6	10.4	2.00%	2.5	4.6	0.90%	2.5	3.6	0.60%
Air cond. outdoor unit	10	11.7	1.80%	4	5.3	0.90%	2.5	4.1	0.90%

4.4. Harmonic analysis

Transformers, motors, cables and other conductive parts are frequently faced with overheating, explosions and faults in power systems by harmonics [32], [33]. Besides, harmonics may cause malfunctions in electronic cards, switchgear and other protection equipment. Some devices, which are fed from AC networks, have distorting effects (harmonics) on the network. These are currently eliminated by filtering methods. When a DC distribution network is modelled, it should be noted that harmonic analysis should be conducted for the AC side since harmonics caused by the switching of AC/DC converters cause disturbances on the AC network side. For this purpose, each of the switching elements should not exceed the limitations of harmonic distortions, which are employed on the AC network side. The equipment, power values, demand factors and accordingly the currents and voltage drop for AC network is given in Table 6.

Table 6. The 380/220 V_{AC} network properties of power values, demand factors, current and voltage drops

Home Appliances	Power (kW)	Demand factor	Length (m)	Cable cross section (mm^2)	Current (A)	Voltage drops
Electrical Panel	8.88	0.72	30	10	18.9	0.46%
LED Lighting	0.15	1.00	15	2.5	0.775	0.09%
LED Lighting	0.18	1.00	20	2.5	1.1	0.14%
Low Power Home Appliances	0.90	0.40	35	2.5	2.1	0.49%
Low Power Home Appliances	0.60	0.40	30	2.5	1.4	0.28%
Vacuum cleaner / iron	1.00	0.70	18	2.5	4.1	0.49%
Electric oven	2.00	0.80	20	2.5	9.3	1.23%
Washing machine	1.15	0.75	20	2.5	6.3	0.81%
Kitchen equipment	1.56	0.70	25	2.5	6.3	1.05%
Dishwasher	1.30	0.80	20	2.5	7	0.95%
Clothes dryer	1.50	0.75	28	2.5	8.3	1.58%
Air cond. outdoor unit	2.00	0.65	38	4	11	0.20%

The rectifiers with 12 and 24 pulses are characterized with reactance in percent of device rating (X_C=5%) and maximum harmonic order (50). Harmonic analysis is conducted and total harmonic distortion (THD) values are computed. THD is an efficient algorithm for analyzing harmonic impact of the rectifier of the conversion system. THD is computed by using the following equations [34]. Initially, arithmetic summation of magnitudes of all components are computed in (8).

$$ASUM = \sum_{k=1}^{\infty} Vi \tag{8}$$

Then root mean square (RMS) of fundamental plus all harmonics is calculated in (9). Finally, THD is computed according to (10).

$$RMS = \sum_{k=1}^{\infty} \sqrt{Vi^2} \tag{9}$$

$$THD_{voltage} = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + ...}}{V_1} \tag{10}$$

In (8) V_i represents amplitude of the V_{TH} harmonic and V_1 is the fundamental component (50 Hz in the proposed model). Table 7 shows the THD of Bus two for 24 pulse and 12 pulse rectifiers. THD limit should be maximum five percent for IEEE 519 [35] systems, which have rated voltage less than 1 kV. Effects of the THD on the AC network are given in Figure 9 and Figure 10, which reveal signal distortions caused by harmonics.

Table 7. TDH for 24 pulse and 12 pulse rectifiers

Bus ID	Bus kV	RMS	ASUM	THD
Bus 2 - 24 Pulse	0.4	99,77	102,65	1,46
Bus 2 - 12 Pulse	0,4	99,78	102,05	1,93

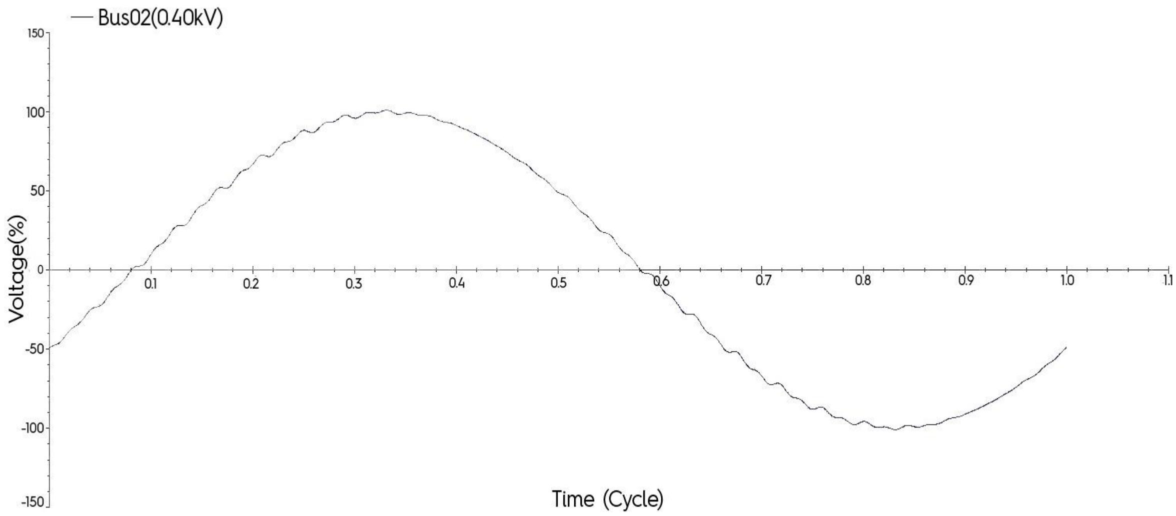

Figure 9. Deterioration in the voltage waveform for 24 pulse rectifiers

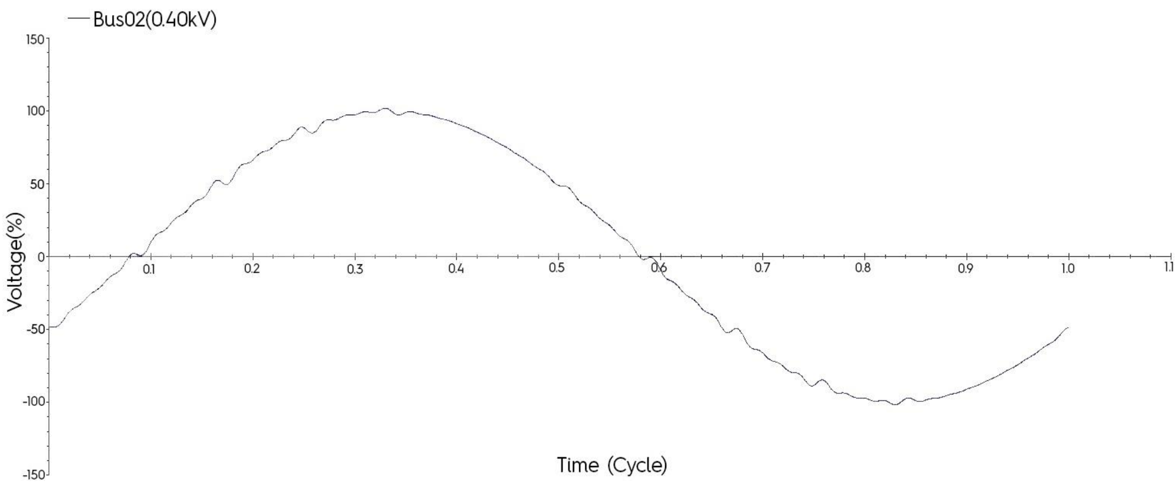

Figure 10. Deterioration in the voltage waveform for 12 pulse rectifiers

4.5. Cable cost analysis and electromagnetic interferences

The power analysis of the model is examined in terms of losses. Cable cross section optimizations have been made by adhering to the voltage drop limits. Since the cable cross sections are increased for low voltage levels, initial cost of the installation will increase. Cost analysis for cable cross sections is given as shown in Table 8. While the total cable costs are at the highest value in 110 V_{DC} distribution and approximately twice as compared to traditional AC distribution, it is at a lower level than AC network in 320 V_{DC}.

Table 8. Comparison of cable costs for AC and DC models

	Cable Cross Sections(mm^2)	Unit Price	220/380 V_{AC}	110 V_{DC}	250 V_{DC}	320 V_{DC}
n2xh	5x10	32,10	30			30
	3x10	20,53				
	3x16	31,62			30	
	3x50	89,68		30		
nhxmh	3x2,5	6,10	231	35	231	269
	3x4	9,60	38	83	38	
	3x6	13,80		113		
	3x10	23,70		38		
Total Cost			2736,90	6160,70	2722,50	2603,90

Electromagnetic radiation was studied for LVDC networks [36], [37]. Common-mode (CM) and radio frequency (RF) electromagnetic interferences (EMIs) in LVDC systems can be decreased with the filters [36], [37]. In addition, the results of the studies show that the rectifier has no effect on the customer-end network CM current [36].

5. CONCLUSION

Recent studies have revealed that the failures in electrical networks tend to result in severe injuries and even deaths. One of the main advantages of the DC system to the conventional AC system is the safety issue of the system. Moreover, most of the transmission companies have a tendency to convert transmission lines to DC, where power losses are significantly decreased in contrast to AC transmission. In this study, an operational typical house is modelled for different rated voltages such as 110 V_{DC}, 250 V_{DC}, 320 V_{DC} and conventional 220V/380V_{AC} for comparison of the system operation under different voltages. Because total human body resistance in 110 V_{DC} is the highest level, it provides the lowest current level which passes through the human body. Therefore, 110 V_{DC} network is observed as the safest network among other DC systems. According to power analysis carried out for each three different voltage levels, the cable cross sections for the 110 V_{DC} system have been increased in some equipment to achieve voltage drop standards among other DC systems. By employing 250 V_{DC}, cable cross sections are the same with conventional 220 V_{AC} systems, however with the increasing voltage as in 320 V_{DC} system, cable cross sections are decreased (2,5 mm^2). When the system is examined in terms of circuit breakers, it is observed that the circuit breakers are inversely proportional to the voltage levels in the system. The capacities of the circuit breakers have been increased due to the high current values generated by the voltage differences. For these reasons, the initial installation cost of the system is inversely proportional to the rated voltage value. Furthermore, it is observed that the total harmonic distortion generated by the inverter on the AC side of the DC network decreased when the system has a rectifier with 24 pulse rather than rectifier with 12 pulse. When harmonic generating equipment operates on the grid such as motor speed control drivers, electronic ballasts, UPS, harmonic distortions can reach disturbing levels. In order to reduce THD, rectifiers with higher number of pulses can be used in addition to harmonic filtering methods, however this increases the initial cost of installation. In this study, a typical residential building is investigated for different DC distribution systems (different voltage levels) in detail as a novel approach since LVDC systems are recently introduced systems which needs to be examined in terms of electrical behavior. With the higher compatibility, increased safety, reduced losses and the advancements in electronic conversion techniques LVDC distribution will be considered frequently in electrical networks.

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