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Potential Energy Savings by Using Direct Current for Residential Applications: A Danish Household Study Case

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***Abstract*—This paper presents a study of the potential energy savings by implementing dc distribution systems for residential applications. In general, it is commonly accepted that the use of dc voltage improves the efficiency of the distribution, due to a decrease in the conduction losses and an efficiency improvement in the power converter units. However, for residential applications, the efficiency is not always improved. A grid connected residential microgrid, with renewable energy sources (RES), energy storage systems (ESS) and local loads, is presented in this work. The microgrid has been modelled for an ac-based and dc-based distribution system, in order to simulate and assess the overall efficiency of the system, for different distribution technologies. Commercially available power supplies for home electronics have been modelled and modified to work with both ac and dc distribution voltages. A Danish household has been used as study case. This study has shown that, depending on the application, architecture, consumption and generation profiles, a dc distribution system might not bring any efficiency improvement, especially when the dc voltage is supplied from a grid rectifier that works at low loads. However, for isolated microgrids, the use of dc voltage has the potential to bring a significant efficiency improvement. Nevertheless the potential for cost reduction in all scenarios is very promising.**

Keywords*—*Residential microgrid, distributed generation energy efficiency, dc microgrid, dc homes, dc distribution.

I. INTRODUCTION

The integration of RES in the low-voltage distribution grid, specially photovoltaic (PV) panels in residential and commercial buildings, has been growing in the past years, in an attempt on reducing the dependency of the energy generation from fossil fuels, and achieve a more sustainable electrical energy system. The concept of a microgrid aims to ease the integration of RES, together with ESS at consumption level, in order to reduce the dependency of the system from the main electrical grid [1]–[5]. Furthermore, a microgrid tends to increase the efficiency of the distribution by bringing the generation closer to te consumption, however further losses can be avoided by using dc voltage for the electrical distribution. Distribution systems based on dc voltages do not have reactive power loading the lines, there is no need for synchronization with the grid frequency, and the equivalent resistance in the conductor tend to be slightly smaller. Therefore, the systems intrinsically tend to become simpler and more efficient [6]–[9].

Microgrids and dc distribution systems applied to residential or commercial buildings bring a potentially higher efficiency improvement, due to the penetration of dc-based loads. The efficiency improvement is achieved by minimizing the number of conversion stages in power converters, when interconnecting dc-based devices. For instance, modern electronics loads (e.g. phones, computers, TVs, LED lights) are all internally dc loads, and also ac-based loads with a front-end power converter unit (PCU) can still benefit from a dc distribution system, especially if the PCU has a back to back configuration with an intermediate dc link. In addition, RES such as PV panels and fuel cells (FCs), are intrinsically dc generators, and as happen with ac-based loads, even wind turbines (WTs), intrinsically ac generators, are more conveniently integrated into a dc grid, since double conversions are avoided. Furthermore, typical ESSs, such as batteries, are dc devices as well, which is also applied for plug-in electric vehicles (EVs). Therefore, a dc distribution system is a more natural interface between mostly dc devices, since avoids non-necessary conversion stages in the power converters, and brings a potentially significant loss reduction, as well as simplicity and cost reduction in the power converter units [8].

There are studies, and experimental demonstrations that have initially assessed how much the efficiency is improved by using a dc distribution system to supply the consumption with local RESs and ESSs [9]–[13]. All the studies have concluded that dc distribution system effectively reduces the overall losses of the system; however for residential applications, where the loads are highly pulsating, the use of dc might not bring a significant efficiency improvement, specially if the power is mostly supply by the front-end rectifier. Basically, the front-end rectifier introduced in the system, replaces all the ac-dc conversion stages that have been avoided by using dc voltage for distribution. Furthermore, most of the PCUs interfacing RES are highly efficient, hence even if a conversion stage is avoided, there is not much space for an efficiency improvement.

This paper presents an study for the assessment of the potential energy savings by using a dc distribution system for residential applications. A Danish household has been used as study case, where recorded mission profiles (i.e. solar irradiation, wind speed, outdoor temperature..) have been used for the estimation of the RES, stochastic modelling [14] is used for the generation of consumption profiles for the different loads in the household, and commercially available PCUs are modelled for the efficiency analysis. In this work, an ac-based and dc-based residential microgrids are modelled. Then both system are simulated for different microgrid configurations, consumption and generation profiles, in order to obtain the overall energy consumption of the system during the operation.

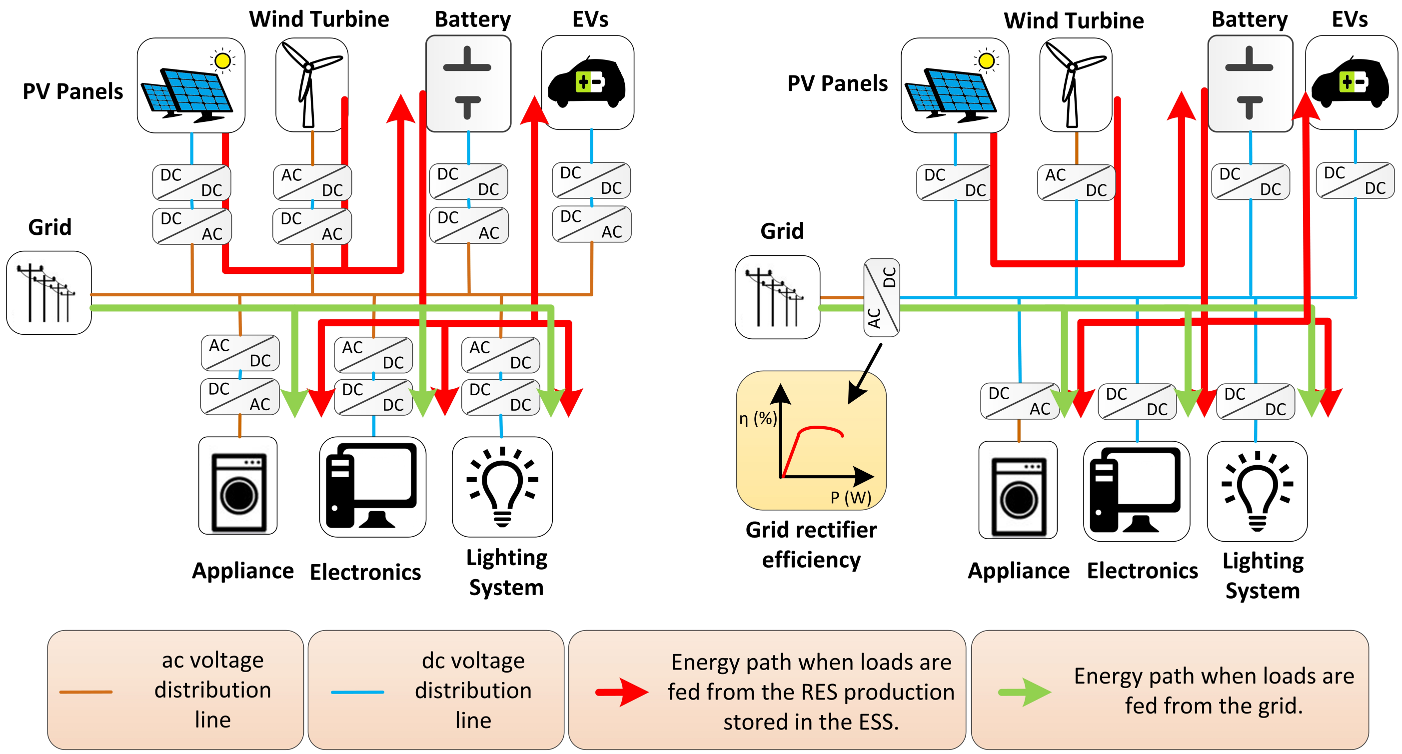

Figure 1: A reduction in power-conversion stages enabled by the implementation of a dc distribution systems for residential applications.

II. Architecture and Potential Benefits of a Residential Grid Connected DC Microgrid

The architecture of the residential grid connected dc microgrid is shown in Figure. 1. The system is formed by typical RESs for Danish households, such as PV panels and small scale WTs, a battery pack as ESS, an EV charger, and typical appliances and electronics loads. Figure 1 shows the potential conversion stages reduction, and therefore efficiency improvement, when comparing a dc-based with an ac-based distribution system. In practise, not all the ac/dc conversion stages can be avoided since most of the household loads are not currently compatible with dc voltages. This issue is strongly related with the lack of standardize voltages for low-voltage dc distribution [8]. However, in order to assess the full potential efficiency improvement, dc compatible loads have been considered in the study. From Figure 1, some initial trends can be observed. First, in both cases, if the loads are fed from the grid, there is not effective conversion stages reduction, since two conversion stages are performed on the power flowing to the loads (green path). Second, when the loads are fed from the local RESs, two extra conversion stages are avoided, when the dc distribution system is used. Third, two extra conversion stages are also avoided if the loads and fed from the local ESSs, however, if the energy in the ESSs has been previously stored from the energy generated by the RESs, four conversion stages are avoided in the whole cycle. Therefore, it can be seen that the highest efficiency improvement is achieved when the loads are fed locally by the RESs or ESSs.

The potential for cost and conversion stages reduction can be easily seen in Figure 3, where the different parts of a 130 W laptop power supply, for a Dell Latitude E6540, are shown. The power supply is composed by two conversion stages, first a rectifier stage (brown area), formed by filter + PFC + diode bridge; and second a dc/dc flyback-based converter (light blue area); interconnected by a dc-link with an electrolytic capacitor (green area). The brown and green areas, which account for approximately 55% of the total power supply, are not needed if the dc voltage is directly supplied. Therefore, the use of dc voltage for distribution can significantly decrease the cost of the power supplies for electronic load, since approximately 55% cost reduction can be expected for this particular case. Specially interesting is to avoid the need of a bulky electrolytic capacitor, because is commonly the first-point of failure of the electronic power supplies.

The front-end rectifier is a key elements in the system, since it handles the power provided or absorbed by the grid. The power rating of this element should be selected to supply the maximum expected consumption of the household. The grid codes and normative define the minimum power, for which an ac distribution system has to be designed, regardless of the power that the user has contracted with the utility company. For instance, the installations should be sized for approximately 6 kW for each individual household. Therefore, in this study, a 6 kW front-end rectifier has been considered.

Finally, the selection of a optimal dc voltage level of the dc distribution bus is not a trivial task [8], [15]. The voltage level is strongly related to the safety and power rating of the installation, for instance, higher rated power will demand a higher voltage, in order to avoid a significant increment in the

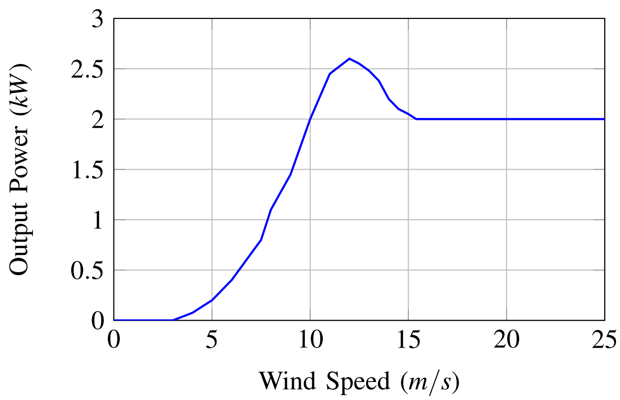

Figure 2: Power curve of 2.6 kWp Skystream 3.7 wind turbine, installed in Microgrid Laboratories.

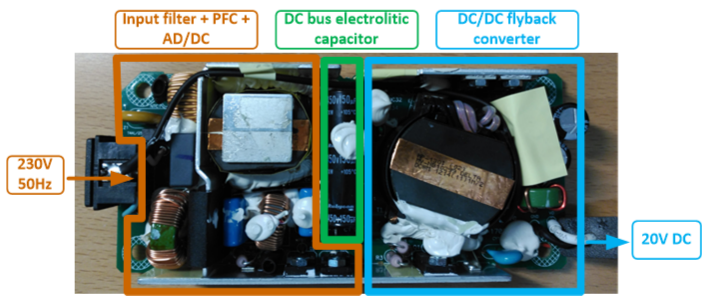

Figure 3: Comercially available 130 W laptop power supply for a DELL Latitude E6540.

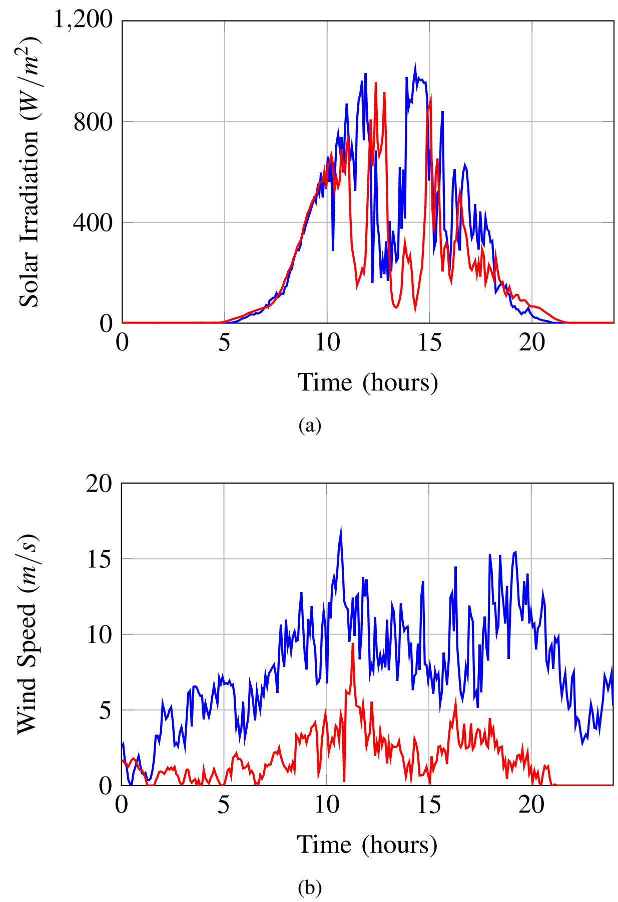

Figure 4: Solar irradiation and wind speed profiles record at Energy Technology Department of Aalborg University.

conduction losses or the size of the cables; while the opposite occurs with safety, the lower the voltage the safer. In this work 380V have been used as voltage for the dc distribution.

III. Methodology and Modelling of the Grid Connected Residential Microgrid

A simulation has been developed in order to analyse the ac-based and dc-based residential microgrids, for different weather conditions and consumption profiles. Average non-switching models have been developed for the PCUs, and daily profiles of the RESs generation and loads consumption, with a 5 minutes resolution, are used for the simulation. The models and profiles are explained in detail in section IV. The power balance in the distribution bus has to be kept at all times, and is described as follows:

$$P_{REC}(t) = P_{PCU_{PV}}(t) + P_{PCU_{WT}}(t) + P_{PCU_{ESS}}(t) - P_{PCU_{EV}}(t) - P_{PCU_{E}}(t) - P_{PCU_{A}}(t) \quad (1)$$

where, $P_{REC}(t)$, $P_{PCU_{PV}}(t)$, $P_{PCU_{WT}}(t)$ and $P_{PCU_{ESS}}(t)$ are the time-dependent power profiles of the front-end rectifier, PV installation, wind turbine, and ESS, respectively; while $P_{PCU_{EV}}(t)$, $P_{PCU_{E}}(t)$ and $P_{PCU_{A}}(t)$ are the time-dependent power profiles of the EV charger, the aggregated electronic loads, and the aggregated appliances; while t is the time variable. Positive power has been considered when the power is injected in the distribution bus.

It has been found that, for the system depicted in Figure 1, with typical consumption power ratings (<3 kW), conductor sizes (1.5-2.5 mm^2), and conductor distances in a Danish household (<40m), the conductor losses account for a tiny portion of the losses in the whole system. Hence, even a significant reduction in the conduction losses by the 380Vdc distribution system, it would not affect the overall system losses; therefore, the cable resistances have neglected in the modelling.

The consumption of the loads in the household has been divided in two different components. The devices in each component has similar characteristics (power rating, interface PCU) and therefore their consumption can be aggregated together. On one side there is the aggregated power consumption of the electronic loads (i.e. TVs, laptops, phones), which work with low dc voltage and have a low rated power (typically 5-24 V and < 500 W), and generally use PCUs with rated low efficiencies (< 75 %). On the other side there is the aggregated power consumption of the high power appliances, typically located in the kitchen, which work at a higher voltage and higher rated power (>500 W and typically >1 kW), and employ higher efficiency PCUs (>75 %).

The power injected/consumed by the different PCUs ($P_{PCU_X}(t)$) are obtained with the efficiency curves of the associated PCUs, and the time-dependent power profiles that the

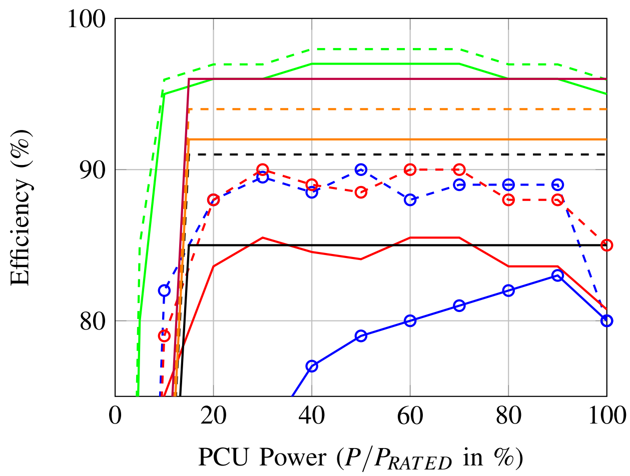

Figure 5: Measures(dots) and estimated efficiency curves of PCUs for ac voltage (solid) and dc voltage (dashed) supply. η_{PV} (green), η_{wt} (black), η_{ESS} (red), η_{E} (blue), η_{A} (orange), and η_{REC} (magenta).

PCUs have to handle, as described in the following equations:

$$P_{GRID}(t) = \eta_{REC}(P_{REC}) \cdot P_{REC}(t) \tag{2}$$

$$P_{PCU_{PV}}(t) = \eta_{PV}(P_{PV}) \cdot P_{PV}(\mathrm{Irr}) \tag{3}$$

$$P_{PCU_{WT}}(t) = \eta_{WT}(P_{WT}) \cdot P_{WT}(v) \tag{4}$$

$$P_{PCU_{ESS}}(t) = \eta_{ESS}(P_{ESS}) \cdot P_{ESS}(t) \tag{5}$$

$$P_{PCU_{EV}}(t) = \eta_{EV}(P_{EV}) \cdot P_{EV}(t) \tag{6}$$

$$P_{PCU_{E}}(t) = \eta_{E}(P_{E}) \cdot P_{E}(t) \tag{7}$$

$$P_{PCU_{A}}(t) = \eta_{A}(P_{A}) \cdot P_{A}(t) \tag{8}$$

where $\eta(\mathrm{P})$ is the efficiency curve of the associated PCU, P_{GRID} is the power consumed from the grid, $P_{PV}(\mathrm{Irr})$ is the aggregated power generated at the terminals of the PV panels, Irr is the solar irradiation [see Figure 4(a)], $P_{WT}(v)$ is the power generated at the terminals of the WT's generator, v is the wind speed profile [see Figure 4(b)], $P_{ESS}(t)$ is the power generated at the terminals of the ESS, $P_{EV}(t)$ is the power consumed at the terminals of the EV's battery, and $P_{E}(t)$ and P_{A} are the raw powers consumed by the electronic loads and high power appliances, respectively.

The power profile of the ESS (P_{ESS}) is usually set by a high-level energy management system (EMS) with an optimization scheme in order to minimize/maximize a given objective function [16], [17]. In the study the ESS balances the mismatch between power generation and consumption, until the state of charge (SoC) reach the maximum or minimum limit.

Finally, once the simulations have been performed, with the different microgrid topologies, weather conditions and consumption behaviours; the evaluation of the energy savings for the different scenarios is performed by the comparison of the energy exchange between grid and the residential microgrid, while accounting for the variation of the energy stored in the ESS at the begging and the end of the simulation. The energy exchange is calculated as follows:

$$E = E_{GRID} + \Delta SoC_{ESS} \cdot E_{ESS} \tag{9}$$

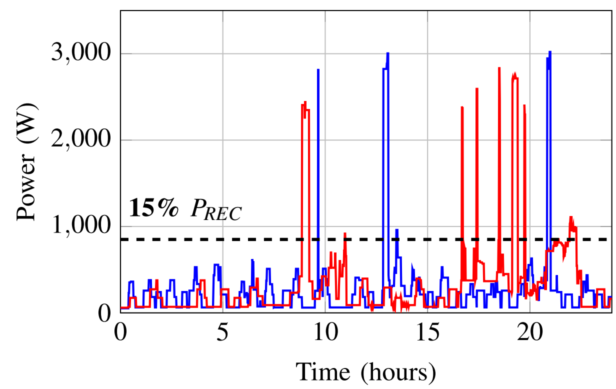

Figure 6: Simulated household consumption profiles obtained from a stochastic model, for a household with one occupant (blue), and a household with four occupants (red).

$$E_{GRID} = \int P_{GRID}(t) \cdot dt \tag{10}$$

where, ΔSoC_{ESS} is the variation of the energy stored in the ESS at the begging and the end of the simulation, in p.u., E_{ESS} is the rated storage capacity of the ESS, and E is the overall energy exchanged in the system.

IV. Study Case: A Danish Household

The study has used a Danish household as a base example for the analysis. The idea is to correlate the theoretical analysis presented in this paper, with a further experimental implementation of an residential microgrid in the Microgrid Laboratories at Aalborg University [18].

A. RES Generation Based on Local Weather Information

The generation of the RES has been estimated based on data recorded by a weather station in the energy technology department at Aalborg university. Figure 4 shows examples of one day solar irradiation and wind speed profiles used in the study; where the weather information has been recorded with a 5 minutes interval. The PV generation profiles are obtained from the solar irradiation profiles. The PV installation is formed by 12 EG-250P60C Eging PV panels, with a total generation power of 3 kWp. The PV panels are facing south, with a tilt angle of 53^{o}. The WT is a 2.6 kWp Skystream 3.7 with an embedded inverter for grid connection. The power generated by the WT turbine has been estimated using the WT's power curve, shown in Figure 2, which has been obtained from the device's datasheet.

B. Stochastic Consumption Modelling

The estimation of the household consumption is obtained from a simulation which implements a stochastic modelling methodology. These method takes into account the unpredictable and chaotic behaviour of the users and estimates the

[1] It has to be noted that, first, the residential microgrid has not been designed as an isolated electrical system, and therefore, the RES and ESS are not sized to ensure the electricity supply for all scenarios; second, the energy saving have been calculated by analysis the SOC of the ESS at the beginning and at the end of the simulation, since $P_{GRID} = 0$. Only the simulations, where the consumption has been met at all times, have been included.

E_{dc}/E_{ac}	Spring	Summer	Fall	Winter
PV	0.99	1.04	0.97	0.92
WT	1.03	1.01	1.02	1.05
PV+ESS	1.03	1.07	1.02	0.92
WT+ESS	1.07	1.06	1.06	1.09
PV+WT+ESS	1.08	1.09	1.07	1.09
PV+WT+ESS (Islanded[1])	1.11	1.11	1.10	1.12

Table I: Simulation results. Energy savings comparison of a dc an ac distribution system for residential applications

aggregated consumption of the household, using the characteristics of different appliances and loads in the system [14]. Figure 6 shows two consumption profiles obtained from the simulation of households with different number of occupants, where as expected, the household with a higher occupancy present a significantly higher daily energy consumption. This methodology for the consumption modelling allows to study how the overall distribution efficiency is affected for different consumption behaviours.

It can be easily appreciated that, for most of the time, the power consumption is well below 15% of the rated power of the front-end rectifier, therefore if the consumption, in this conditions, is supplied from the grid, the overall losses of the distribution system would be increased. Althoug, this working conditions can be avoided by supplying the consumption directly from the RESs or the ESS.

C. Modelling of Power Converter Units

Each individual PCU used in the simulation has been modelled by its equivalent efficiency curved. In general, the efficiency curve of an average PCU can approximated by a generalized efficiency curve. The generalize efficiency curve shows 0% efficiency at 0% of the rated power. From that point, the efficiency increases as the power delivered increases, until the PCU achieves rated efficiency between 10-20% of its rated power. Then the rated efficiency is maintained until 100% of the rated power. This is approach has been used for the PCUs which efficiency curves have not been measured because of its commercial unavailability.

In addition, the commercial PCUs, that will be used in the microgrid test-bed, has been tested and its efficiency curves measured. Figure 5 shows the efficiencies of the different PCUs, that have been used in the analysis. The efficiency curve, of the laptop power supply, shown in Figure 3, have been measured, both ac and dc supply voltages (solid blue and dashed blue curves). Since, this methodology cannot be applied for all the PCUs used in the analysis, the efficiency curves, that have not been measured, have been approximated using information obtained from datasheets, which usually provide the whole efficiency curve, or the efficiency at nominal conditions.

Likewise, the power curve of the PCU that regulates de ESS (7kWh battery pack) has also been measured. The PCU is a TDK EZA2500 380/48V 2.5kW isolated DC/DC converter (dashed red curve), alternatively the efficiency curve for an ac supply voltage has been estimated by including a series ac/dc conversion stage with 95% efficiency (solid red curve). The PV inverter modelled is a SUNNY BOY 3000TL, and the efficiency curve obtained from the datasheet (solid green); likewise, the efficiency curve for the PV converter supplied by dc voltage, has been obtained assuming the losses in the PV inverter where equally distributed both conversion stages (dashed green). Furthermore, the efficiency curves of the WT have been estimated from the rated efficiency value, and assuming that the ac/dc conversion has an efficiency of 94%.

V. SIMULATION RESULTS

The modelled residential microgrids have been simulated for different weather conditions, system configurations, and consumption profiles. Weather profiles of eighty different days along a year have been used for the estimation of the RESs power generation. The profiles have been randomly picked across the different seasons of the year, so its influence of the RESs and therefore on the overall system efficiency can be assessed.

The simulation results have been summarized in Table I. First it can be seen that the use of dc for a more efficiency distribution might not bring any efficiency improvement, it can even increase the overall energy consumption in the system ($E_{dc}/E_{ac} < 1$). This is observed for the scenarios where there is a low RESs generation, and therefore the loads are mostly supplied by the grid rectifier. It has been shown in Figure 6 that the average power consumption of typical household is well below the power rating, for which the installation is designed, and therefore the grid rectifier is providing the loads consumption while working with a poor efficiency.

Second, there is a higher potential for efficiency improvement when the RES is based on an small scale WT, rather than a PV installation. On one hand, the average efficiency of a small scale WT power converter is typically worse that the PV inverter counterpart, therefore the elimination of the ac/dc conversion stage can significantly reduce the losses in the WT power converter. On the contrary, typical PV inverter nominal efficiencies, as the one modelled in the study, are approximately 97-98%, therefore there is not much room for an efficiency improvement by conversion stages reduction, when the PV installation is connected to a dc distribution system.

On the other hand, it has been found that in average, the WT power generation better matches the consumption profiles. In this working conditions, the loads are mostly supplied locally, avoiding power consumption from the grid rectifier.

Third, the highest potential efficiency improvement is obtained for the scenario where the residential microgrid is isolated from the main grid. This can be easily expected, since it has been shown that, the grid rectifier was artificially increasing the losses of the overall dc distribution system, in comparison with the a conventional ac distribution system, where grid rectifier is not needed.

VI. Conclusion

This paper presents an analysis on the potential energy savings by using a dc distribution system for residential applications. A Danish household has been modelled and used as study case for the analysis. It has been found that, depending on the weather conditions and configuration of the microgrid, the use of dc for distribution can increase the energy consumption of the system. Furthermore, it has been shown that in general a dc distribution system would effectively increase the efficiency of the distribution, and therefore reduce the household energy consumption. However, ir order to achieve a significant efficiency improvement, a direct supply of the consumption from the front-end rectifier must be avoided, This can easily be achieved by increasing the share of energy generated on-site by the RES, in comparison with the energy consumed from the grid. It is also clear that, in terms of efficiency improvement, an isolated microgrid would more likely obtain a higher benefit from the implementation of a dc distribution system, rather than an ac distribution system.

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