

Review Article

Energy Efficiency Performances of LVDC Nanogrids Powered Buildings

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The Low Voltage Direct Current (LVDC) system concept has been growing in the recent times due to its characteristics and advantages like renewable energy source compatibility, more straightforward integration with storage utilities through power electronic converters, and distributed loads. This paper presents the energy efficiency performances of a proposed LVDC supply concept and other classical PV chains architectures. A PV source was considered in the studied nanogrids. The notion of relative saved energy (RSE) was introduced to compare the studied PV systems energy performances. The obtained results revealed that the use of the proposed LVDC chain supply concept increases the nanogrid efficiency. The installed PV power source in the building should be well sized regarding the consumed power in order to register a high system RSE. The efficiency of the new LVDC architecture is 10% higher than the conventional LVDC one.

1. Introduction

The photovoltaic electricity was primarily established for standalone applications deprived of any connection to a power grid. Such was the case of satellites or isolated habitations. Currently, PVs are found in many power applications like personal calculators, watches, and other objects of daily use; they can supply many individual DC loads without difficulty. Due to the evolution of photovoltaic systems connected to the grid, the PV has been considerably exploited as a solution to produce electricity.

The main objective of this paper is to investigate the energy efficiency performance of a proposed Low Voltage Direct Current (LVDC) PV system regarding a classical LVDC architecture and classical PV systems using AC loads. All the studied PV chains are on-grid ones and are supposed to be supplying offices.

In general, electric energy consumption in office applications and housing is achieved by using the alternative current plugs even for Grid Tie PV panel systems. In this

case, the use of ACs can increase system loss especially when DC current is used at the load levels.

LVDC systems have been gaining more interest during the past few years in both academia and industry. LVDC systems offer many advantages covering higher energy efficiency and easier integration of modern energy resources in comparison to conventional AC systems. Multiple factors affecting the reliability performance and power quality of the electricity supply permit the use of DC systems instead of AC systems. Direct use of DC power would reduce many power conversion losses by exploiting self-consumption of the energy produced on site and decreasing imports of electricity from the grid. DC loads used in households and office buildings also operate on DC; heating/cooling systems and larger equipment used in industry such as variable frequency drives have also adopted DC motors. Direct current power systems are essentially more efficient than their AC counterparts, since in DC systems do not suffer from skin effect or reactive power [1–4].

A literature research has exposed the study of the first system analysis that explored the use of very low voltage (<120 V) in small-size systems, particularly residential dwellings [5].

Subsequently, Lasseter proposed the concept of the DC Microgrid as a low voltage distribution network. This concept was projected as the future low voltage distribution systems which were facing revolutionary variations at the time due to emanation of distributed generation and market liberalization. The basic idea behind this concept is to combine micro sources and loads into one entity which could be interpreted as a single dispatchable load that could respond in short time to meet the transmission system needs [6].

For many years, The LVDC system has been developed for specific applications like aerospace, automotive, and marine [7–9]. Literature review reveals that, over the last decades, LVDC systems are growing rapidly for industrial applications, essentially in the telecommunication industry, ships, and buildings, Table 1.

Adopting direct current in data centers improves efficiency, decreases capital cost, increases reliability, and boosts power quality [11]. In data centers, LVDC architectures have been widely studied. Various leader projects have been installed in Europe, the United States, Oceania, and Asia. From these projects it was registered that the profit of DC in data centers is about 10% to 30% reduction in energy consumption, about 15% lower capital costs, simpler design, potential increase in reliability, less physical area requirements, a smaller carbon footprint, and less cooling demand [17, 18].

The most significant challenge that DC distribution systems face today is the lack of standardization inducing varied architectures and operations of DC distribution systems [12, 19].

A recent analysis conducted by Vossos et al. [14] shows that a typical house using a PV system could reduce its electric demand by 5% if there was no energy storage and by 14% if it was equipped with storage system.

The work presented in [14] was accomplished in many various locations through the country, with different types of system topologies. Further, distribution topologies were carried out for both cases, with and without energy storage.

The daily energy savings are intensely correlated with the consumption of residential load profile. Hence, the peak PV production can only be attained during the midday, while demand for electricity peaks is in the afternoon and evening. Energy storage systems can store extra solar power for later use and avoid DC/AC and AC/DC conversion losses of transmitting the extra electricity on the grid. Studies conducted in [14, 19] aim to accomplish 25–30% of energy savings. The environment conditioning loads are very significant part in buildings and should be explored in further studies.

The authors of [20] reported that the majority of electricity used in office building passes through power converters enclosing further conversions. Average conversion efficiency is close to 68%. When using high quality electronics, only a 10% loss from each stage of conversion is considered as generous number.

Hence, the losses are multiplicative and not additive. An uninterruptable power supply (UPS) uses the battery to keep supported loads up. For storage in a battery, power is converted from AC power to DC. For the server plug, DC/AC conversion is crucial. The processors use the DC power achieved by the server so multistage conversion structures (AC/DC/AC/DC) are used in this case.

The DC power is directly produced from residential solar panels and inverter is commonly added to supply AC loads.

Despite that, the multistage conversion is basic to extract power from the solar panel into the server; losses resulting from these conversions are expected to be between 10% and 25%.

Through review of the available literature [1, 4, 12, 13], local DC grids are a promising option for buildings to link natural DC power sources such as photovoltaic power systems with DC loads like lighting applications and data centers [12, 17].

Ammous and Morel [21] reported that DC microgrids are alternatives promising conventional AC distribution networks especially for the integration of renewable energies. They allow, for example, to reduce consumption energy of 25% when supplying buildings directly from sectors and by photovoltaic panels.

The majority of works on DC distribution grids assume that converters are installed at each household, which connect the local DC or AC nanogrids [10, 15]. In case of distributed energy resources, nanogrids in buildings could be functioned separately from the main grid in islanding mode [10] and typical low voltage subsystems like 48 V, 24 V, or 12 V can be applied [16]. They could, for example, be used for low power LED lighting or for connecting loads by USB Type-C connector and USB Power Delivery.

The paper is organized as follows: In the first part, we focused our study on the state of the art related to the use of the LVDC supply concept and the proposition of an on-grid LVDC PV chain. The disadvantages of the use of classical on-grid PV systems and of using AC plugs to supply electric DC loads are shown. The used average model of power converters is then presented. This model allows the evaluation of the different converters efficiencies in the studied PV chains. The last part of the paper treats the energy efficiency performances of the proposed LVDC system compared to others classical ones. For this purpose, offices loads are considered and Jeddah location (in KSA) was chosen in our study.

2. The Proposed LVDC PV System

Electronic appliances, such as computers, gaming consoles, printers, economic or LED lights, televisions, and so on, need DC supplies. Additional AC to DC converters are needed in such equipment.

Figure 1 shows one of the classical chains used to connect PV panels to the low voltage grid with a transformerless solution. The DC/DC converter, Converter #1, allows the extraction of the maximum power from the PV panels when climatic conditions change. The Maximum Power Point

TABLE 1: Main DC voltage levels and applications.

Voltage level	Applications
1500 V	PV systems, traction systems, marine, aircraft system, LVDC distribution system. Distributed energy network using interconnected DC nanogrids [3, 7, 8, 10]
750 V, 400 V	Industry and transportation (metro, Tram power systems) Electric vehicles [3]
380 V 48 V	Standard in the data center industry, buildings, commercial buildings centers [11–14] Telecom, small PV systems [10, 15, 16]
24 V	Lighting systems (LED) standards for DC distribution, according to industry experts interviewed. DC-house DC-DC converter: $380 V_{DC}/24 V_{DC}$ [10, 15, 16]
12 V	Lighting, automotive industry [10, 15, 16]
5 V	Microprocessors and electronics [10, 15, 16]

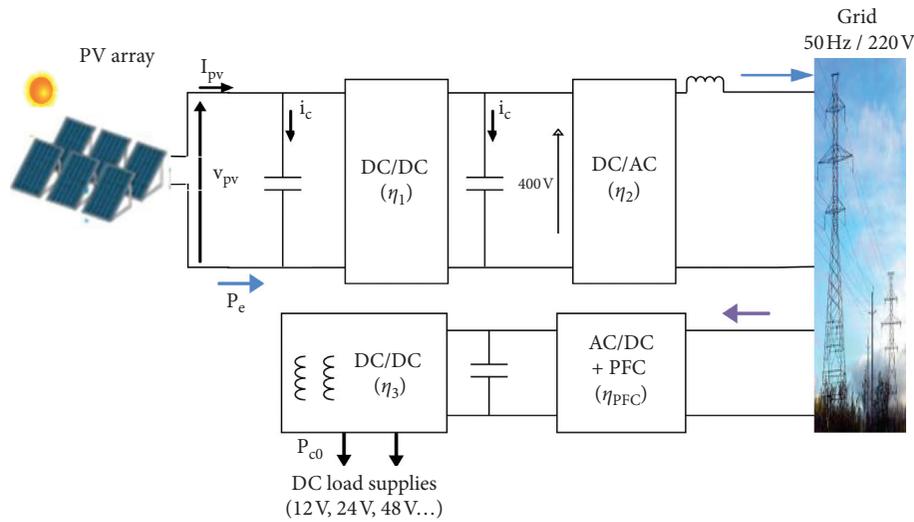


FIGURE 1: Classical configuration (syst1) of the on-grid LVAC PV system and DC load powered from AC sockets.

Tracking (MPPT) algorithm is used to act on this DC/DC converter control.

The DC/AC converter, Converter #2, transfers the PV generated power to the grid and ensures the regulation of the DC voltage value (400 V) of the inverter input. This DC value is mainly used value for single phase PV systems allowing easily obtaining the standard 230 V AC. The injected current to the grid has a quasi-sinusoidal waveform.

The main used and conventional LVDC photovoltaic architecture is shown in Figure 2. This system involves direct current chain from PV panels to load. The regulated DC bus (400 V) was used for this purpose and a DC/DC converter (η_3) adapts LVDC loads supplies to this DC bus.

The efficiency of each PV conversion chain depends on different considerations like the type of used power semiconductor devices and the magnitude of the transferred power.

Circuit oriented simulations on Saber tool (from Synopsys) allowed generating the evolutions of different converters efficiencies as a function of transferred power.

Figure 3 shows the classical on-grid PV chain implemented in Saber simulation tool.

The evolution of the injected current into the grid, by the PV system, is shown in Figure 4. The current is quasi-sinusoidal.

In what follows, we present the proposed new PV architecture for DC loads supplies and the developed average model of power converters. The proposed LVDC PV chain uses the DC bus available directly after the PV panels. This bus is not regulated but its value varies in a given range depending on PV panels associations (parallel/series), open circuit voltage across each panel, and the operating point in the $I(V)$ characteristic of the PV panels.

The regulation of the DC voltages supplying loads is regulated by DC/DC converters (in general Buck ones). The proposed architecture is the one shown in Figure 5. The DC/DC converter connecting the PV panels to the inverter becomes a reversible DC/DC converter (Buck-Boost). The last converter allows the transfer of power from PV panels to the inverter when the generated power is higher than the consumed power. This reversible converter works as a Buck converter in the case when the consumed power is higher than the PV generated one.

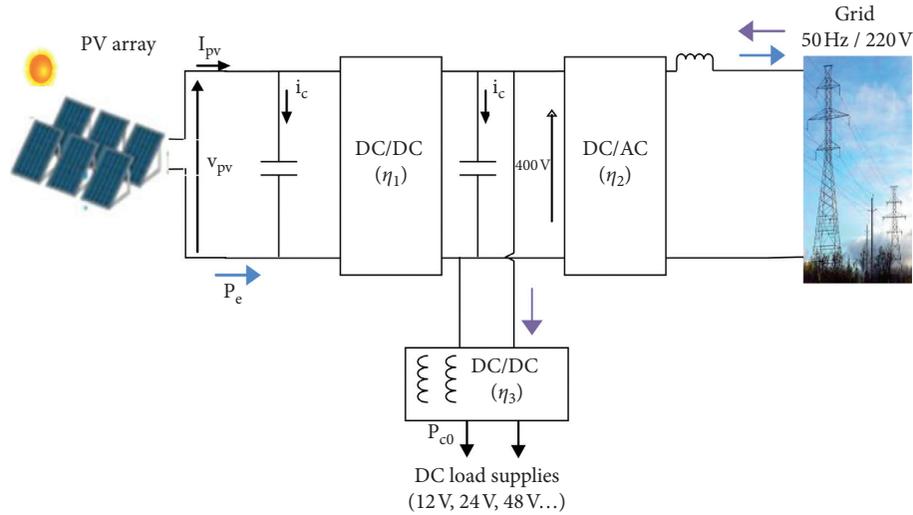


FIGURE 2: Possible LVDC classical architecture (syst2).

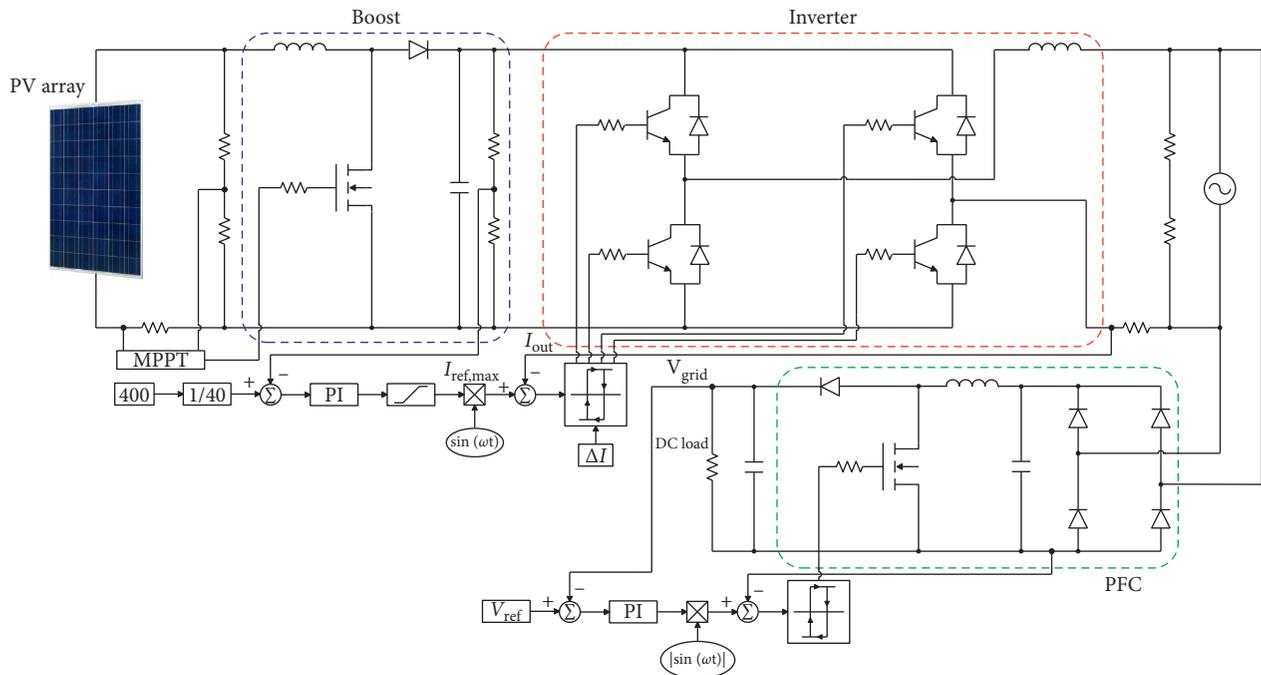


FIGURE 3: On-grid PV chain (syst1) implemented in "Saber" simulation tool.

3. Power Converters Models

Modeling is required to analyze the dynamic behavior of a power converter in several applications. Both accuracy and simulation rapidity are essential particularly for long time simulations and for complicated circuits. The averaging method is the widely used technique for complex power electronics systems. Based on the classical averaged model, the converter is considered to be a linear system using ideal switches. Contrarily, the nonlinear averaged model is established on semiconductor device models including static and dynamic characteristics of the switches as it was used in our case. Figure 6(a) shows the considered inverter leg with

two active switches (IGBTs or MOSFETs) directly controlled by external control signals and two passive switches (DIODES). In Figure 6(b), the adopted leg circuit, based on the used averaged model, is presented. In this developed model, the leg switches are replaced by a controlled voltage source V_1 in series with a controlled current source I_1 given by

$$\begin{aligned} V_1 &= \langle U_{as} \rangle, \\ I_1 &= \langle i_{e2} \rangle, \end{aligned} \quad (1)$$

where $\langle U_{as} \rangle$ and $\langle i_{e2} \rangle$ are the time averaged values of the instantaneous terminal waveforms of $U_{as}(t)$ and $i_{e2}(t)$,

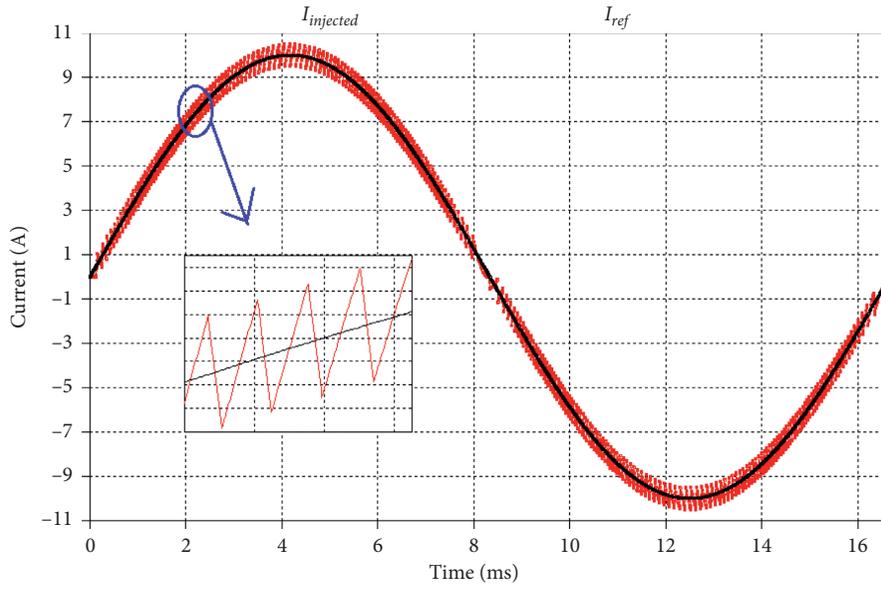


FIGURE 4: Evolution of the injected current (magenta) into the grid and its reference (blue).

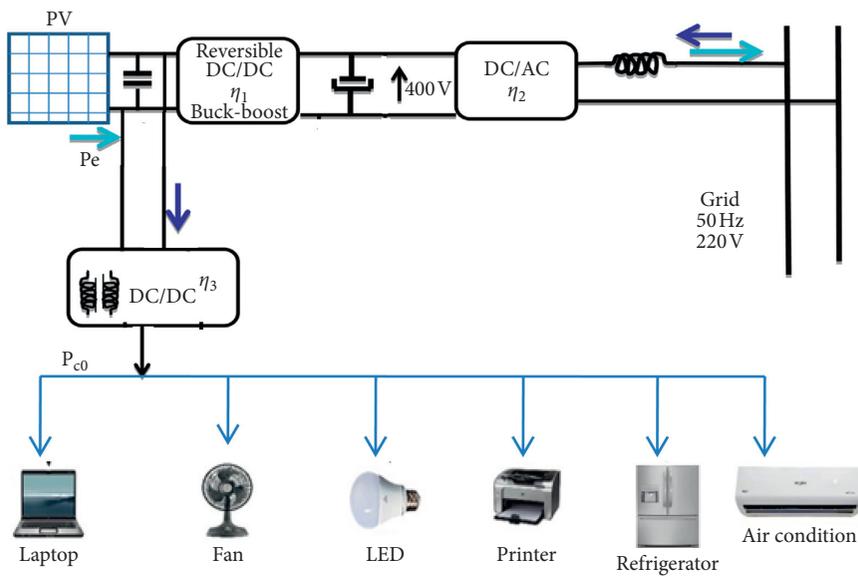


FIGURE 5: Proposed LVDC architecture (syst3).

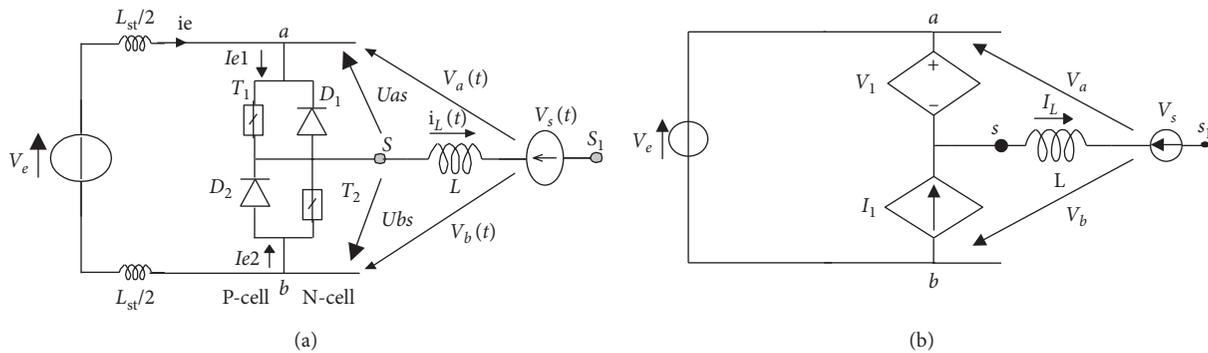


FIGURE 6: (a) The PWM switch. (b) The corresponding averaged model.

respectively, over one cycle T_s (switching period of the controlled switches).

Figure 7 shows the adopted switching waveforms of the active switch ($U_{as}(t)$, $i_{e1}(t)$) and the passive switch ($U_{bs}(t)$, $i_{e2}(t)$) during the switching period T_s . The driving signals e_{g1} and e_{g2} are the control signals of T_1 and T_2 , respectively.

The power losses of semiconductors (P_{switch} and P_{diode}) are estimated using analytical representation of the switching characteristics which include both conduction and switching losses and considering the various conduction and switching times.

Different static and dynamic power devices parameters can be deduced from their data sheets or by experiments. The developed average model allows computing all the dissipated power in the semiconductor devices and then deducing the different converters efficiencies. Time domain simulations will be more rapid for the whole PV chain system.

The efficiencies of the different converters used in the different chains were evaluated by mean of refined simulations. The evolutions of these efficiencies as a function of the transferred power $\eta(P)$ are shown in Figure 8. The used, controlled, devices in the converters are the N-channel SiC power MOSFETs SCT3080KL. Internal antiparallel diode of the MOSFETs is used for reverse current in the switch.

We defined the saved energy, W_i ($i = 1, 2, 3$), by a PV chain, the excess of energy injected into the grid after satisfying the load need. It is the energy balance per month. We note that the chosen peak power generated by the PV panel is 1500 W for a 25°C temperature and 1000 W/m² irradiance conditions.

4. Study of LVDC Solutions Efficiencies

Jeddah-KSA location (21°32' 34" N, 39° 10' 22" E) was chosen to perform energy efficiency performances of the different studied PV chains. Jeddah features an arid climate under Koppen's climate classification, with a tropical temperature range. Unlike other Saudi Arabian cities, Jeddah retains its warm temperature in winter, which can range from 15°C (59°F) at dawn to 28°C (82°F) in the afternoon. Summer temperatures are extremely hot, often breaking the 48°C (118°F) mark in the afternoon and dropping to 35°C (95°F) in the evening. The lowest temperature ever recorded in Jeddah was 9.8°C (49.6°F) on February 10, 1993. The highest temperature ever recorded in Jeddah was 52.0°C (125.6°F) on June 22, 2010.

4.1. Solar Irradiance Data in Jeddah for Each Season. The following graphs in Figure 9 show the solar irradiance during a typical day in each month for Jeddah city. Data were monitored from the station of University King Abdul-Aziz. In this figure typical days for each season month are chosen. A higher value of solar irradiance is registered in July and reaches 984 W/m².

4.2. Temperature in Jeddah for Each Season. The following graphs in Figure 10 show the air temperatures of typical days of each month from sunrise to sunset for the city of Jeddah.

These waveforms were monitored from the University of King Abdul-Aziz station.

The generated power by the panels during a typical day of January in Jeddah is shown in Figure 11. The PV panels generated energy in this case is 6600 Wh/day. The annual generated energy by the used PV panels W_{PV} is equal to 3.006 MWh. This generated energy was calculated based on irradiance, ambient temperature, and wind speed in Jeddah during each typical day/month in the year.

In what follows, we will describe the assessment of the efficiency of the proposed LVDC PV chain solution (syst3) compared to the LVDC classic one (syst1) and the classical on-grid PV chain (syst2) using AC loads.

First, a load profile of an office was chosen in order to make comparison of the saved energy by the three studied PV chains. The profile of the load is shown in Figure 12 and the daily consumed energy by one office is 2919 Wh. The annual consumed energy by one office is about $W_{Load} = 1.068$ MWh.

The considered office load is composed due to desktop computer, laptop, laser printer, two led lamps, small TV, and a fan. Since the DC/DC converter (η_3) is common for the three studied converters and located just before the load, its effect was not taken into account in the study.

The saved energy by the three models during each month of the year in Jeddah city is shown in Figure 13. It is evident that the saved energy decreases with the increase of consumed power.

From Figure 13, it is clear that the proposed new LVDC architecture (syst3) is the best one and registers a higher saved energy ($W_3 = 1.467$ MWh/year when only one office load is considered) compared to the other chains ($W_2 = 1.357$ MWh/year and $W_1 = 1.319$ MWh/year when only one office load is considered too). This improvement of the saved energy is due to the localization of the load connection in the PV chain.

In fact, in the proposed system 3, the load is close to the PV panels and a short traveled path of the energy will be registered. We note that when the saved energy W_i is negative, this means that the consumed energy is higher than PV generated one and so, this energy is transferred from the grid to the load.

We varied the consumed energy by the load (more offices) and we registered the saved energy by each PV system. It was remarked a very interesting propriety of the PV LVDC systems related to the increase of their efficiency compared to classical PV chain (system 1).

In fact, we define the relative saved energy (RSE_j %) of the PV LVDC chain (syst j) to the classical PV chain (syst1) as the ratio of the excess of saved energy of the given LVDC chain (W_2 or W_3) regarding the classical PV system (W_1) by the value of the annual generated PV energy W_{PV} .

The defined PV system RSE_j with respect to the classical LVAC PV chain (system 1) is given by the following equation:

$$RSE_j(\%) = \frac{(W_j - W_1)}{W_{PV}} \times 100\%, \quad \text{with } j = 2, 3. \quad (2)$$

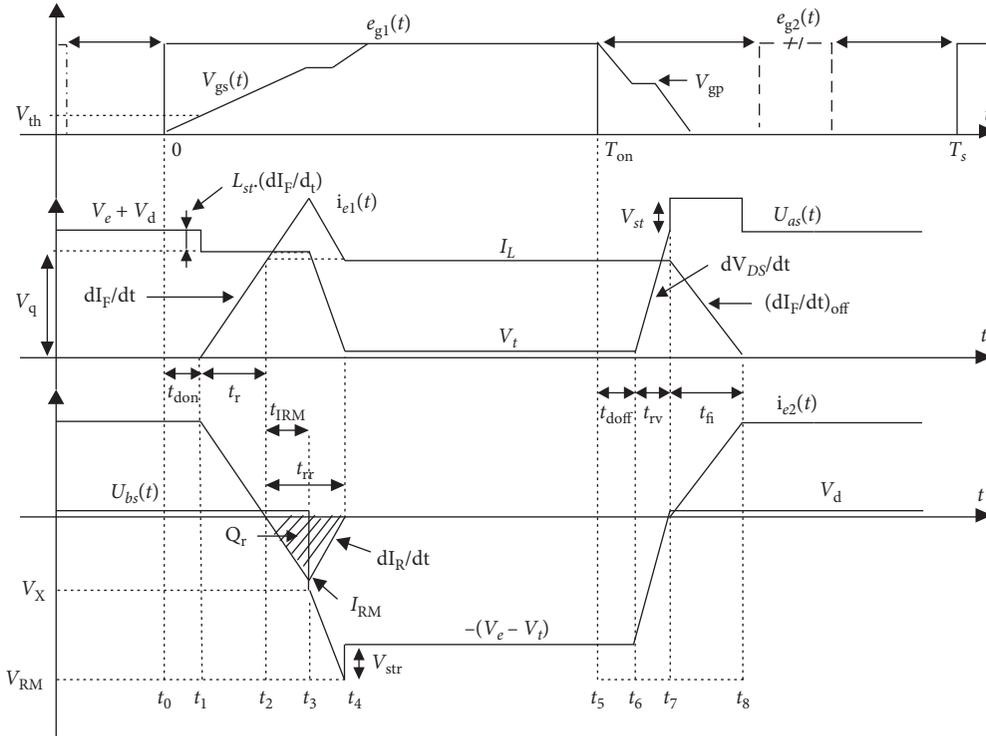


FIGURE 7: Adopted switching characteristics for the controlled switch and the diode components in the PWM-switch cell.

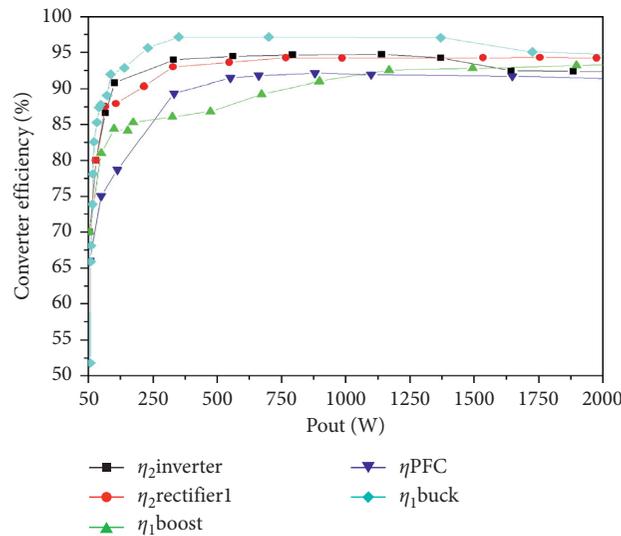


FIGURE 8: Different converters efficiency.

If the defined efficiency is negative this means that classical on-grid PV chain (system 1) using AC sockets for load supplies is better (in terms of energy saving) than the PV LVDC supplies (systems 2 and 3) concept.

Figure 14 shows the relative saved energy for the two systems 2 and 3 in each month (office = 1); it illustrates that the relative saved energy for system 3 is more important than system 2. It is more interesting to use the proposed LVDC architecture than the conventional LVDC one.

The waveforms giving the evolution of the RSE_j LVDC chains, as function of the rate of load consumed energy by

the PV generated energy (W_{Load}/W_{PV}), are shown in Figure 15.

4.3. Discussions. Two main observations can be highlighted when interpreting Figure 15 waveforms:

First, it is clear that the RSE of the proposed LVDC chain (syst3) is higher than the classical LVDC one (syst2) till a high load consumed energy (W_{Load} equal to 2.5 times the PV generated energy W_{PV} in our case).

Second, optimums of these waveforms are registered when the consumed energy is around the generated energy

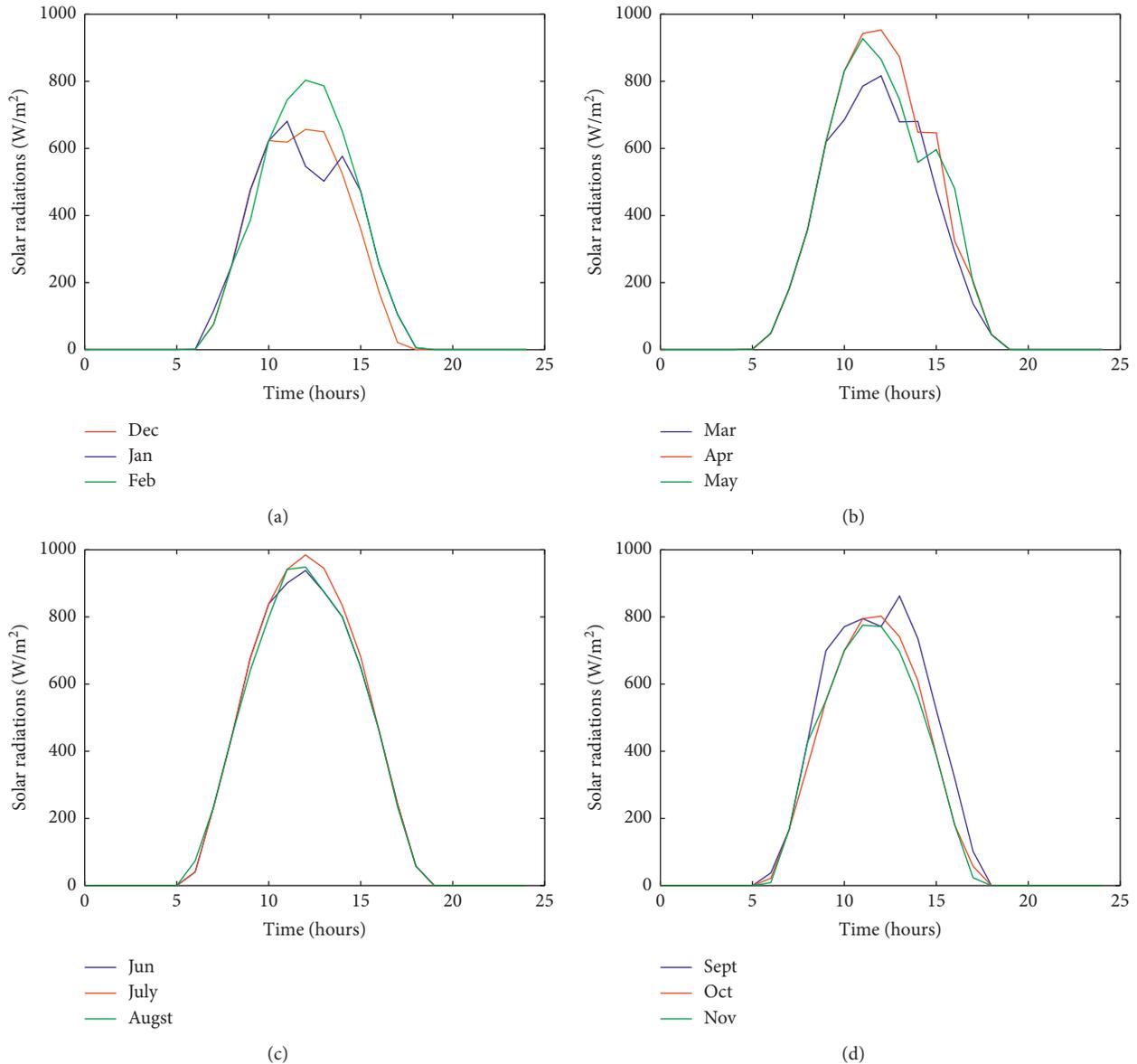


FIGURE 9: Solar irradiance of typical days for each month in seasons. (a) Winter, (b) spring, (c) summer, (d) autumn.

by the PV panels. The maximum yearly RSE of the new LVDC architecture (syst3) is about 12% while the one registered by the conventional LVDC chain (syst2) is about 2.3%.

From Figure 15, we can remark that when the load power consumption increases, the RES becomes negative; this means that the classical LVAC chain (system1), using AC supply to feed loads, is better solution than the LVDC ones in this case.

We can remark also that, for a high load consumption magnitude, the LVDC chain (syst2) becomes more interesting than the proposed LVDC chain (syst3).

In addition, the use of system 3 allows the increase of the load energy consumption range (more than two times the PV generated energy) where the LVDC supply concept efficiency is higher than other systems.

In the proposed LVDC architecture, the power generated by PVs takes a shorter path heading towards the load directly without going through the power controller (η_1). This means that it is more interesting to locally use the PV generated power with a minimum conversion. This is the main idea and contribution of our work. The proposed architecture will be more interesting if DC loads exist during day hours which is the case, in general, for office loads.

All the obtained results show that the use of the LVDC chain supply concept is very interesting and the use of DC loads instead of AC loads, when a PV power is generated locally, increases the PV system efficiency especially in the case of the proposed supply concept.

The installed PV power in the building should be well sized regarding the consumed power in order to register a high system RSE. In this case, an LVDC system RSE can be

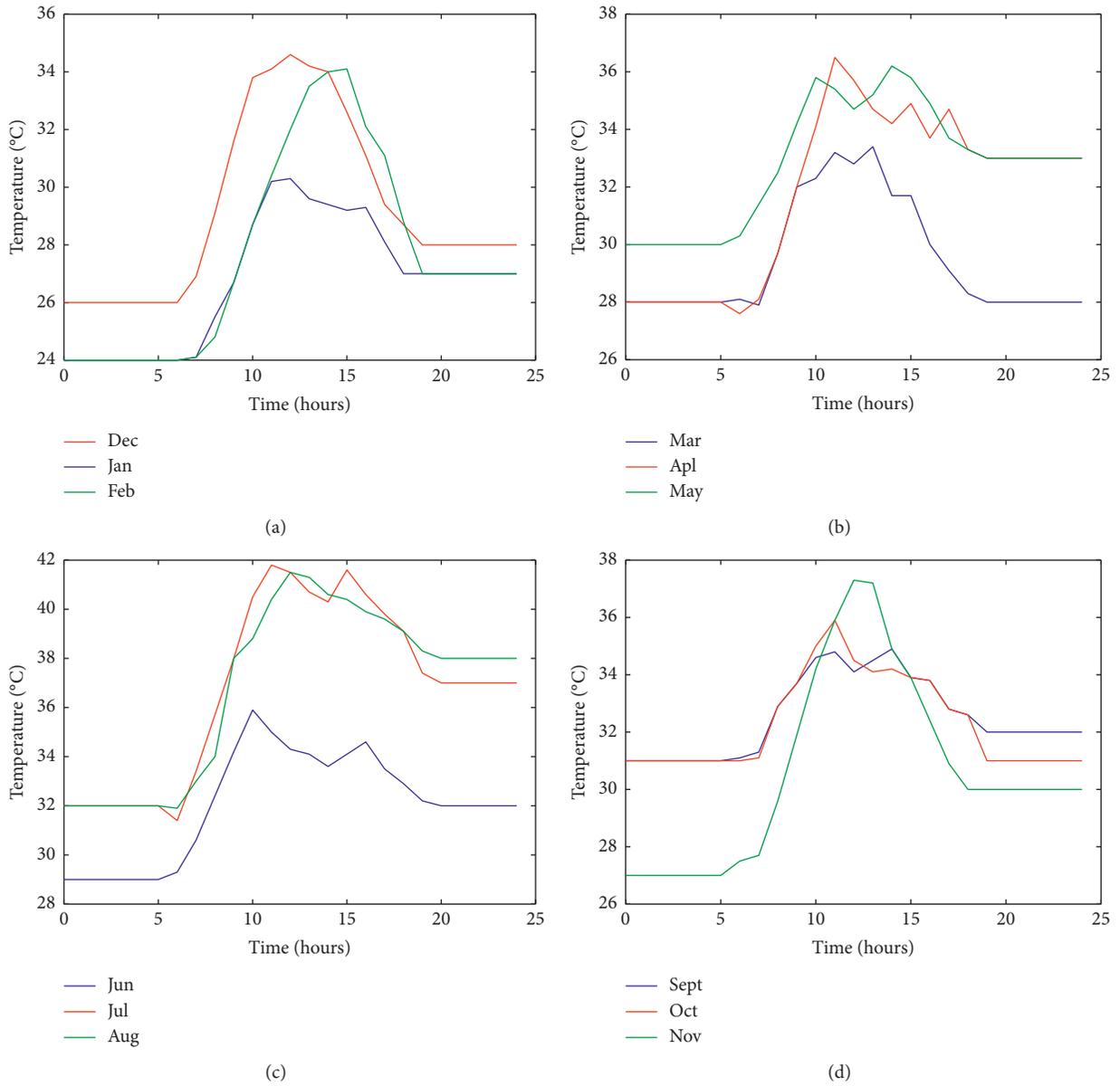


FIGURE 10: Temperature of typical days for each month and season. (a) Winter, (b) spring, (c) summer, (d) autumn.

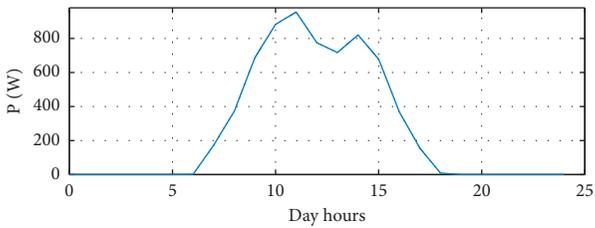


FIGURE 11: Generated power, by the used panels, during a typical day of January in Jeddah.

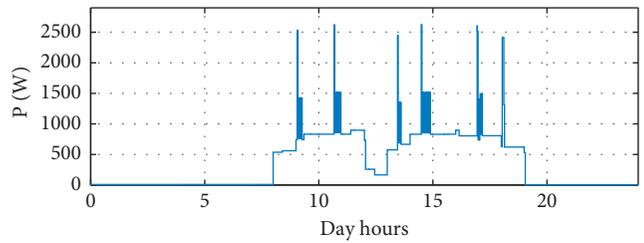


FIGURE 12: The assumed daily office load consumption (by 1 office).

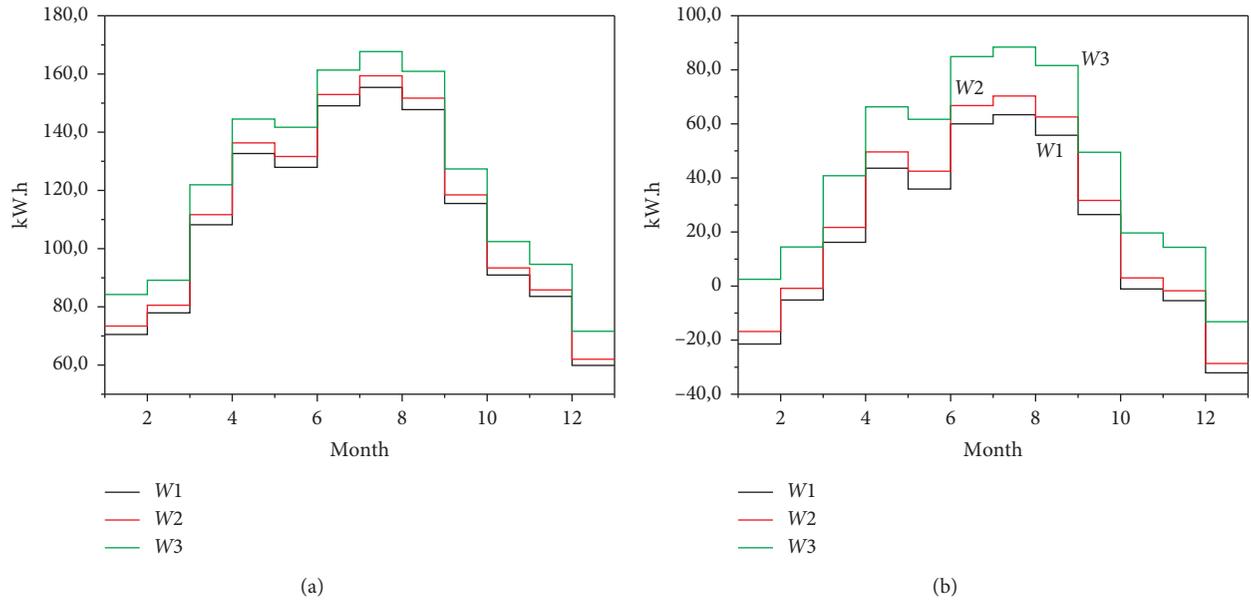


FIGURE 13: Annual saved energy by the three PV chains models (classical LVAC on-grid (syst1), conventional LVDC (syst2), proposed LVDC (syst3)) for each month of the year in Jeddah city (for (a):one office and (b): two offices' load).

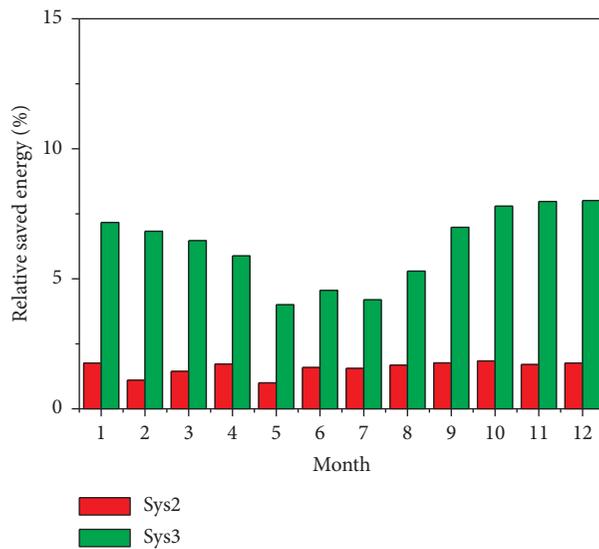


FIGURE 14: Relative saved energy for the two systems, 2 and 3, in each month (number of offices = 1).

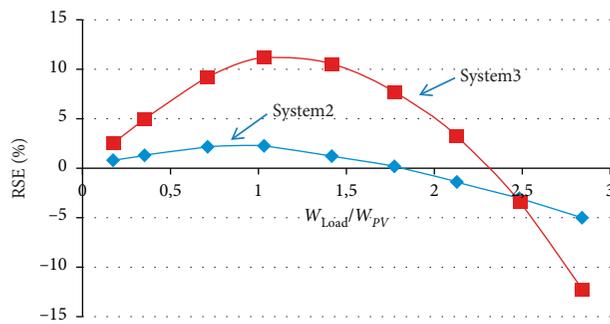


FIGURE 15: Yearly relative saved energy of classical LVDC system 2 and proposed LVDC system 3.

higher than 10% compared to the classical LVAC supply in PV systems.

5. Conclusion

In this paper we proposed a new architecture of a Low Voltage Direct Current (LVDC) supply concept. The proposed on-grid PV chain system, involving DC loads, can replace the classical on-grid LVAC systems using AC plugs to supply electric AC loads. To evaluate the efficiency of some different PV chains, nonideal averaged models of the different converters have been used. The used models have the propriety to be accurate and suitable for complex systems including many converters. The energy efficiency of the different PV chains was estimated by mean of simulations. The evaluation of the efficiency of the proposed new LVDC architecture compared to the conventional LVDC one was performed in the case of building offices in Jeddah city. The superiority of the proposed LVDC PV chain was shown; it can reach 10% higher than the conventional system and depends on the consumed load energy to PV generated energy ratio. In the future, the performance study of this proposed LVDC system can be done for residential loads and efficiency rate can be discussed and compared to the case of offices loads.

Conflicts of Interest

There are no conflicts of interest among the authors.

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