Review on A DC Environment for PV-Powered Household Appliances

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Abstract- DC power has spread back, especially in residential microgrid PV systems, as a variety of modern electronic loads became available commercially. The compatibility of household appliances with a DC distribution system with the best voltage-level is the areas that not yet made a practically extensive appearance, and it is still in the research phase. This work mainly explores these issues by 1) providing a review on the concerning research efforts, 2) identifying the gaps in the existing knowledge, and 3) exploiting the recent advances in the commercial household appliances. The paper discusses the electrical diagrams of household appliances, classifying them, and understanding how each one consumes the power. The work also extrapolates a new architecture to reduce the losses of the overall system and grow its efficiency up. These improvements are achieved by proposing a DC-environment with two levels of voltage to cover all the recently produced appliances. The energy transfer efficiency is the key factor that calculated to evaluate the appliance performance. The study outcomes can serve as a guide for establishing standardizations for DC microgrid and designing a more efficient DC power distribution networks with minimal energy converters.

***Keywords* - Household appliances, DC microgrid, architectures, power supply, smart grid, and standardizations.**

I. INTRODUCTION

THE conventional battery-based on-grid or off-grid PV systems are usually based on the AC bus of a power distribution, where the PV power is regulated to provide the DC link employing an MPPT-based charge controller. The battery voltage indicates the level of the system DC bus and thereby, the inverter uses this voltage level to generate the AC bus, which represents the appliances AC distribution. This scheme has many components that expose losses, even when using high-quality equipment. The efficiency values per each stage were indicated according to the corresponding researches in the literature [1][2]–[9]. To account for the efficiency uncertainty for the proposed system components, Table I lists a range of efficiencies of main components addressed in the literature.

TABLE I
RANGE OF THE EFFICIENCIES FOR THE MAIN COMPONENTS OF A GRID-CONNECTED PV MICROGRID SYSTEM.

Description	Min μ	Max μ	Source
DC-AC inverter	0.85	0.99	[10] [9]
AC-DC converter	0.9	0.95	[11] [12] [9]
DC-DC converter	0.8	0.9	[13] [14] [9]
Solar-Battery charger	0.95	0.95	[15] [9]

The efficiency is denoted by (μ).

Traditional DC microgrid systems show about 81% efficiency, as shown in Fig. 1 (a). Technological difficulties of existing systems are concerning the use of DC/AC inverters that consequently requires a phase synchronization of some system elements, especially when combinations of parallel power sources are employed. Also, such AC bus systems have facing the presence of a reactive power that never exists in systems of pure DC-bus solutions. Numerous recent studies develop a DC distribution system to overcome the power conversion losses of the conventional configuration since the local market offers appliances with an electronic power supply that consumes DC power. This scheme can be configured, as shown in Fig. 1 (b), where the overall efficiency has increased due to dispensing use of a DC-AC inverter, thereby no AC bus, but with limited appliances and there are still DC-DC converters in the system.

Regardless of inverters' self-consumption during the standby, the major difference between the two above architectures is the effective efficiency between DC-AC inverters and DC-DC converters in actual operating conditions. Furthermore, the average value of using direct solar power or energy storage needs to be taken in to account for calculating the conversion efficiency between AC and DC systems. The proposed system aims to overcome 1) the losses problem due to power conversions and, 2) the limitations of using locally available appliances based on the recent advances in the household appliances towards electronics dependency in power-consuming. A voltage-matching of a source-load concept is adopted to solve these problems by configuring batteries

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for the DC-bus such that the fully-charged voltage of their series connection (V_{FC}) should be equivalent to the PV voltage at MPP (V_{mp}). This system provides a tap voltage less than V_{FC} appropriates for the resistive appliances category, we call this voltage level as (V_{FCR}). A detection circuit to extinguish the resistive load category is essential to select automatically between V_{FC} and V_{FCR} when resistive appliances being connected. The proposed scheme with the estimated efficiency is demonstrated in Fig. 1 (c).

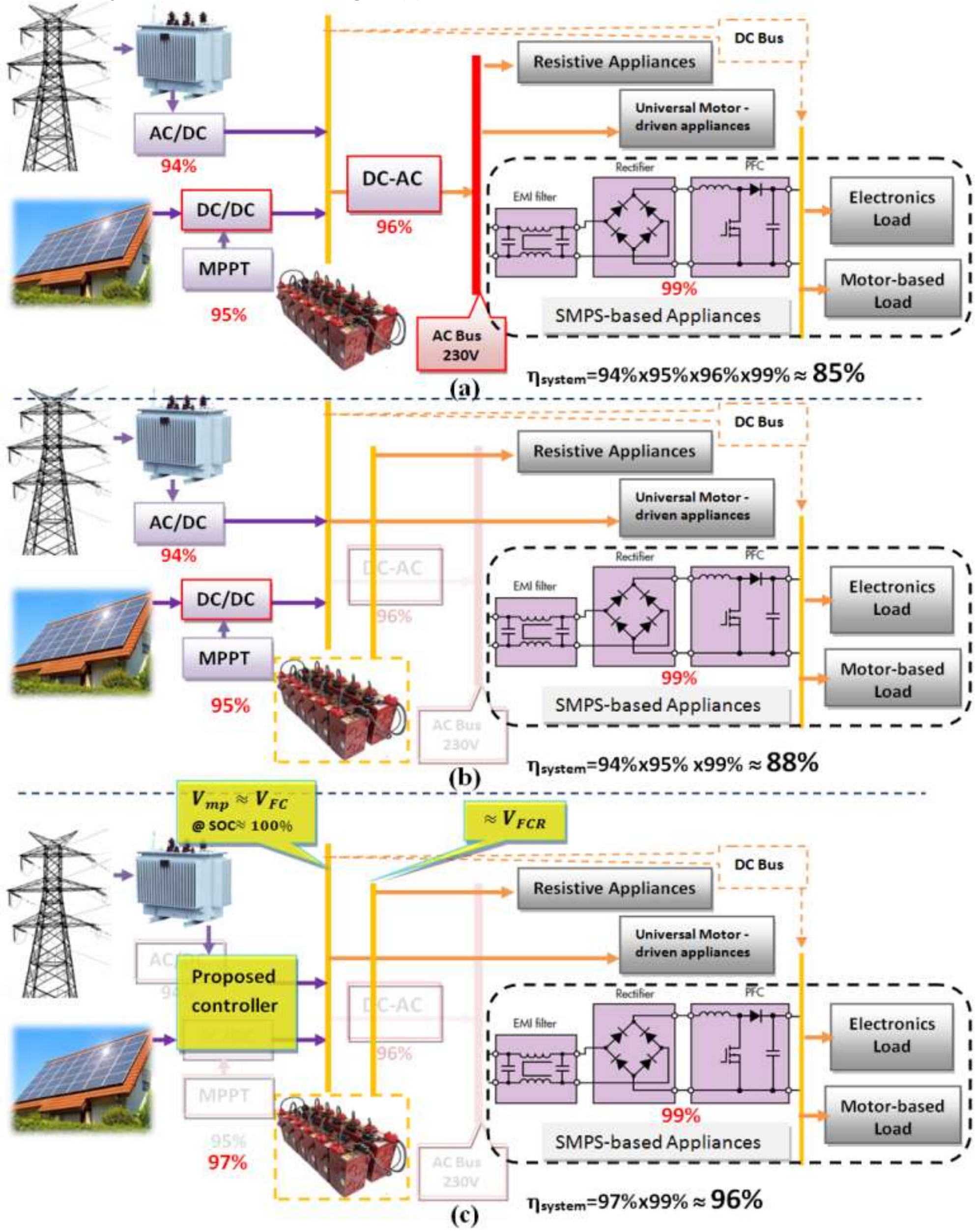

Fig. 1. DC microgrid with Storage topologies: (a) ON-grid traditional with DC distribution includes AC bus, (b) solar farm power source and DC distribution with no inverters, (c) recommended DC distribution system for recent household appliances.

However, the importance of proposed configuration appears because the future residential buildings seem to remain to depend on the grid as a main power source for the prospective future because the cost of switching to fully off-grid is currently higher and more complex than a need for the PV alternative supply with energy storage. Generally, these aspects activate a robust argument to investigate the prospect benefits of directly connecting DC energy sources with household appliances of a residential building, since this architecture can avoid the conversion losses of the intermediate DC-AC and AC-DC circuits.

To analyze power consumption in the microgrid system, modeling with standards describing components are essential for low voltage DC systems; IEEE Std. 399-1997 [16][17], and IEC 61660 [18], that cover the load flow and the short circuit computations of DC auxiliary power networks. Loads according to these standards are modeled as constant resistance (CR), constant current (CC) or constant power (CP) loads, based on load characteristics. The steady-state characteristic as a general load modeling can be given by [19]:

$$P(V) = A_{CP} + A_{CC}V + A_{CR}V^2 \tag{4}$$

where A_{CP} denotes CP coefficient, A_{CC} denotes CC coefficient, and A_{CR} denotes the CR coefficient. The model described (4) is not appropriate for all categories of the resistive loads, since some resistive loads such as an incandescent lamp, where its consumption is a function of current.

The work proposes a DC link equivalent to the DC value of the 230 V AC of the utility grid and connects to the PV source based on a voltage-matching of a source-load concept. This concept is applied by configuring batteries for a DC-bus such that the fully-charged voltage of their series connection (V_{FC}) be equivalent to the PV voltage at MPP (V_{mp}). An auxiliary voltage less than V_{FC} sets to appropriate the resistive appliances category, which is equivalent to the active power of the 230V AC, thus 230V DC, this voltage level called (V_{FCR}). The work also includes a classification for the recently produced appliances, and basically, the criteria are relied on: practical experiences, related publications, and datasheet of appliances. Details of each category will discuss in the later subsections. A data acquisition card, with a sampling frequency of 11.67 Hz, has been employed for monitoring the power consumption and capturing the potential surge power that might happen in the starting time from the refrigerator operation [20], [21].

II. CLASSIFICATION OF HOUSEHOLD APPLIANCES

To investigate the compatibility of household appliances with DC sources, this work classifies the appliances into four categories according to the way that their components consume electrical power. Therefore, the classification is resistive, electronic, and motor-driven appliances [22][23], as well as universal motor-driven appliances. There is a mix between these categories, as represented by the hairdryer. The other two categories have a common circuit called switching mode power supply (SMPS), which initially converts the input power into DC when receiving the power from a source. These two categories are electronic appliances and motor controller-based appliances.

2.1 Resistive Appliances

According to the above literature, resistive appliances can directly connect with the DC-link through an appropriate fuse and circuit breaker (CB). A DC value of (220-230)V that equivalent to (220-230)V AC is appropriate for this category of appliances. A coffee maker, Rice cooker, and Electrical stove are resistive load with a heating coil, they consume power at a constant rate, but the induction stoves that are using nowadays heat the cookware directly through electromagnetic induction and require pots and pans with ferromagnetic bottoms [24]. Five types of heaters have tested, that are curling brush, coffee maker, kettles, stove, and sandwich makers. The measurements of the steady-state tests show that all the heaters have constant resistance characteristics [25]. Fig. 2 demonstrates the operations of comparing the AC and DC power source when applying on resistive load and shows their output power waveforms.

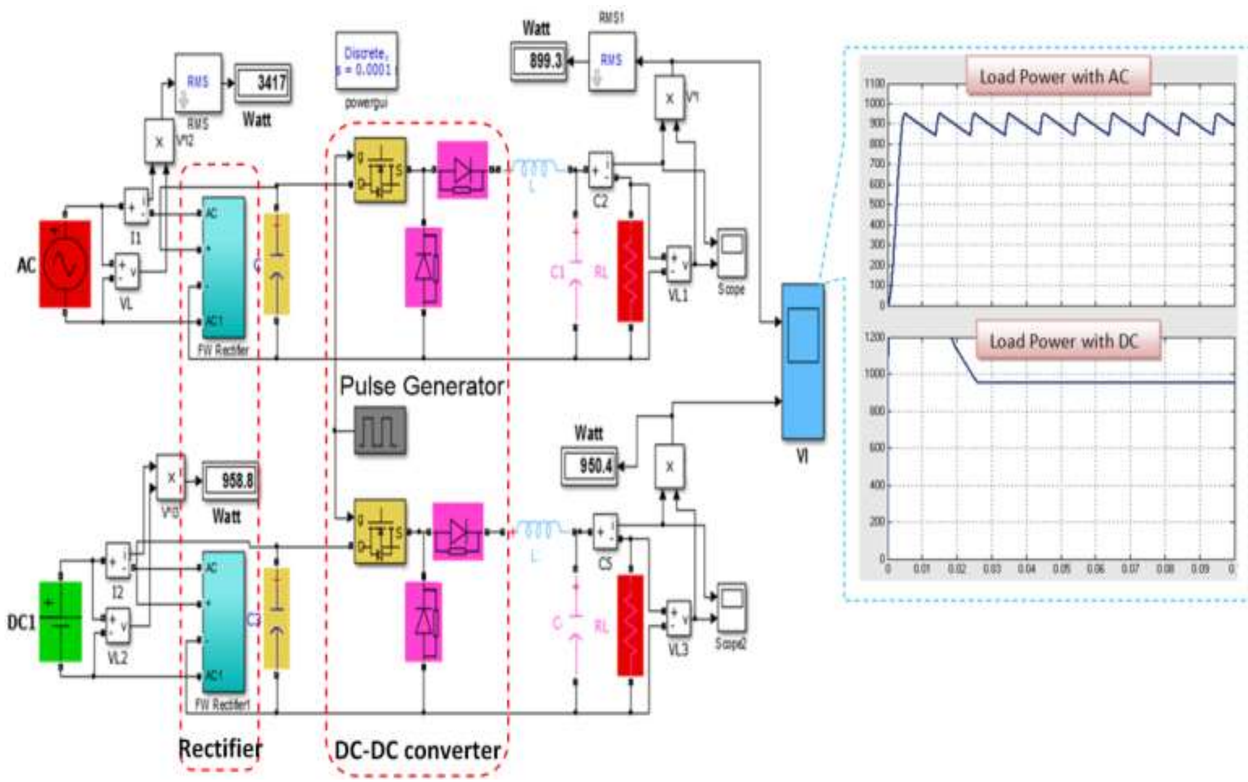

Fig. 2. AC vs. DC as a power source applied at Electronic load, and output waveform

All resistive loads are possible to function with DC without any amendments, but the problem appears when the appliance has switches inside, which are not appropriate to interrupt a DC [19][5]. Moreover, incandescent lamps are affected by overvoltage, which reduces their life. In contrast, lighting compatibility with DC is completely solved by LED lights that will discuss in the next section within the electronic appliances. Some of the common resistive appliances (traditional and their corresponding DC ones) are listed in Table II.

TABLE II
COMMON RESISTIVE APPLIANCES (TRADITIONAL AND THEIR CORRESPONDING DC ONES).

	Traditional appliance	Alternative towards DC compatibility	References
1	coffee maker	Electronic coffee maker	[26]
2	Rice cooker	Electronic Rice Cooker	[27][28]
3	Electrical stove	induction stoves	[24]
4	incandescent lamps	LED lights	[8]

2.2 Universal Motor-Driven Appliances

The universal motor is included in some household appliances, such as mixers, vacuum cleaners, and some home electrical tools, such as saws and drills [29][30]. It uses a commutation and performs similar to a series-motor, consumes the same current regardless of the power source type, the current flows via both the field-excitation windings, which is the stator, and the armature windings, which is the rotor through its brushes in a one closed path. The universal motor can be defined as the series wound commutated motor where stator windings are connected in series to rotor windings, the brush type commutation enables to reverse the motor current direction when it rotates to create regular torque. The universal motor can operate on both AC or DC supply [31][21] because it consumes the same power that establishes the magnetic field of the stator, which will flow through the windings of the rotor. It is usually used in AC household appliances because it offers a certain desirable sort more general to the DC motor. The universal motor also offers a high starting torque with more compact size than that induction equivalent. They are usually used in applications requiring high speed, irregular operation, such as; Vacuum Cleaners, Power Tools, and Food Mixers. Universal motors usually operate between 15000- 20000 RPM, while the AC induction motor commonly cannot operate over 3500 RPM [32].

A disadvantage of utilizing such a motor is the restricted life of the brush or the commutator. Traditionally, universal motors presented a reasonably priced way to attain high-speed operation for small appliances, in spite of these downsides. On the other hand, like variable speed inverter drives (used with induction motors and permanent magnet motors) it becomes more readily available in the local market to change to universal motor-based machines [33]. DC-powered universal motor joined to a constant torque can be shown in Fig. 3.

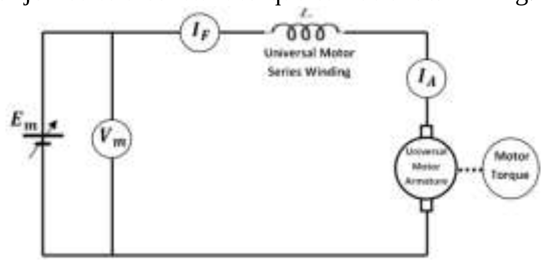

Fig. 3. DC-powered universal motor joined to a constant torque.

For constant-power motors, the power consumption is fixed, and its bandwidth control faces a Negative Incremental Resistance. Therefore, voltage-current instantaneous value of the impedance is positive (V/I> 0), while the relative rate is a negative (dv/di <0) [34]–[38]. To maintain the stability point, the system needs to keep running on a specific point against any disturbances. The steady-state operation of a system can be obtained when satisfying the balance between the source and constant-power load voltages.

Appliances' manufacturers are continually developing to integrate more advanced electronics to appliances' functions that also include their motor drivers. The development in motor-driven appliances pushes toward further energy-efficient appliances, which starts by replacing AC induction motors by BLDC motors. The future step will be moving toward a lower level of operation voltage to offer more safety, lower costs, and more precise control for both consumers and manufacturers.

2.3 SMPS-Based Appliances

One of the recent advances in household appliances is the wide dependence on power electronics for handling the energy from the source to the consumer components. A switching mode power supply (SMPS) is an electronic circuit in most appliances to transfer electric energy from a power source to a load [39], [40]. The main functions of a typical SMPS are; 1) to change the current from the grid AC to DC power, which is required for electronic circuits; 2) to regulate the main input voltage when varies worldwide between 100 to 240V as the circuit components normally require stabilized voltage; 3) to provide safe isolation, which is required in most low-voltage output applications to be isolated from input. In such devices, the switching semiconductor device handling the power by switching with high frequency the transfer of electric energy via energy storage components, inductors, and capacitors. By varying the duty cycle and frequency, the device can control the average value of output voltage or current [41], [42]. The existence of SMPSs in various household appliances compositions is in a continuous increase. The conceptual circuit diagram of a typical SMPS is shown in Fig. 4.

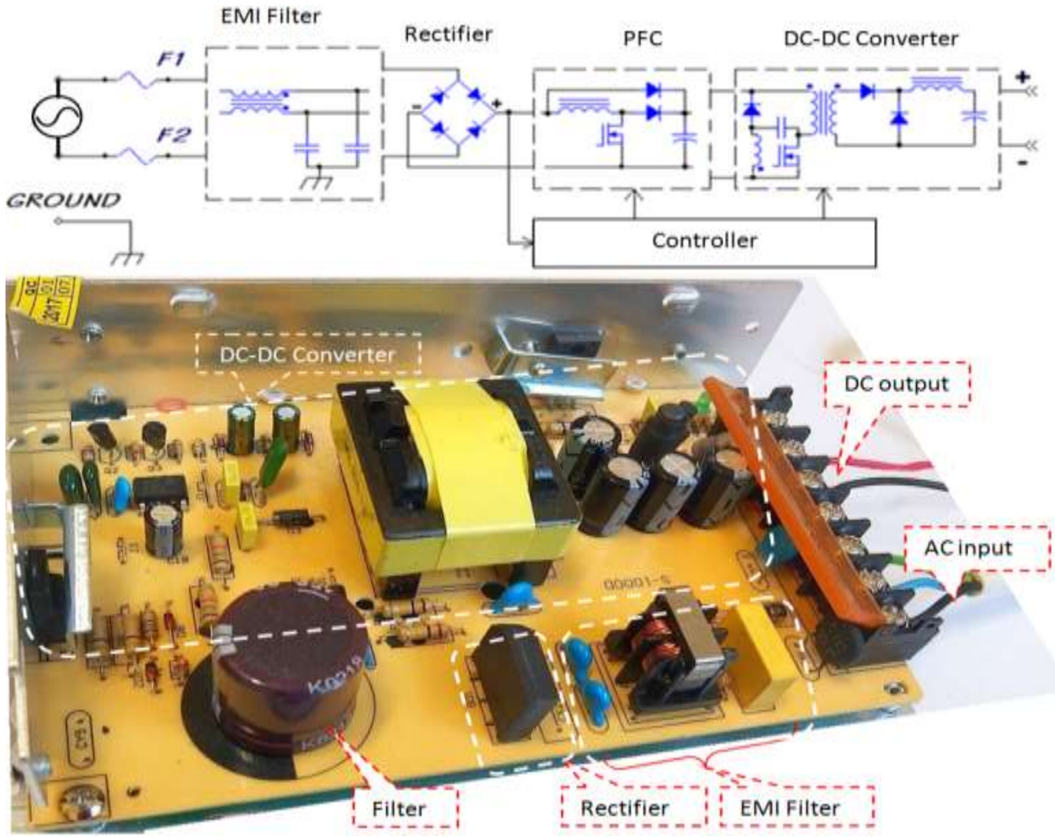

Fig. 4. The conceptual circuit diagram of a typical SMPS.

AC power initially passes via a fuse and a line filter before it is rectified via full-wave bridge diodes. Then the rectified output wave is passed via a power factor correction (PFC) circuit that is a pre-regulator to be applied to the DC-DC converters. PFC is a passive or active circuit utilized to certify that the line current harmonic content of a device connected to the AC supply is limited to meet regulatory standards [43]–[46]. To prevent the interference between devices and limit high-frequency currents getting back into the AC line within acceptable levels, the low-pass EMI filter is used. The DC-DC converters run off the PFC output to generate single, or several DC busses feeding the load and provide input-output isolation. Several topologies for DC-DC converters, buck converter with single or multi-level outputs are commonly used in household appliances.

As mentioned in the previous section, the greater influence of energy losses in distribution systems results from power converter dissipations. For understanding the possibility of saving energy with DC-distribution, the efficiencies of these converters need to be studied. As per power supply manufacturers, the efficiency of AC-DC converters grows with power output. Individual AC/DC adapters for household appliances have analyzed by Lawrence Berkeley National Laboratory (LBNL) and reported that the estimated average efficiency is about 68%, and 90 % for rectifier circuits only [47]. Exchanging to centralized conversions, such as the proposed DC bus, is an efficient topology due to eliminate excessive dedicated conversions, make possible potential improvements, and simplifies the supply system.

2.4 Electronic Appliances

The production of SMPS-based appliances has witnessed a significant increase in the last few years. All these loads have a common topology through which they consume the input power. According to own experimental tests and many studies, all these products can be operated on AC and DC power sources [21], [23], [48]–[53]. It is worth mentioning that the very old electronic appliances use a low-frequency transformer for stepping down the input and then rectified using bridge-diode that works only within narrow voltage and frequency range with low efficiency. In contrast, SMPS has a wide range input; it can be supplied with 100–240 V/50–60 Hz, which corresponds 90–265 V DC. Therefore, the power consumption of electronic appliances does not highly influence by voltage fluctuations under DC distribution systems. As mentioned earlier, the use of a DC power adds a possibility to remove the input rectifier from appliances and adds improvements on system efficiency [52], [54]. As it's well known, diodes present conduction and switching power losses (P_L), which is given by:

$$P_L = D.V_f\,.I_f \quad (3)$$

Supposing zero turn-off and turn-on times of the diode, because they are much smaller than the switching period. D is the duty cycle, V_f is the forward voltage and I_f is the forward current. Conduction losses occur because of the built-in potential and non-zero on-state resistance. In (3) the forward voltage keeps account of both of them. Explicating (3) can be written as:

$$P_L = D * \left(V_{bi} + R_{on} + I_f\right) * I_f = D * I_f * V_{bi} + D * R_{on} * I_f^{\,2} \quad (4)$$

The power losses in the off state are often negligible. Besides avoiding losses, removing the input rectifier gives another advantage [55].

To verify the ability of DC power to drive electronic appliances within the SMPS-based category, an experimental test has been conducted on a 19" LCD monitor. Since the electronic appliances are internally DC, their power supply has a DC-DC converter, which always has a wide range of supply voltage levels. Since energy transfer efficiency is the key factor that adopted to evaluate the appliance performance, the efficiency, which represents the ratio between the delivered power of the DC supply and the consumed power by the monitor, was calculated. The measurement parameters and efficiency results are listed in Table III.

TABLE III

DC VS. AC SUPPLY COMPARISON FOR AN ELECTRONIC APPLIANCE (19" LCD MONITOR) TEST

Supply Type	**DC**	**AC**
Power supply voltage (V)	101	12
Power supply current (A)	0.1	2.21
Inverter	No	Yes
Load Voltage (V)	101	240
Load Current (A)	0.1	0.0424
LCD Consumption (W)	10.1	10.18
Efficiency	99 %	10.18/(12*2.21)=38.38%

The experimental test shows the significant difference of efficiencies of the direct source-load over the source-inverter-load configuration from one side and the successful operation of using DC power instead of AC for an electronic appliance that commercially available as an AC-powered load.

2.5 Motor Controller Based Appliances

The variable speed controller is used to control the speed of a compressor motor to regulate a setting temperature continuously. Nowadays, appliance designs are changing to a brushless DC motor (BLDC) since it offers lower audible noise, high efficiency, a high degree of control, higher power density, and a long lifecycle. BLDC requires more complex electronic as driving, management, and sensor schemes when compared to a traditional AC induction motor. BLDC can be more efficient than induction motor with about 10% age point [32]. Several researchers analyzed the motor-driven load to behave as a constant power load, where a DC-AC inverter is tightly regulated and used to control the motor speed. These studies show that when the motor rotates, it behaves with torque-speed characteristics of a linear relationship [56]–[61]. For appliances such as refrigerators and washing machines, the key feature for energy improvements is to drive and control the mechanical powers [62]–[64].

2.6 Compressor-Based Air-Conditioner

In conventional refrigerator and air-conditioner, the compressor includes an AC induction motor and limited to a fixed running speed. The rotation of the shaft must be a particular multiple of the input line-frequency, reduces by a small percent. Running the compressor with a fixed-speed causes strong influences on compressor mechanics, piston or scroll, and the whole temperature control mechanism. This type of compressor operation is controlled simply via a thermostatic scheme [64]. Accordingly, it is not possible to run such types of appliances with DC supply.

Fortunately, the recent advances in household appliances have represented through the dependence on electronic components for handling the source electrical energy to drive their equipment. The outcome of the experimental inspections for all these commercial appliances has proved that they are also SMPS-based appliances since the SMPS is the input power stage. Therefore, It is possible to operate such types of appliances by a DC power supply directly; this voltage is preferred to be with a DC level equivalent to the input AC. Like a refrigerator, the fan of the indoor evaporator, outdoor condensers, and the compressor for a split air-conditioner, in LG brand as an example, are with an electronic power driver to control the motors' speeds. They are commercially called inverter technology-based appliances with a variable speed motor-driven compressor.

The evaporator fan and compressor will increase the speed and, consequently, cooling power when the set point is lower than the current temperature while running at a low speed otherwise. The saving energy concept in this type considers the low-speed rotation for the compressor but rise in high rate acceleration to achieve the set temperature. At this time the compressor slows down the rotation speed but in such manner that this running maintains the gas pressure for keeping the temperature constant by fluctuating over the setting value with low ripple rate [65], [66], as shown in Fig. 5. The block diagram of an air-conditioner with a variable-speed compressor/motor is demonstrated in Fig. 6. The red circles represent the points at which the direct DC power is proposed to connect.

The AC-DC rectifier block creates a high-voltage DC bus, typically 311 V, which powers the inverter circuit, and includes insulated-gate bipolar transistors (IGBTs) or power MOSFETs. The driving circuit requires auxiliary voltage levels: 3.3 or 5 V DC for the microcontroller and 12-15 V for the feedback circuitry and gate drivers that produced by the SMPS. The generic schematic diagram of an air-conditioner with a variable-speed compressor/motor is shown in Fig. 7.

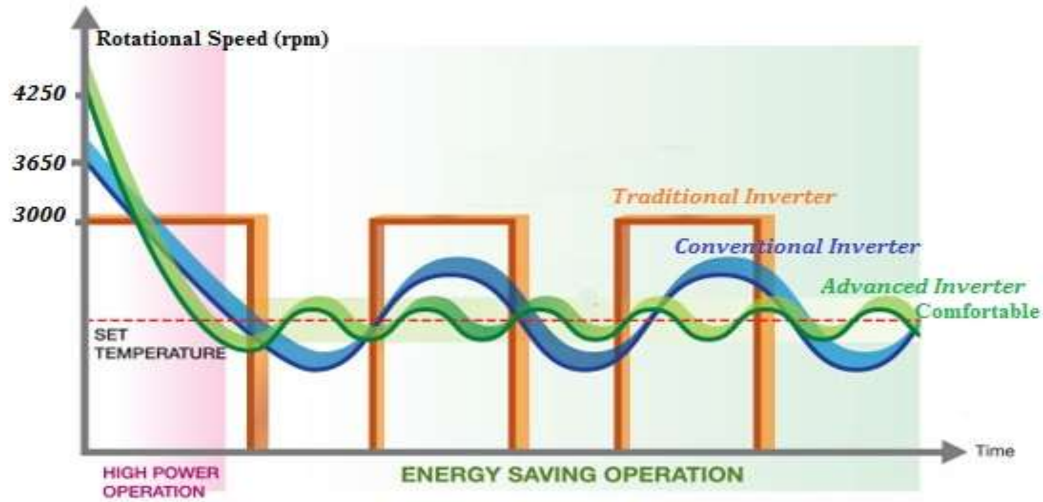

Fig. 5. Variable speed-based compressor operation as compared with a traditional one.

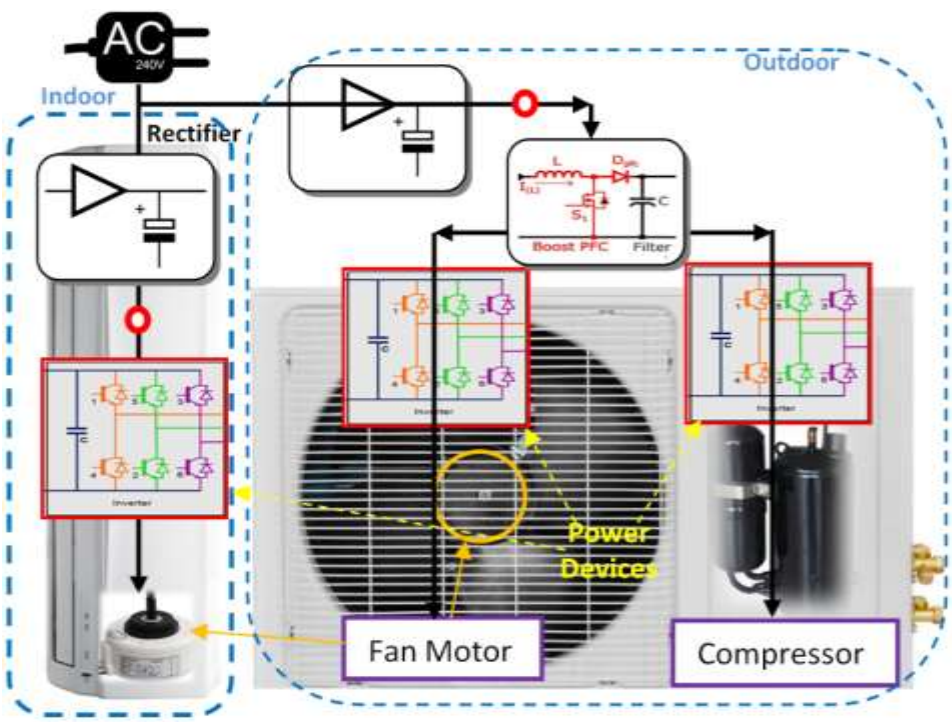

Fig. 6. Block diagram of an air-conditioner of a variable-speed compressor/motor.

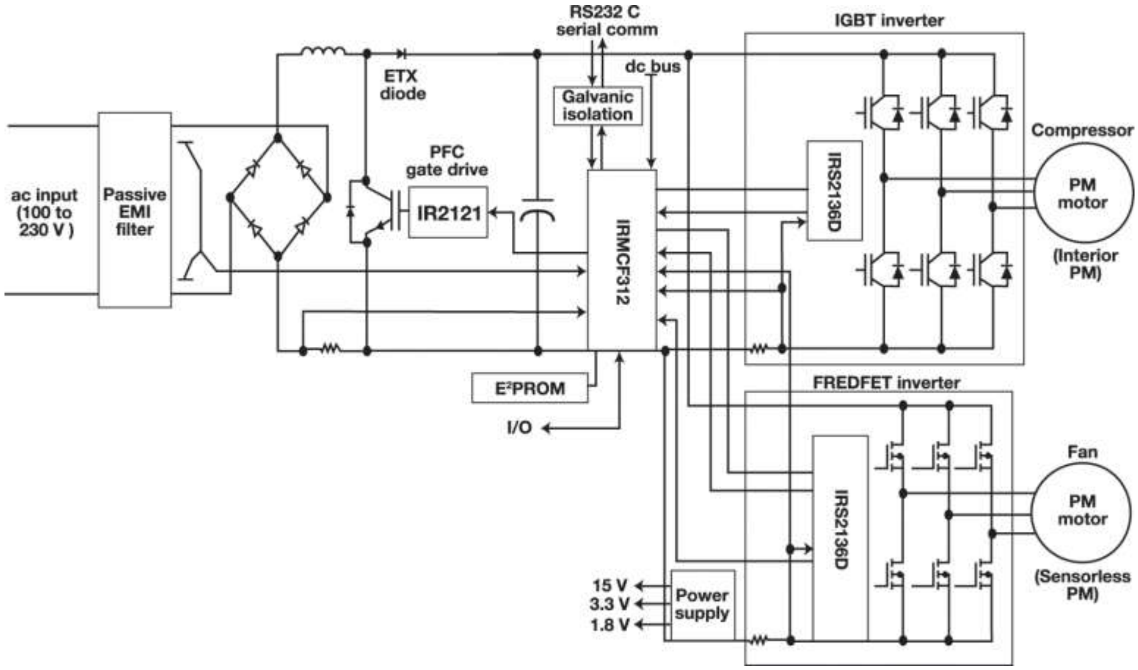

Fig. 7. A generic schematic diagram of an air-conditioner with a variable-speed compressor/motor.

Unfortunately, when we checked the components, we found that the fan of the outdoor condenser was a single-phase induction motor with a fixed speed, where it is not yet changed to be controlled electronically. Therefore, we replaced it with a fan of 24V BLDC motor. A DC power with a voltage level ≈310V DC was used to operate the air-conditioner, while a 24V SMPS is used to provide the 24V to the fan. The experiments have been conducted on an air-conditioner of LG brand, 1.0 HP, Btu/h= 8600, 3.9 Amp, 220-240 V, 50 Hz [67]. A wireless ZigBee-based monitoring circuit with current and voltage sensors were utilized to record the energy measurements at a sampling frequency reach 123Hz maximum [21].

Like the conventional air-conditioner, the consumption profile of the new inverter-based air-conditioner starts with the indoor fan and biasing power consumption of electronic elements for several minutes. Then the compressor smoothly starts run with growing speed according to the difference between the set and the actual temperatures. The electronic-based control strategy of variable speed variable voltage (VVVF) performs a significant behavior with lower consumption as compared with the traditional one, which consumes about three times its rated power [65], [68]–[70].

An energy measurement has been conducted to test the performance of inverter-based air-conditioners under operating conditions, a normal AC power and the proposed 310V DC supply, as shown in Fig. 8. It is found that this air-conditioner consumes electricity amounting to 11.466 kWh, including the DC-AC inverter for the (DC source-inverter-load) configuration (red color) while amounting to 9.850 kWh per day when connected directly to the proposed DC for the (DC source-load) configuration (blue color).

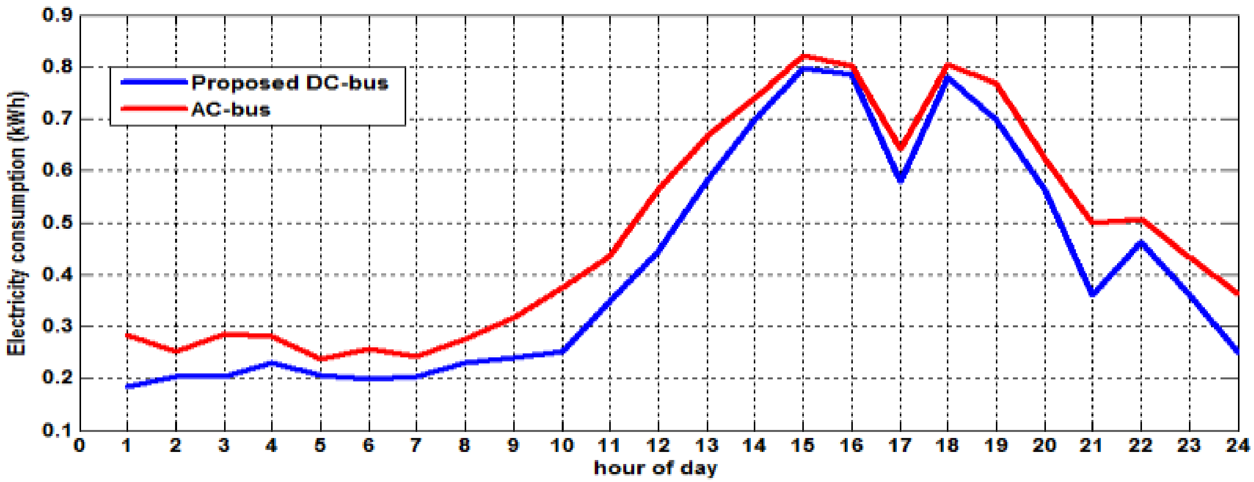

Fig. 8: Air-conditioner energy consumption over a day.

From this experiment, It can be concluded that the curves of the power consumption under AC and DC tend to be converged when the average consumption becomes higher, which occurs at noon period (14:00-19:00). This converges due to the rise of the inverter's efficiency when the power approaches (70-80)% of its maximum. The total daily energy is calculated by the integration of the area under the power curve over the daytime employing the Trapezoidal method. This result indicates a significant difference in energy consumptions between the traditional and proposed topologies, especially at lower levels of power.

2.7 Motor-Driven Appliances (Washing Machines)

The conventional washing machine generally depends on an AC induction motor to drive mechanical parts, which allows high torque for washing cycles and high spinning speed. Performing both tasks, washing, and spinning in a single motor will reduce the system cost and weight. In the recent years, a variable-speed electronic drive is used but with permanent magnet motors that deliver higher torque as compared to the consumed current, which improves the system energy efficiency and their linearity advantage of torque-speed characteristic [71]. Different components have used to implement the controlling of the motor speed electronically, where a microcontroller or digital signal processing (DSP) with IGBTs is the most commonly used. The common circuit diagram for a variable speed controller of recently produced motor-driven washing machines can be described in Fig. 9, where the red circle shows the point at which a DC power possibly be connected.

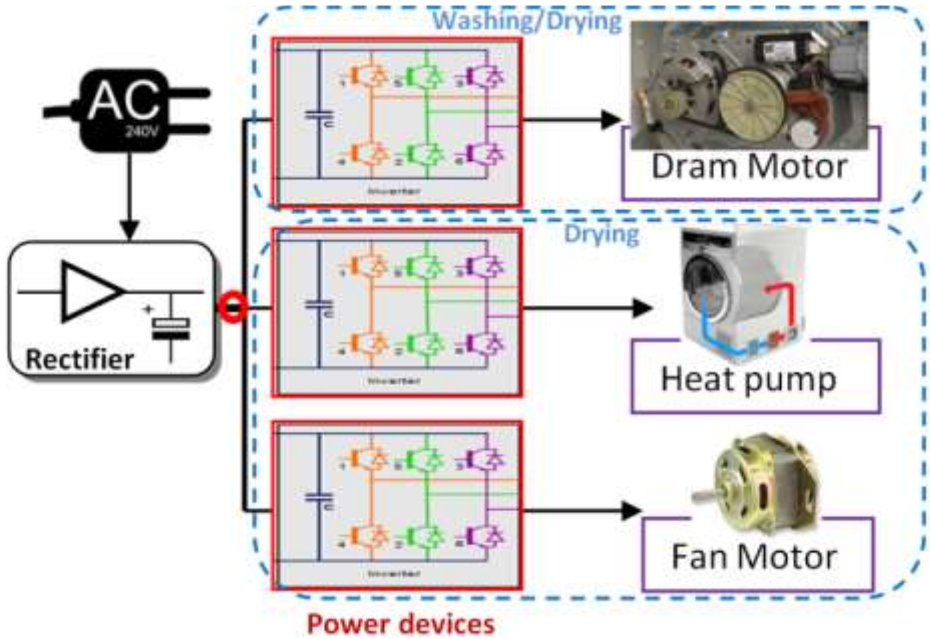

Fig. 9. Block diagram of the speed-controlled motor-driven appliance (Washing Machine).

III. Appliances Comparison Results

In order to validate the proposed configuration (DC source-appliances) and show its effectiveness over traditional one (DC source-inverter-appliances), experimental energy measurements have been conducted for the most common appliances and the quantitative comparison are listed in Table IV**Error! Reference source not found.**. Based on the savings that were harvested when switching to the proposed topology, the results verify the hypothesis of the work that is based on the voltage-matching concept in a DC system.

TABLE IV
Energy Experimental measurements for common when switching to the proposed system.

Appliance	P (W)	h/day	AC (Wh)	NDC (Wh)	PDC (Wh)	SwAC (Wh)	SwNDC (Wh)
Light bulb	60	12	797	728	722	75	6
Oven	800	1.5	1676	1380	1208	468	172
Rice cooker	500	0.75	412	387	375	37	12
Kettle	700	0.5	387	364	354	33	10
Washing machine	500	0.95	523	489	475	48	14
Vacuum cleaner	300	2	656	634	613	43	21
Iron	900	0.3	308	287	276	32	11
Refrigerator	125	13	1804	1661	1629	175	32
Split unit air conditioner	800	12	11466	9975	9850	1425	154
Laptop	50	7	398	382	353	45	29
CPU, LCD monitor, Printer	230	5	1320	1198	1156	164	42
19”, LCD television	90	5	508	465	454	54	11
Electric stove plate	850	1	943	869	853	90	16
Juicer mixer grinder	230	0.1	31.4	25.3	23.7	7.7	1.6
Total Daily Savings (Wh)						2696.7	531.6

P is the power, h/day is the On-time hours/day, AC (Wh) is the AC-bus Daily energy (Wh), NDC(Wh) is the New DC-bus Daily energy (Wh), PDC(Wh) is the Proposed DC-bus matching Daily energy (Wh), SwAC is the Saving w.r.t AC-bus, SwNDC is the Saving w.r.t New DC-bus, and (w.r.t) denotes the (with respect to).

IV. Conclusions and Future Directions

After discussing electrical diagrams of household appliances, classifying them, the recent advances in each category, and understanding how each one consumes the power, a new architecture has been introduced to reduce the losses of the overall system and grow its efficiency up. These improvements are achieved by considering the DC-environment of a single battery bank with two levels of voltages for all the locally available appliances.

1.1. Conclusions

1) This effort offered an extensive survey about the works carried out on the recent advances in household appliances and their compatibility with DC microgrids and DC power systems. This can provide a clear view to know where we are standing and how to benefit from the provided guidelines to continue toward more efficiency, eco-friendly, smarter, and economical energy systems relying on the DC system.
2) Fortunately, the recent advances in household appliances have represented through the dependence on electronic components for handling the source electrical energy to drive their equipment. Therefore, these revolutions enable them to be operated under the DC environment with appropriate voltage levels.
3) From conducted experiments and Table IV outcomes, it is found that the efficiency and reliability of a power distribution system can be better performed when decreasing the number of power conversion devices starting from the flow of power from sources (utility grid, solar PV, wind turbine, or on-site power generator) to consume by loads (household appliances).
4) According to the differences between DC and AC power distributions and the evaluation of efficiency and reliability presented in this work, it is found that a DC-based architecture has more efficiency improvements than that of an AC system, which agrees with the results that have been stated in the literature review. According to this overview, the feasibility of using DC bus systems became explicit, particularly in the technology existence of advanced power electronics. Modeling, Voltage level selection, isolation, and grounding of DC distribution systems are highly investigated.

1.2. Future Directions

- A detection circuit to extinguish the resistive load category is essential to select automatically between V_{FC} and V_{FCR} when resistive appliances being connected.
- The proposed architecture promises more energy-efficient for Solar PV microgrid systems in residential and commercial buildings since it eliminates DC-AC inverter and reduces the number of conversion devices. However, it still requires a comprehensive analysis to investigate its impacts and practical aspects. The topology and architecture of a single DC bus system may need to match special requirements of particular loads like the pulse loads as future work.
- It is expected that more and more improvements in such systems efficiency achieved by considering a proposed concept called Voltage-Matching between the source (represented by the solar PV or grid) and the load (represented by the system battery) to eliminate the DC-DC converter from the existing solar charge controller.

REFERENCES

[1] B. Bogno *et al.*, “230 VDC elementary block in off-grid PV systems,” *Sustain. Energy Technol. Assessments*, vol. 29, no. June 2017, pp. 1–11, 2018, doi: 10.1016/j.seta.2018.06.013.
[2] P. Muthuvel, S. A. Daniel, and D. G. Yazhini, “Retrofitting domestic appliances for PV powered DC Nano-grid and its impact on net zero energy homes in rural India,” *Eng. Sci. Technol. an Int. J.*, vol. 19, no. 4, pp. 1836–1844, 2016, doi: 10.1016/j.jestch.2016.09.019.
[3] V. Esteve *et al.*, “Improving the efficiency of IGBT series-resonant inverters using pulse density modulation,” *IEEE Trans. Ind. Electron.*, 2011, doi: 10.1109/TIE.2010.2049706.
[4] A. K. Rathore, J. Holtz, and T. Boller, “Generalized optimal pulsewidth modulation of multilevel inverters for low-switching-frequency control of medium-voltage high-power industrial AC drives,” *IEEE Trans. Ind. Electron.*, 2013, doi: 10.1109/TIE.2012.2217717.
[5] K. Garbesi, V. Vossos, and H. Shen, “Catalog of DC Appliances and Power Systems,” *Lawrence Berkeley Natl. Lab.*, vol., no. October, pp. 1–77, 2012, doi: LBNL-5364E Copyright.
[6] V. Vossos, K. Garbesi, and H. Shen, “Energy savings from direct-DC in U.S. residential buildings,” *Energy Build.*, vol. 68, no. PARTA, pp. 223–231, 2014, doi: 10.1016/j.enbuild.2013.09.009.
[7] J. M. Logue, M. H. Sherman, I. S. Walker, and B. C. Singer, “Energy impacts of envelope tightening and mechanical ventilation for the U.S. residential sector,” *Energy Build.*, 2013, doi: 10.1016/j.enbuild.2013.06.008.
[8] B. A. Thomas, I. L. Azevedo, and G. Morgan, “Edison Revisited: Should we use DC circuits for lighting in commercial buildings?,” *Energy Policy*, vol. 45, no. Department of Engineering Mellon University, 5000 Forbes Ave., 129 Baker Hall, Pittsburgh, PA 15213, United States article, pp. 399–411, 2012, doi: 10.1016/j.enpol.2012.02.048.
[9] B. Glasgo, I. L. Azevedo, and C. Hendrickson, “How much electricity can we save by using direct current circuits in homes? Understanding the potential for electricity savings and assessing feasibility of a transition towards DC powered buildings,” *Appl. Energy*, vol. 180, pp. 66–75, 2016, doi: 10.1016/j.apenergy.2016.07.036.
[10] Solar, “Inverters.” https://www.gosolarcalifornia.org/equipment/inverters.php (accessed Dec. 24, 2019).

[11] A. Note, “AC-DC Power Supply Efficiency Testing for Regulatory Standards AC-DC Power Supply Efficiency Testing for Regulatory Standards.”

[12] M. Starke, L. M. Tolbert, and B. Ozpineci, “AC vs. DC distribution: A loss comparison,” in *Transmission and Distribution Exposition Conference: 2008 IEEE PES Powering Toward the Future, PIMS 2008*, 2008, doi: 10.1109/TDC.2008.4517256.

[13] X. Liu, P. Wang, and P. C. Loh, “A hybrid AC/DC micro-grid,” in *2010 9th International Power and Energy Conference, IPEC 2010*, 2010, doi: 10.1109/IPECON.2010.5697024.

[14] J. P. Johnson, “DC-DC converters,” in *Handbook of Automotive Power Electronics and Motor Drives*, 2017.

[15] S. Haghbin, S. Lundmark, M. Alakula, and O. Carlson, “Grid-connected integrated battery chargers in vehicle applications: Review and new solution,” *IEEE Transactions on Industrial Electronics*. 2013, doi: 10.1109/TIE.2012.2187414.

[16] P. Systems, R. Subcommittee, P. Systems, and E. Committee, *IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems (Gold Book)*. 1998.

[17] K. Fleischer, “Power systems analysis for direct current (DC) distribution systems,” *IEEE Trans. Ind. Appl.*, 1996, doi: 10.1109/28.536855.

[18] A. Berizzi, “Short-circuit current calculations for DC systems,” *IEEE Trans. Ind. Appl.*, 1996, doi: 10.1109/28.536856.

[19] Anon, “Load representation for dynamic performance analysis,” *IEEE Trans. Power Syst.*, 1993, doi: 10.1109/59.260837.

[20] A. H. Sabry, W. Z. W. Hasan, M. A. Kadir, M. A. M. Radzi, and S. Shafie, *Processing and monitoring algorithm for solar-powered smart home in DC-environment system based on RF-radio node*, vol. 10607 LNAI. 2017.

[21] A. H. Sabry, W. Z. W. Hasan, M. Z. A. Ab Kadir, M. A. M. Radzi, and S. Shafie, “DC-based smart PV-powered home energy management system based on voltage matching and RF module,” *PLoS One*, vol. 12, no. 9, p. e0185012, Sep. 2017, doi: 10.1371/journal.pone.0185012.

[22] D. Salomonsson, *Modeling , Control and Protection of Low-Voltage DC Microgrids*. 2008.

[23] K. Garbesi, “Catalog of DC appliances and power systems,” no. LBNL Paper LBNL-5364E, 2012.

[24] Y. Arafat and M. Amin, “Feasibility study of low voltage DC house and compatible home appliance design,” 2011.

[25] D. Nilsson, “DC Distribution Systems,” pp. 1–125, 2005.

[26] “Coffee Machine integrated circuits and reference designs | TI.com.” http://www.ti.com/solution/coffee_machines (accessed Sep. 02, 2019).

[27] Panasonic, “Product FAQ - Panasonic Manufacturing Malaysia Berhad.” http://pmma.panasonic.com.my/highlights/product-faq/ (accessed Sep. 02, 2019).

[28] F. Sharp, D. Symanski, and M. S. Dudzinski, “Scalable DC Micro Grids provide cost effective electricity in regions without electric infrastructure,” in *Proceedings of the 4th IEEE Global Humanitarian Technology Conference, GHTC 2014*, 2014, doi: 10.1109/GHTC.2014.6970255.

[29] G. Papa, B. Koroušić-Seljak, B. Benedičič, and T. Kmecl, “Universal motor efficiency improvement using evolutionary optimization,” *IEEE Trans. Ind. Electron.*, 2003, doi: 10.1109/TIE.2003.812455.

[30] M. P. Kazmierkowski, “Electric Motor Drives: Modeling, Analysis and Control,” *Int. J. Robust Nonlinear Control*, 2004, doi: 10.1002/rnc.811.

[31] N. Ayai, T. Hisada, T. Shibata, H. Miyoshi, T. Iwasaki, and K. I. Kitayama, “DC micro grid system,” *SEI Tech. Rev.*, no. 75, pp. 132–136, 2012.

[32] W. Goetzler and T. S. C. Reis, “Energy Savings Potential and Opportunities for High-Efficiency Electric Motors in Residential and Commercial Equipment,” Burlington, MA 01803, 2013. [Online]. Available: http://www.eere.energy.gov/buildings.

[33] A. Hughes., *Electric motors and drives fundamentals, types and applications*. 2013.

[34] A. Khaligh, A. M. Rahimi, A. Chakraborty, and A. Emadi, “Analysis and stabilization of a buck-boost DC-DC converter feeding constant power loads in parallel with conventional loads in vehicular systems,” in *IECON Proceedings (Industrial Electronics Conference)*, 2006, doi: 10.1109/IECON.2006.347633.

[35] A. Khaligh, A. Emadi, G. A. Williamson, and C. Rivetta, “Constant power load characteristics in multi-converter automotive power electronic intensive systems,” in *SAE Technical Papers*, 2005, doi: 10.4271/2005-01-3451.

[36] A. Khaligh and A. Emadi, “Power alignment, new digital control approach for a DC-DC flyback converter with constant power loads,” in *2006 1st IEEE Conference on Industrial Electronics and Applications*, 2006, doi: 10.1109/ICIEA.2006.257187.

[37] A. Khaligh, A. M. Rahimi, and A. Emadi, “Negative impedance stabilizing pulse adjustment control technique for DC/ DC converters operating in discontinuous conduction mode and driving constant power loads,” *IEEE Trans. Veh. Technol.*, 2007, doi: 10.1109/TVT.2007.897248.

[38] M. Zhang, Y. Li, F. Liu, L. Luo, Y. Cao, and M. Shahidehpour, “Voltage stability analysis and sliding-mode control method for rectifier in DC systems with constant power loads,” *IEEE J. Emerg. Sel. Top. Power Electron.*, 2017, doi: 10.1109/JESTPE.2017.2723482.

[39] F. V. P. Robinson, “Power electronics converters, applications and design,” *Microelectronics J.*, 2002, doi: 10.1016/s0026-2692(97)87859-7.

[40] M. H. Rashid, *Power Electronics Handbook*. 2007.

[41] H. J. Zhang, “Basic Concepts of Linear Regulator and Switching Mode Power Supplies,” *Linear Technol. Appl. Note*, vol. 140, no. October, pp. 1–16, 2013.

[42] On_Semiconductor, “Switch − Mode Power Supply Reference Manual,” *Semicond.*, vol. Fourth, p. 73, 2014, [Online]. Available: www.onsemi.com/orderlit.

[43] H. Azazi and E. EL-Kholy, “Review of passive and active circuits for power factor correction in single phase, low power AC-DC converters,” in *International Middle East Power Systems Conference (MEPCON’10)*, 2010.

[44] W. Santiago and A. Birchenough, “Single phase passive rectification versus active rectification applied to high power Stirling engines,” in *Collection of Technical Papers - 3rd International Energy Conversion Engineering Conference*, 2005.

[45] V. Vachak, A. Khare, and A. Shrivatava, “Power Factor Correction Circuits: Active Filters,” *Int. J. Eng. Res. Gen. Sci.*, 2014.

[46] M. Rashad, D. M. Minhas, M. Ashraf, and S. Hussain, “PFC topologies for AC to DC converters in DC micro-grid,” in *Proceedings of the 18th Mediterranean Electrotechnical Conference: Intelligent and Efficient Technologies and Services for the Citizen, MELECON 2016*, 2016, doi: 10.1109/MELCON.2016.7495376.

[47] “EMerge Alliance Updates Key DC Power Standards for Commercial Buildings.” http://www.prweb.com/releases/2015/11/prweb13086939.htm (accessed Mar. 10, 2019).

[48] Y. Zhang, Z. Yan, L. Li, and J. Yao, “A Hybrid Building Power Distribution System in Consideration of Supply and Demand-Side: A Short Overview and a Case Study,” *Energies*, vol. 11, no. 11, p. 3082, 2018, doi: 10.3390/en11113082.

[49] S. Whaite, B. Grainger, and A. Kwasinski, “Power quality in DC power distribution systems and microgrids,” *Energies*, vol. 8, no. 5. pp. 4378–4399, 2015, doi: 10.3390/en8054378.

[50] Electric Power Research Institute (EPRI), "DC Power Production , Delivery and Utilization," 2006.
[51] M. Ryu, H. Kim, J. Kim, and J. Baek, "Test Bed Implementation of 380V DC Distribution System Using Isolated Bidirectional Power Converters," *2013 IEEE*, pp. 2948–2954, 2013.
[52] D. J. Hammerstrom, "AC versus DC distribution systems-did we get it right?," in *2007 IEEE Power Engineering Society General Meeting, PES*, 2007, pp. 1–5, doi: 10.1109/PES.2007.386130.
[53] L. Steigerwald, "Power Electronic Converter Technology," *Proc. IEEE*, 2001, doi: 10.1109/5.931484.
[54] K. Techakittiroj and V. Wongpaibool, "Co-existance between AC-distribution and DC-distribution: In the view of appliances," in *2009 International Conference on Computer and Electrical Engineering, ICCEE 2009*, 2009, vol. 1, pp. 421–425, doi: 10.1109/ICCEE.2009.85.
[55] G. A. Laudani and P. D. Mitcheson, "Comparison of cost and efficiency of DC versus AC in office buildings," pp. 1–52, 2015, [Online]. Available: http://www.topandtail.org.uk/publications/Report_ComparisonofCost.pdf.
[56] A. Emadi, A. Khaligh, C. H. Rivetta, and G. A. Williamson, "Constant power loads and negative impedance instability in automotive systems: Definition, modeling, stability, and control of power electronic converters and motor drives," *IEEE Trans. Veh. Technol.*, 2006, doi: 10.1109/TVT.2006.877483.
[57] A. Emadi, B. Fahimi, and M. Ehsani, "On the concept of negative impedance instability in the more electric aircraft power systems with constant power loads," in *SAE Technical Papers*, 1999, doi: 10.4271/1999-01-2545.
[58] S. Singh, A. R. Gautam, and D. Fulwani, "Constant power loads and their effects in DC distributed power systems: A review," *Renewable and Sustainable Energy Reviews*. 2017, doi: 10.1016/j.rser.2017.01.027.
[59] A. Griffo and J. Wang, "Large signal stability analysis of 'more electric' aircraft power systems with constant power loads," *IEEE Trans. Aerosp. Electron. Syst.*, 2012, doi: 10.1109/TAES.2012.6129649.
[60] M. WU and D. D. C. LU, "Active stabilization methods of electric power systems with constant power loads: a review," *J. Mod. Power Syst. Clean Energy*, 2014, doi: 10.1007/s40565-014-0066-y.
[61] M. K. AL-Nussairi, R. Bayindir, S. Padmanaban, L. Mihet-Popa, and P. Siano, "Constant power loads (CPL) with Microgrids: Problem definition, stability analysis and compensation techniques," *Energies*. 2017, doi: 10.3390/en10101656.
[62] *Practical Variable Speed Drives and Power Electronics*. 2016.
[63] F. Blaabjerg and P. Thoegersen, "Adjustable speed drives - future challenges and applications," in *Proc. of. {IPEMC}*, 2004.
[64] E. Persson, A. Kulatunga, and R. Sundararajan, "The challenges of using variable-speed motor drives in appliance applications," in *2007 Electrical Insulation Conference and Electrical Manufacturing Expo*, Oct. 2007, pp. 453–458, doi: 10.1109/EEIC.2007.4562659.
[65] T. Kubota *et al.*, "Energy Consumption and Air-Conditioning Usage in Residential Buildings of Malaysia," *J. Int. Dev. Coop.*, vol. 17, no. 3, pp. 61–69, 2011, doi: 10.15027/32444.
[66] P. Name and S. Launch, "New Sales Launch of the Container Refrigeration Unit ZESTIA TM Approximately 45 % Energy Savings in an Industry First Use of DC Inverter Non-Inverter," vol. 2011, pp. 9–10, 2013.
[67] LG, "LG Inverter V Air Conditioner | LG Electronics PH," *LG*, 2017. http://www.lg.com/ph/residential-air-conditioners/lg-HS-09ISM (accessed Dec. 25, 2017).
[68] M. a. McNeil and V. E. Letschert, "Future air conditioning energy consumption in developing countries and what can be done about it: the potential of effi ciency in the residential sector," *ECEEE Summer Study Proc. Sav. Energy – Just do it!*, 2007.
[69] N. Chaiyat, "Energy and economic analysis of a building air-conditioner with a phase change material (PCM)," *Energy Convers. Manag.*, 2015, doi: 10.1016/j.enconman.2015.01.068.
[70] B. J. Huang *et al.*, "Design of direct solar PV driven air conditioner," *Renew. Energy*, 2016, doi: 10.1016/j.renene.2015.11.026.
[71] A. Beloglazov, J. Abawajy, and R. Buyya, "Energy-aware resource allocation heuristics for efficient management of data centers for Cloud computing," *Futur. Gener. Comput. Syst.*, vol. 28, no. 5, pp. 755–768, 2012, doi: 10.1016/j.future.2011.04.017.