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► To cite this version:

Colette Garron, Delphine Riu, Nicolas Chaintreuil. Towards the optimisation of a DC nanogrid considering technical and environmental criteria. CIREN 2023 - 27th International Conference on Electricity Distribution, Jun 2023, Rome, Italy. pp.2011 - 2015, 10.1049/icp.2023.1149 . cea-04520582

HAL Id: cea-04520582

<https://cea.hal.science/cea-04520582>

Submitted on 25 Mar 2024

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TOWARDS THE OPTIMISATION OF A DC NANOGRID CONSIDERING TECHNICAL AND ENVIRONMENTAL CRITERIA

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ABSTRACT

With distributed generation and new electrical loads, current electrical grids in buildings are becoming obsolete. DC nanogrid can then improve the overall efficiency of the buildings network. Moreover, as no standards exist yet for such grids, new optimisation criteria can be considered to better address current stakes. Thus, in this paper, a first approach to optimize a DC nanogrid is proposed, integrating power losses in the grid with different voltage values to design the best topology of the system. Then, data associated to CO₂ equivalent emissions are integrated to the optimization to size the cross-section cable of a line through an environmental point of view. Finally, we discuss the results and the next steps of the optimisation for the DC nanogrid.

INTRODUCTION

Current designs of electricity networks have been proposed and optimized in the XIXth century and have not fundamentally changed since. However, our way of producing and consuming electricity has evolved. Distributed generation and renewable energies have brought the production sites closer to the areas of consumption and introduced new conversion systems into the electrical grid. Moreover, most of industrial and residential loads are now associated to rotating machines supplied by power electronics components in order to improve their global efficiency and performances. This evolution, combined with climate issues and a need for energy independence, may question the goals and decision-making processes currently used to design electrical grids.

At the consumer side, self-consumption is gaining attractivity with the increase of energy prices along with a rise of awareness for environmental issues. This new model of production and consumption gives the opportunity to rethink and improve the electrical distribution inside buildings. The matter is discussed in literature through the concept of nanogrid. As no consensus exists to define a nanogrid, in this paper it will concern a microgrid at a building scale. Most of the time,

nanogrids are studied with a DC or a hybrid AC/DC electrical distribution. Indeed, the production and storage systems used in such configurations imply usually PV panels and batteries, both operating in DC mode. Moreover nowadays, most of electrical devices are powered through multiple power electronics converters as AC/DC and DC/DC converters [1],[2]. Consequently, a building grid operated in DC mode could allow to remove conversion stages at the production and storage level as well as at the load side. DC nanogrid also enables to reduce losses in cable due to the absence of reactive power.

However, no standard exists yet to define the architectures and topologies of DC nanogrids. The level of DC voltage to adopt and the benefits of DC over AC are more and more discussed in the literature but the applications, the methods and the results are various and do not always tally. Indeed, in [3], the authors are using a 380Vdc bus to power a commercial building. Several studies have been also conducted in India for residential applications using 72 Vdc and 48 Vdc [4], [5]. And in the context of U.S residential building, authors in [6] are looking at a grid with two voltage levels : 380Vdc and 24Vdc. It can be noticed that such an evolution has been already studied and implemented for microgrids dedicated to supply electrical loads for data centers and on-board systems for boats, planes and electrical vehicles. In addition, grid architectures are often evaluated based on techno-economic criteria but their environmental impacts are rarely addressed. Thus, new scientific analysis and technological solutions may help to contribute meeting socio-ecological challenges.

The purpose of this paper is to progress in the construction of an optimized DC nanogrid and give the first elements to improve the electrical distribution in residential buildings. The first part of the article is dedicated to a description of the nanogrid studied. Then, the influence of different DC voltages on the power losses is looked at in order to determine the voltage of the DC nanogrid. A rapid comparison of AC and DC nanogrid is made through the analysis of their respective power losses. Finally, the last part is a study on the sizing of cable by looking at the impact of the cross-sections on the line losses and on copper carbon emissions.

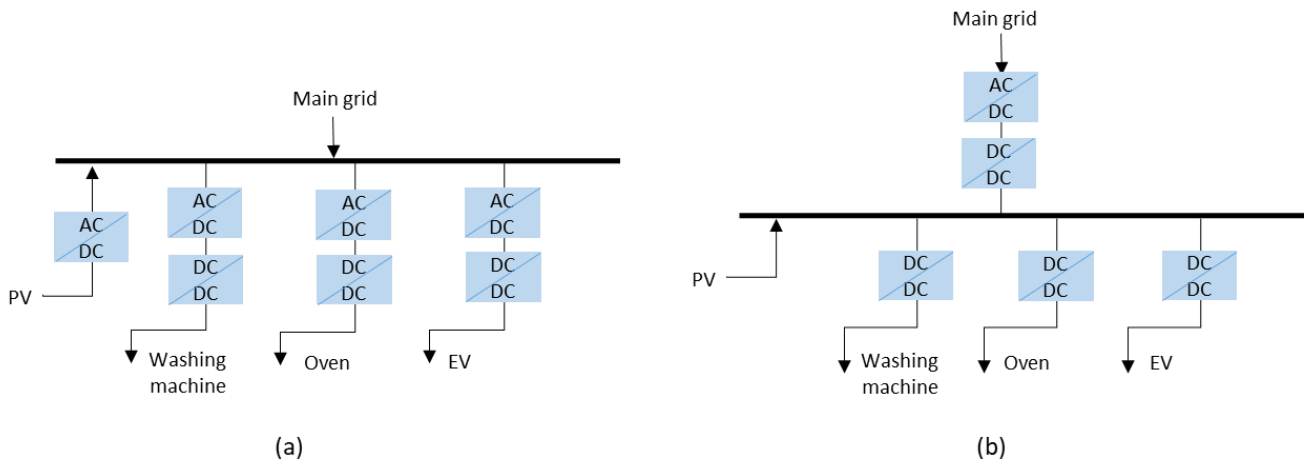


Figure 1: configurations of the nanogrid in AC (a) and DC (b)

DESCRIPTION OF THE CASE STUDY

The nanogrid studied in this article, represents an individual house at a reduced scale, with only three loads: a 2000W washing machine, a 3000W oven and a 7400W charger for an electrical vehicle (EV). The nanogrid is connected to the main grid (at a low level voltage) and a 5kW photovoltaic (PV) installation. Two grid configurations are then studied and will be compared, according to the DC or AC with single-phase distribution. The AC reference is based on French standards with a RMS voltage of 230V and a frequency of 50Hz.

Thanks to the power electronics converters, AC and DC architectures are different. They are depicted in figure 1. Converters are represented by their efficiency values. As many different topologies of converters exist, it is difficult to estimate an efficiency without entering in the details of the architectures and choices of converters. Therefore, the first model to study nanogrids has been chosen with fixed efficiencies whatever the power or the input and output voltages. Such parameters may be easily introduced in our optimization process in further works. Moreover, because of their high stakes in the energy transition, converters technologies are rapidly improving. Thus, efficiencies are chosen in the high range of what exist today. The efficiencies of the DC/DC, AC/DC and PV inverter are then respectively set to 97%, 94% and 97%. No difference is made between step-down and step-up choppers as they are considered bidirectional. The MPPT converter on the PV installation is the same for both architectures and is not taken into account.

MODEL OF THE NANOGRID FOR STEADY-STATE ASSESSMENT

To assess power losses in the nanogrid, a load flow analysis is developed. To implemented original and adapted models of power electronics converters into a radial electrical network, the iterative back and forward

sweep method (denoted by BFS) coded in Matlab is preferred to the classical Newton-Raphson algorithm to design the topology of the grid respecting some constraints as voltage drops at load nodes or power factor at the slack bus.

The backward sweep consists in a calculation of line currents from the values of node voltages. The forward sweep allows calculating the voltage considering the voltage drops across each lines [7]. The PV installation is considered as a negative load. Power electronics converters are modelled as particular “lines” for the load-flow calculations, for each technology considered in such nanogrid:

- A DC/DC line for buck or boost converters, for which input and output voltages are linked by the duty-cycle of the converter,
- A DC/AC line for controlled or uncontrolled rectifier or inverter.

The input data are the power of the loads and the PV installation, the fixed efficiencies of converters, the lines lengths and the cross-sections of the cables. Their resistances and reactances are calculated thanks to the following equations:

$$R_{line} = \frac{\rho_{cu}}{S} \times l \quad \text{and} \quad L_{line} = \frac{\mu_0}{\pi} \ln \left(\frac{D}{0.7788 \sqrt{S/\pi}} \right) \times 2\pi f,$$

where ρ_{cu} is the copper resistivity, S the cross-section of the cables, l the length of the line, μ_0 the vacuum permeability, D the distance between two cables and the grid frequency. In DC mode, the reactances are equal to zero since there is no frequency.

INFLUENCE OF THE GRID VOLTAGE ON THE POWER LOSSES

To get further in the model implementation, a DC voltage has to be set. However, as said previously, no standard

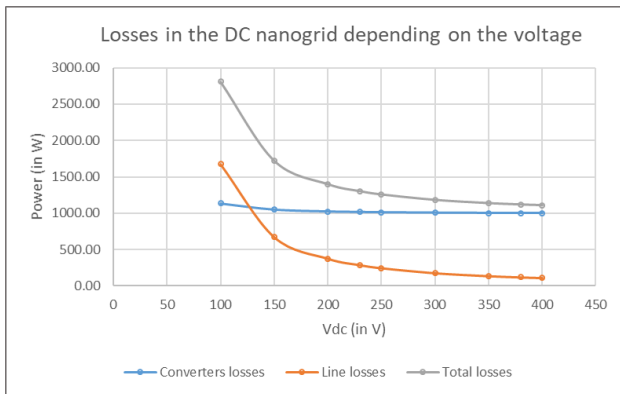


Figure 2: influence of grid voltage on power losses

exists yet for DC grids except for security considerations against electrical risks for people.

The first step is then to assess the power losses of the nanogrid over several different voltages. Two power losses are distinguished: those associated to the lines and those to the power electronics converters. Figure 2 presents these losses for different voltages going from 100V_{dc} to 400V_{dc}. As the efficiencies are not dependent of the voltage, converters losses are almost constant. The line losses, however, are significantly decreasing when the voltage increase, which is of course a classical result. In a DC mode, the line losses are then lower than in AC because of the absence of reactance and reactive power. As the voltage of the DC nanogrid is higher than in standard AC grid, the current flowing into the cables is reduced. It causes a diminution of the losses and the overheating due to the Joule effect.

Therefore, considering only the power losses, the best DC voltage is the highest one possible. Nevertheless, other factors have to be taken into account. First, the efficiencies of the converters depends in reality of the input or output voltages. Secondly, the voltage level of the grid has to be not too far from the voltages of the electrical loads. Therefore, for the rest of the paper, the DC voltage will be set at 380V.

In AC mode, the RMS voltage remains set on the French standard of 230V.

COMPARISON OF AC AND DC NANOGRIDS

With such a design, a comparison of the AC and DC topologies is proposed, focusing on the global power losses, for steady-state behaviour and when the PV installation produces the maximal power point for standard conditions of irradiation and temperature.

Considering both the lines and converters losses in the two configurations, the total losses are of 9.59% and 6.44% of the power of the loads (including PV) for the AC and DC architectures respectively. This represents a difference of over 550W. However, it is important to note that these

results are just an approximation of the possible gains since the models of the converters have to be improved. If we focus on the “real” line losses, they represent 1.75% of the total power of the AC nanogrid against only 0.69% in DC. As the nanogrid modelled in this study is at a reduced scale, the possible energy savings in a real domestic installation can have a real impact on the reduction on the total costs of energy. Moreover, in addition to the impact of the grid voltage design, other studies can be investigated to optimise the DC nanogrid even more. One is given in the next section through the choice of the cross-section of the cables.

OPTIMISATION OF THE CROSS-SECTION OF CABLES

Cross-section of cables are then not yet standardized in DC as for AC grids. The standards are set to limit the drop voltage and the overheating of the cable cause by the Joule effect. Nanogrids give the opportunity to set parameters not only based on technical performances but also on environmental ones. Therefore, the choice of the cross-section of cables is done regarding also to the carbon footprint, one of the nine planetary limitations. For that, the problem has been simplified in order to analyse the coupling between technical and environmental assessments, regarding only the line from the EV charger to the grid. This line has a length set at 50m and supply a 7.4kW power (a common power in single-phase AC EV chargers). In an AC configuration, according to French standards, the cross-section of such cable would be fixed to 10mm² and the drop voltage authorized for this sort of load would not exceed 5%.

Method used to size the cross-section based on carbon emissions

Firstly, the line losses in the EV line are calculated with different cross-sections. The study starts with the AC standard of 10 mm² and decrease with the common cross-sections of 6mm², 4mm², 2.5mm² and the smaller one equal to 1.5mm². For each case, the drop voltage and the line losses are calculated, respecting the constraint of 5% of the rate value. Then the CO₂ equivalent emissions of the copper in the EV line are calculated by multiplying the mass of copper in the cable for each cross-section by the global warming potential (GWP) of copper (2.8 kgCO₂-eq/kg) to obtain the carbon emissions associated to the extraction of raw materials. The GWP used was established by Nuss et Eckelman and takes into account the mining, purification and refining of copper [8]. Of course, this GWP should be improved by integration of CO₂ emissions associated to the process, transportation

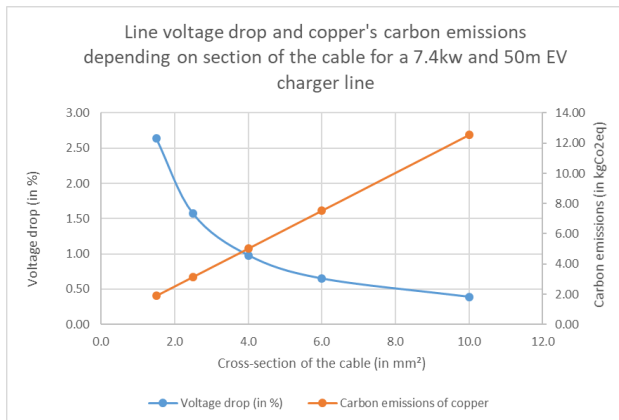


Figure 3: influence of the cross-section of cable on voltage drop and carbon emissions of copper

and installation of electrical cables in the grid. The results are presented in Figure 3. It can be observed that when the cross-section of the cable decreases, the voltage drops and the losses increase which remains a classical result regarding the links between the cross-section and the current flowing into such a cable.

From a more innovative point of view, the carbon emissions of the copper are evaluated in regard of the environmental impact of power losses. Carbon emissions due to the line losses are obtained by multiplying the losses by the carbon emissions of the French electrical grid. This hypothesis is questionable since the nanogrid has a PV installation. Nevertheless, the French electrical grid has a very low carbon footprint due to nuclear plants and the PV installation considered here is quite small in regard of the power of the loads. A sensitivity analysis will be conducted in the future to improve the hypothesis. Moreover, an electrical installation has a lifespan of 30 years, therefore a study has to be considered to evaluate the losses in the EV charger line during its life. This data is found by estimating the energy going through the line during one year. For a single-phased 7.4kW charger, based on a daily average distance covered by an electrical vehicle and its average range we approximate the number of time a vehicle is charged [9]. From then, with the data on the charging time (for a battery of 22kWh) gave in [10], we estimate the number of hours for the charging mode at 250h for one year. By multiplying this result by 30, we get the energy passing through the line over its lifespan. Then we obtain the carbon emissions due to the loss in the line by multiplying this figure by the percentage of line losses calculated earlier and the carbon emissions of the French grid (36 gCO₂-eq/kWh [9]).

Finally, we can compare the CO₂ equivalent emissions associated to the line losses and the copper volume for the lifespan of the EV line depending on the cross-section of the cable. Results are given in figure 4.

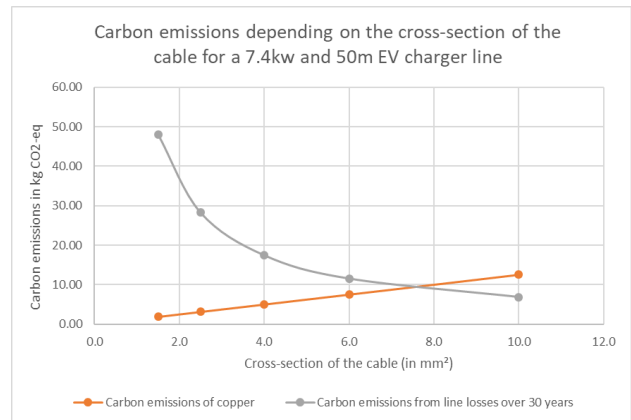


Figure 4: influence of the cross-section of cable on carbon emissions

Discussion over the results

In the simple case of the EV line, if we consider only carbon emissions associated to cables (uses of raw materials and losses), the right cross-section is around 8mm². However, this result is highly dependent on the energy passing through the line over the cable lifespan, and this study may be a little hard to take into account of all the loads of an industrial building. Though, we can imagine some sort of abacus for the main loads in the house that would allow to size properly the cross-section of cables by limiting carbon emissions and power losses. In this first work, only carbon emissions of copper were taken into account because it is the parameter that most depends on the cross-section of cables. Nevertheless, we can detail the model further by taking into account the overall process of cable production in the calculation of CO₂ emissions.

Moreover, knowing and be able to reduce the mass of copper used in an electrical installation is important not only from an environmental perspective. Indeed, copper is a metal with geopolitical stakes. It holds an important place in the energy transition and its demand should highly increase in the future. The biggest copper mines are located in Chile and the fusion of the metal is realized principally in China [10]. Therefore, in the future, it can be subject to volatile prices and scarcity.

CONCLUSION AND PERSPECTIVES

In this paper, we conducted a first approach to optimise the electrical distribution in buildings. The DC nanogrids have good perspectives to save energy and lower the environmental impact of electric installations. We determined a first estimation of the possible energy savings they could allow over the traditional AC configuration. We also highlight some areas of improvement through the two studies on the influence of voltage and cross-section cables on the efficiency and carbon emissions of the nanogrid.

The next steps in the optimisation of the nanogrid are to

add more accurate model of converters and realize a real life cycle analysis on the overall installation as well as an economical analysis. These criteria will be used in an optimisation algorithm to find the best installation depending on cost, efficiency and environmental concerns.

Acknowledgement

This work was supported by the French Environment and Energy Management Agency (ADEME) and the CEA, in association with the French National Program "Programme d'Investissements d'Avenir INES.2S" under Grant ANR 10 IEED 0014 01.

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