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Solar photovoltaic integrated building scale hybrid AC/DC microgrid

Mashood Nasir* and Hassan Abbas Khan †

*Department of Electrical Engineering, SBA School of Shience and Engineering, Lahore University of Management Sciences (LUMS), Pakistan, *14060018@lums.edu.pk, †hassan.khan@lums.edu.pk*

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Abstract

The paper describes a system level design and analysis of a solar photovoltaic (PV) integrated building scale hybrid AC/DC microgrid. The proposed architecture minimizes the AC/DC inter-conversion losses by allocating DC power to DC loads and AC power to AC loads via an intelligent power electronic controller. The system design ensures that optimum power is available for both DC and AC loads and the surplus power (if available) can be delivered to the utility grid. Conversion and distribution losses along with system efficiencies are analysed for AC-only (conventional), DC-only and the proposed AC/DC hybrid microgrid for a typical residential building. A scaled down hardware implementation shows lower distribution losses for the propsed architecture. Conversion losses analysed analytically and through simulations, also exhibit higher conversion efficiency for hybrid AC/DC microgrid architecture. It has been shown that for a typical residential building having an average load of 1.65kW, overall losses in AC/DC hybrid microgrid are approximately 63% lower as compared to losses in AC-only microgrid and approximately18% lower as compared DC-only microgrid.

1 Introduction

Growing rate of urbanization, industrialization and rural electrification have increased the stress on conventional utilities in terms of an immense upsurge in the utilization of electricity [1, 2]. According to 2015 world energy statistics by International Energy Agency (IEA), the total electricity consumption during year 2013 was 19.5 trillion kilowatt hours (KWh), out of which around 50% was used by commercial and residential buildings [3]. Currently, 20% of the consumed electricity in these building loads is wasted due to the constraints of legacy grid built over a 100 year ago [4]. These constraints mainly include long distance transmission and distribution losses as well as unnecessary AC/DC inter-conversions from generation end to consumption end [5]. While the utility grid is AC, it is important to employ more efficient building level distribution to cater for changing load dynamics. In addition, these newer building architectures must also efficiently incorporate green technologies such as solar photovoltaics (PV) for reduced carbon emissions [6].

Lower energy consumption through efficient building level distribution and integrated generation is likely to play a key role in mitigating some of the detrimental effects of relatively expensive and environment unfriendly peak power generation by reducing the overall burden on utilities. Roof mounted solar PV in many developed countries has already gained impetus in the last decade due to highly incentivized feed-in tariffs and consistently decreasing PV component prices [7]. These developed countries generally have established means for meeting their electricity needs; therefore, the availability of a stable grid is conducive for building level PV integration. However, most of the developing countries are not self-sufficient in their electricity generation. They have to rely upon schedule and non-schedule load shedding, in order to maintain the balance between generation and demand. Therefore, due to power outages and associated grid instability, the constraints of building scale PV integration are higher in developing countries. In these grid intermittent environments, battery storage system is the key component to ensure the reliable and continuous supply of electricity to critical loads in buildings. Therefore, in order to expand the role of building industry in extracting the potential of abundantly available solar energy, ensuring minimum distribution and conversion losses, an optimized storage-based architecture is needed.

Based upon the stable grid environments in developed countries many hybrid architectures are reported in literature [8-11]. Wang *et al.* [5] proposed harmonizing AC and DC grids in a single architecture to gain advantages of both types of power may be extracted simultaneously. A. Q. Huang *et al.* [4] and B. T. Patterson *et al.* [12] proposed that hybrid AC/DC microgrid may serve as a base unit for future renewable electric energy delivery and management (FREEDM) system enabling the enernet (energy internet) vision for an automated and flexible power distribution. Further, N. Sasidharan *et al.* [10] presented a method to reduce both current and voltage harmonics for grid connected distributed energy resources in hybrid implementation. The proposed topologies presented in [4, 5, 10, 12] are well suited for developed countries, where the availability of grid is not subjected to frequent power cuts. Moreover, the aforementioned studies [4, 5, 10, 12] do not present the comparative efficiency gains and reduction in losses achieved via hybrid implementations. Therefore, a storage based optimized structure is needed for regions with intermittent (weak) grids with onus on maximizing the system efficiency.

This paper is therefore aimed to provide a comprehensive analysis of efficiency and losses associated with hybrid AC/DC implementation while taking into account the changing architectures of loads, heavy incorporation of building integrated PV resources and the battery backup utilization during the events of power outages. Moreover, the proposed hybrid AC/DC microgrid architecture will serve as a base-line for energy internet in developing countries by taking control of backup system to provide real time power compensation for critical loads during power outages.

The organisation of the paper is divided in the following sections. Section I introduces the need of building level renewable energy integration and an optimized architecture to process the integration in grid intermittent environments. Section II outlines the possible grid architectures for building level PV integrated a) AC-only b) DC-only and the proposed c) AC/DC hybrid microgrids. The analysis of the presented architectures is presented in section III. The case study on implementation of the proposed analysis on a typical residential building is presented in section IV. Section V presents the results and discussion followed by conclusions.

2 Architectures for Building Scale PV Integrated Microgrids

The system level block diagrams and design of three possible microgrid architectures for a typical building having AC utility and in-house DC PV as input sources of power, DC batteries as a backup source of power and a mix of AC and DC loads as consumption are presented.

2.1 AC-only Microgrid

Conventionally, there has been major share of central AC power generation in the existing power systems that is located far away from load side and needs to be transmitted via subsequent up and down voltage conversions for efficient transmission and distribution. In early times, this up and down voltage conversion was favored by the invention of transformers (primarily a voltage level conversion device that works on AC). This fact made AC power as the main choice for generation, transmission, distribution and utilization of electricity [13]. Consequently, the current standards for building level power distribution are also of AC nature. In order to integrate the PV output with the utility, it has to be inverted following the standards of AC link integration and synchronization. Such a system topology processing inversion, integration, synchronization and distribution of AC power to both AC and DC loads in the building is referred as AC-only microgrid shown in figure 1.

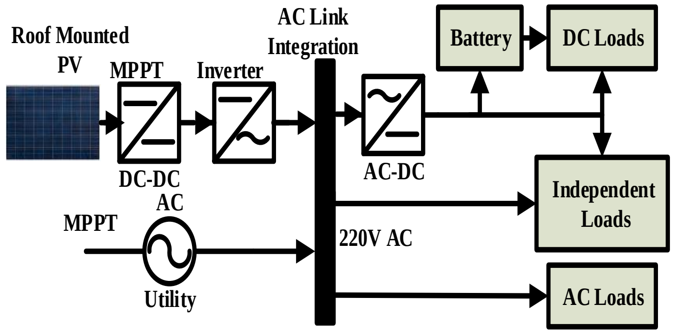

Figure 1. Topological Diagram of AC-only microgrid

In AC-only microgrid topology, AC power has to be rectified via built in rectifiers within the DC loads, thus adding extra AC/DC inter-conversion losses in the system operation.

2.2 DC-only Microgrid

Due to advancements in digital technologies, there is an increased share of DC loads in commercial and residential buildings [12]. Today most of the building consumption consists of DC based digital computing; LED lightings and controllable variable frequency drive (VFD) loads. Fortunately, PV panel output is DC in nature along with the battery systems. In such a DC dominant environment, one possible microgrid architecture processing rectification of utility AC, its DC link integration with PV output and distribution of DC power to both AC and DC loads in the building is referred as DC-only microgrid. The system level topological diagram of DC-only microgrid is shown in figure 2.

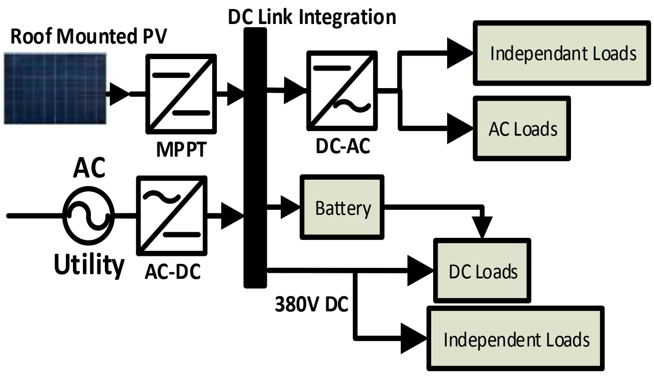

Figure 2. Topological Diagram of DC-only microgrid

A DC-only microgrid has some will also not add much benefit to the system as the main source of losses and deterioration i.e. AC/DC conversions are still present in the DC distribution system. Further, complex power electronic controls must have to be employed for DC-DC conversions, which were much simpler to achieve through transformers in AC distribution network.

2.3 Hybrid AC/DC Microgrid

For a typical building with a) AC utility and in-house DC PV as input sources of power, b) DC batteries as a backup source of power and c) a mix of AC and DC loads as consumption, it is not possible to entirely mitigate the unnecessary AC/DC inter conversions. In proposed hybrid AC/DC microgrid, interconnection of generation, backup and load networks are made through intelligent power controller IPC as shown in fig. 3. Intelligent power controller continuously monitors the available input resources of energy, evaluates the building load scenarios, channelizes the power between the sources, backup and loads such that minimum DC/AC conversions are encountered throughout the path of power flow. Thus IPC enables the hybrid routing of both ac and dc power in the building, ensuring minimum inter-conversion stages while connecting power creation to power consumption.

Another priority task for IPC is to ensure the reduced dependency upon the grid electricity and feeding in the excess PV electricity back to the grid. IPC consists of a multi-modular serial connected AC-DC and DC-AC power converter whose mode of operation is decided by real time changing load and source scenarios such as

a) allocating DC power to DC loads

b) allocating AC power to AC loads

c) rectifying the utility AC and integration with DC output of building integrated PV panel and batteries to perform DC link integration when the building DC load is higher than the PV output

d) performing AC link integration and derive AC loads to reduce the overall burden on utility, when PV output exceeds the DC load requirements.

Along with the gain in distribution and conversion efficiency, the implementation of the proposed hybrid AC/DC microgrid will require minimum modifications in the legacy electric power infrastructure, thereby adding a parallel thread of DC distribution with the existing AC distribution in buildings. Hence, advantages of both AC and DC power may be combined in a single architecture, facilitating the direct integration of both AC and DC based loads, energy storage systems and distributed generation with minimum number of interface elements and conversion stages required. The complex control strategy for the synchronization of generation and storage units is also eliminated as they can be directly connected to AC or DC networks. Moreover, the implementation of proposed hybrid topology will result in simplified architectures of inherently DC loads, eliminating the embedded rectifiers and reducing the cost of electronic products.

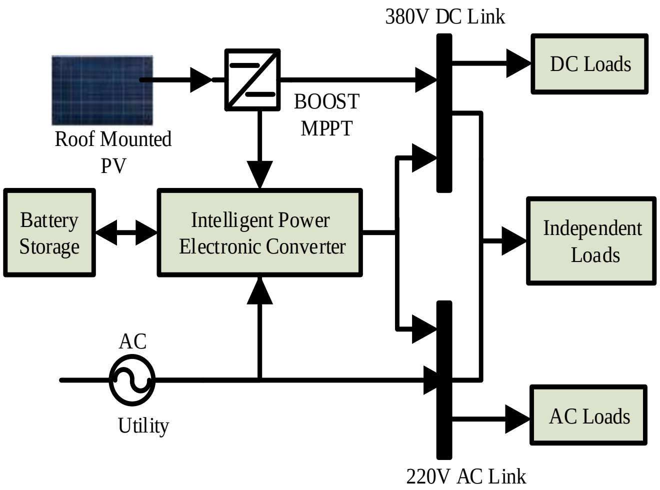

Figure 3. Proposed Architecture of Hybrid AC/DC Microgrid

3 Loss Analysis of Building Scale PV Integrated Microgrids

The main sources of loss in building level distribution are AC line losses, DC line losses, AC to DC rectification losses, DC to AC inversion losses and DC-DC conversion losses.

3.1 Line losses

For a DC distribution network having voltage source having dc value “V_{dc}” at one end and the dc load consuming power “P” at the other end connected through a distribution cable having resistance “r” per unit length “l”, the current “I_{dc}” and line losses “LL_{dc}” and are given by (1) and (2) respectively [14].

$$I_{dc} = \frac{P}{V_{dc}} \tag{1}$$

$$LL_{dc} = 2.\cdot r \cdot l \cdot I_{dc}^{2} = 2.\cdot r \cdot l \cdot \left(\frac{P}{V_{dc}} \right)^{2} \tag{2}$$

Similarly, rms value of current “I_{ac}” and line losses “LL_{ac}” for ac distribution network having voltage source “V_{ac}” at one end and the dc load consuming active power “P” at the other end connected through a distribution cable having resistance “r” per unit length “l” is given by (3) and (4)

$$I_{ac} = \frac{P}{V_{ac}\cos\theta} \tag{3}$$

$$LL_{ac} = 2.\cdot r \cdot l \cdot I_{ac}^{2} = 2.\cdot r \cdot l \cdot \left(\frac{P}{V_{ac}\cos\theta} \right)^{2} \tag{4}$$

Where, cosθ is the power factor of the applied ac load.

3.2 Conversion losses

In a building level distribution system, conversion losses may occur due to AC-DC, DC-AC inter-conversions and AC-AC, DC-DC voltage level conversions from source to load. The losses associated with DC-DC, DC-AC and AC-DC conversions are based upon the characteristics of switching devices used in these converters along with the switching frequency for conversion operation. These conversion losses "P_{conv}" mainly include conduction losses "P_{cond}", switching losses "P_{sw}" and blocking losses "P_b". Blocking losses corresponds to leakage of current and are relatively smaller in magnitude, therefore, neglected for building level distribution systems [15, 16].

$$P_{conv} = P_{cond} + P_{sw} + P_b \approx P_{cond} + P_{sw} \quad (5)$$

The converters used for inter-conversion generally consists of a controlled power electronic switching devices such as diodes, IGBT, MOSFET and SCR. In order to estimate the conduction losses of IGBT "$P_{i,conv}$" and power diode "$P_{d,conv}$", these may be modelled as a series combination of voltage source and a resistance, while conduction losses in mosfet "$P_{m,conv}$" are modelled as power losses across a resistance [15, 16].

$$P_{i,cond} = V_{i,on}.I_{i,avg} + I_{i,rms}^{\,2} \cdot r_{i,on} \quad (6)$$

$$P_{d,cond} = V_{d,on}.I_{d,avg} + I_{d,rms}^{\,2} \cdot r_{d,on} \quad (7)$$

$$P_{m,cond} = I_{m,rms}^{\,2} \cdot r_{m,on} \quad (8)$$

Where, subscripts i, d and m represent the parameters for IGBT, diode and MOSFET respectively with "V_{on}" being the on-state voltage, "I_{rms}" being the rms value of the current, "I_{avg}" being the average value of the current and "r_{on}" is the on state resistance of the device.

Switching losses of IGBTs "$P_{i,sw}$", diodes "$P_{d,sw}$" and MOSFETs "$P_{m,sw}$" associated with DC-DC voltage level conversion as well as DC/AC inter-conversions are dependent upon the switching frequency "f_{sw}" and are given by [15, 16]

$$P_{i,sw} = \left(E_{i,on} + E_{i,off}\right) \cdot f_{sw} \quad (9)$$

$$P_{d,sw} = \left(E_{d,on} + E_{d,off}\right) \cdot f_{sw} \approx E_{d,on}.f_{sw} \quad (10)$$

$$P_{m,sw} = \left(E_{m,on} + E_{m,off}\right) \cdot f_{sw} \quad (11)$$

Where, subscripts i, d and m represent the parameters for IGBT, diode and MOSFET respectively with "E_{on}" being the turn on energy loss and "E_{off}" is the turn off energy losses.

4 Case Study

For the purpose of analysis a typical residential building having three types of load i.e. AC, DC and Independent loads (may operate on both AC and DC) are considered [17]. Typical load variations in the building throughout the day are categorized in three sub-intervals i.e. Night, Day-1 and Day - 2 [17]. The conversion losses, distribution line losses, and system efficiencies are analysed for AC-only, DC-only and AC/DC hybrid microgrid for various conductor sizes and load distributions throughout the day. The proposed hybrid microgrid is analysed for 220V AC / 380V DC distribution levels for a typical length of 100m distribution wire in a house. The conversion losses associated with DC-DC voltage conversions (380V DC to 5/12/19 V DC) are independent of the type of architecture and are similar in all three types of grids. Therefore, for the purpose of comparative loss analysis, these losses are not considered. The power factor of AC load is considered 0.95.

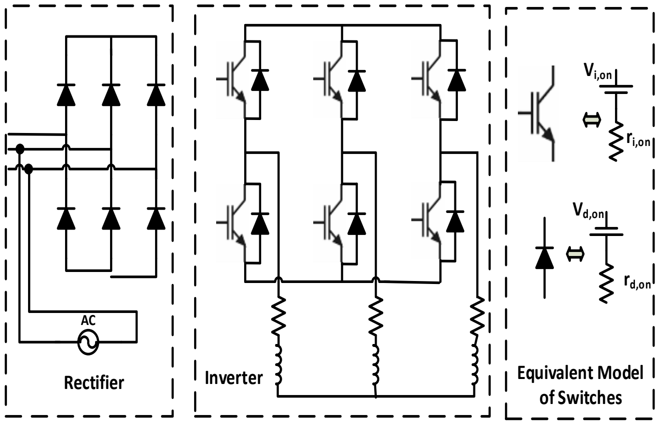

Figure 4: Topologies for AC/DC Conversions and Equivalent Models of their Switches

Topologies for three phase rectification and inversion presented in [18] are used (figure 4.), however, per phase analysis is performed. Parameters values of standard data sheets from a well-known manufacturer are used [19, 20]. Considering the constant forward voltage drop "V_D" across the diodes as constant, AC/DC rectification losses "P_{rec}" are given by (12).

$$P_{rec} = 2V_D \cdot \frac{P_{ro}}{V_{dc}} \quad (12)$$

Where, "P_{ro}" is the dc output power of rectifier and "V_{dc}" is the dc link voltage.

Considering diode and IGBT on state voltage drop and on resistance almost same for power module, and third harmonic injection sinusoidal PWM is used, DC/AC inversion losses "P_{inv}" are given by [19, 21]. The advantages of third harmonic injection PWM include, increased voltage gain of inverter, balanced load sharing on switching devices and reduced switching losses.

$$P_{inv} = \frac{2\sqrt{2}V_{on}.I_{rms}}{\pi} + I_{rms}^{\,2} \cdot r_{on} + \frac{2\sqrt{2}}{\pi}\frac{I_{rms}}{I_{nom}}\left(E_{on} + E_{0ff}\right) \cdot f_{sw} + E_{d.on} f_{sw} \quad (13)$$

Where, $V_{i,on}$= $V_{d,on}$= V_{on} , $r_{i,on}$= $r_{d,on}$= r_{on} and I_{nom} is the nominal current for the module with the assumption that switching losses are proportional to the loading ratio I_{rms}/I_{nom} .

For MPPT, MOSFET based DC-DC boost converter is used and losses can be found using (5), (7), (8), (10) and (11) with the following current output characteristics [16].

$$I_{m,rms} = \sqrt{D}\,\frac{P_{in}}{V_{in}},\; I_{d,avg} = (1-D)\frac{P_{in}}{V_{in}},\; I_{d,rms} = \sqrt{1-D}\,\frac{P_{in}}{V_{in}}$$

Interval	*Timings*	*Building Load distribution (KW)*			*Total Load (KW)*
		AC	*DC*	*I*	
Day-1	06:00-15:00	0.763	0.484	0.440	1.687
Day-2	15:00-00:00	1.003	1.022	0.678	2.703
Night	00:00-06:00	0.301	0.101	0.158	0.560
Average	00:00-23:59	0.689	0.535	0.425	1.650

Table 1: Building Load distribution in defined intervals[17]

Where, “D” is the duty cycle of the converter, “P_{in}” is the input dc power and “V_{in}” is the input dc voltage of the DC-DC converter.

5 Results and Discussions

In order to ascertain the distribution line losses, total AC, DC and independent load demand is calculated from table 1 for an entire day. Using (2) and (4), distribution line losses are calculated and are shown in figure 5 for AC-only, DC-only and hybrid AC/DC microgrid for various mass produced conductors. Independent loads are considered being driven through DC power in AC-only microgrid, DC-only microgrid and Hybrid AC/DC microgrid. In practice, an intelligent governing mechanism constantly monitors the PV generation and building changing load thus independent load may be driven through either AC or DC power depending upon the availability of grid, battery state of charge as well as PV output.

Conversion losses, including switching and conduction losses are calculated for different load distributions of a typical residential building for AC-only, DC-only and hybrid AC/DC microgrid (figure 6). It has been observed that over all load scenarios, hybrid grid has higher efficiency and lower conversion losses in comparison to DC-only and AC-only grid due to unnecessary and redundant AC/DC inter-conversions. Secondly, the results show that conversion losses are higher at lower loads; therefore, efficiency drops down at night interval when over-all loading is low. Therefore, with the hybrid grid implementation it is possible to achieve conversion efficiency greater than 97 % even at the lower loads in night time.

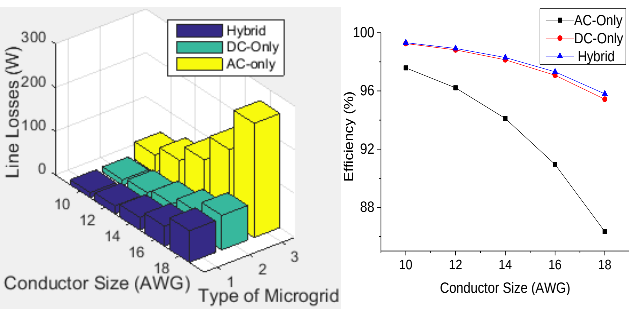

Figure 5. Distribution line losses and Efficiency for AC-only DC-only and Hybrid microgrid at various conductor sizes

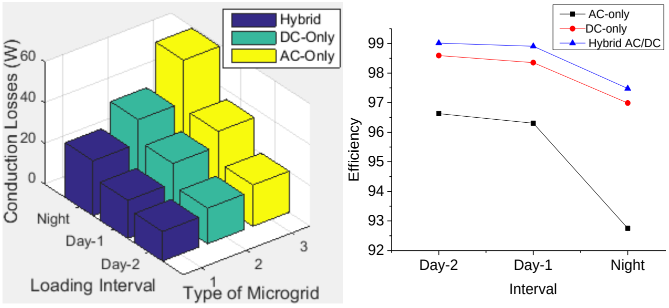

Figure 6. Conversion losses in AC-only DC-only and Hybrid AC/DC microgrid for different intervals i.e. day-1, day-2 and night intervals

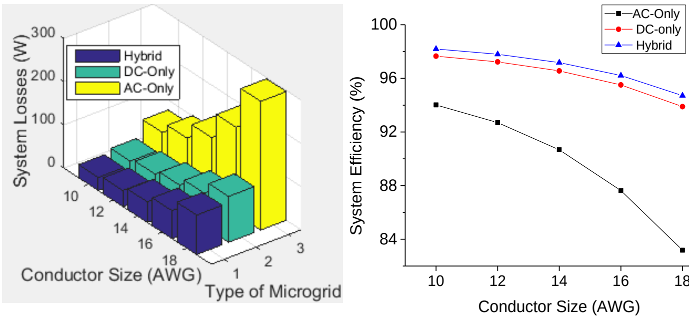

Figure 7. System losses and efficiencies including line losses and conversion losses at different conductor sizes for

For an average case building load, the overall system losses, including distribution and conversion losses at different conductor sizes for AC-only, DC-only and hybrid AC/DC grid are shown in figure 7. For a typical conductor size of AWG 14, overall losses in AC/DC hybrid microgrid are approximately ~63% lower as compared to losses in AC-only microgrid and ~18% lower as compared DC-only microgrid.

In order to validate the efficiency of the proposed architecture, a scaled down hardware version is implemented in laboratory for the calculation of distribution line losses. For the calculation of conversion losses, PSIM based models for rectification; inversion and DC-DC conversion are simulated with the data sheet parameters [19, 20]. The scaled down hardware implementation for the calculation of line losses is shown in figure 8.

Figure 8. Scaled Down Hardware Implementation for the Calculation of Line Losses and Line Distribution Efficiency

For 20m length of typical mass produced conductors available in the market i.e. 3-0.029'' (16 AWG), 7-0.0029'' (12.5 AWG) and 6.5mm^2 (9 AWG) and 500W loading, hardware analysis of AC-only, DC-only and Hybrid microgrid is conducted. Analytical v/s simulated results for distribution line efficiency are shown in figure 9.

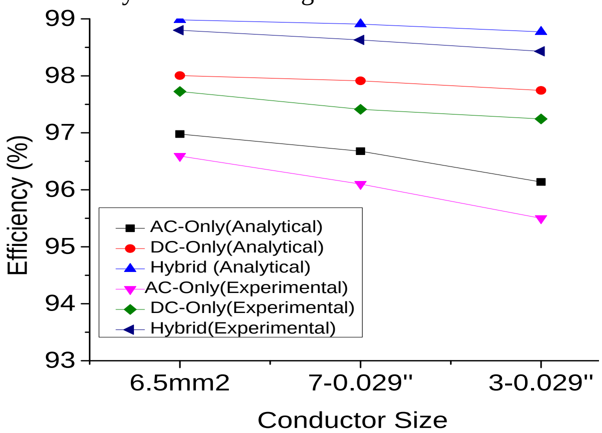

Figure 9. Analytical v/s Measured Results for Distribution Line Efficiency of AC-only DC-only and Hybrid AC/DC Microgrid at Various Conductor Sizes

For average load distribution on the building, AC-only DC-only and hybrid AC/DC architectures are simulated on PSIM and resultant conversion efficiencies are plotted against analytical results in figure 10.

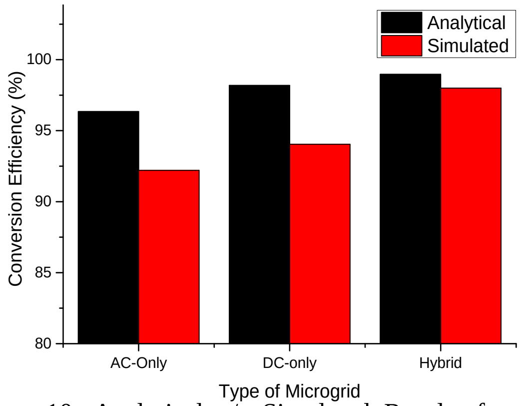

Figure 10. Analytical v/s Simulated Results for Highest Conversion efficiency of AC-only, DC-only and Hybrid AC/DC microgrid at average building load distribution.

Simulated results show lower efficiency as compared to analytical results due to the absence of third harmonic injection PWM, which was assumed for simplification in analytical calculations.

6 Conclusion

Design and analysis of a hybrid microgrid for photovoltaic integrated buildings in poor grid environments has been presented. The proposed topology in conjunction with the AC-only and DC-only topologies is analysed for line losses and conversion losses including switching and conduction losses of power electronic converters for a typical residential building of developing countries. Power losses and efficiencies are evaluated with respect to building loading and conductor size. It has been shown that by separating AC and DC networks will ensure minimal AC/DC inter-conversions, and lower line loss. For a typical residential building having an average load of 1.65kW, overall losses in AC/DC hybrid microgrid are approximately ~63% lower as compared to losses in AC-only microgrid and ~18% lower as compared DC-only microgrid. Based upon the findings, it is concluded that the proposed AC/DC hybrid microgrid is a candidate solution for PV integrated buildings with storage.

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