PARTICIPATION OF STORAGE DEVICES FOR STEADY-STATE VOLTAGE MANAGEMENT IN LV GRID WITH PV INTEGRATION

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ABSTRACT

This paper focuses on the implementation of two main solutions (reinforcement and energy storage systems) in a low-voltage (LV) network with an important photovoltaic (PV) integration. The electrical network considered is a rural low voltage network which includes 20 clients and its PVs. The study is carried over 30 years with constant consumption and a rate of installation of PVs set to 3%. The model uses a Monte Carlo approach to model consumption and PV production. It can determine a planning of reinforcement and also the power of batteries needed to prevent overvoltage. The results indicate that energy storage systems have more benefits than reinforcing cables in this particular situation. Sensitivity analysis have been performed on different parameters which show the different conditions where reinforcement can compete with energy storage systems.

INTRODUCTION

Because solar energy is widely available, solar photovoltaic (PVs) energy can contribute to the reduction of CO_2 emissions. Hence, PV's share of global electricity could reach 16% by 2050 to compare with 11% in 2010 [1]. However, the PV integration creates unwanted overvoltage in the grid as PV production occurs when electricity consumption is low [2] [3]. Therefore grid operators need to apply solutions to prevent overvoltage. One common solution is grid reinforcement but it can be very expensive and it has to be forecasted a long time in advance [4].
For this main reason, grid operators are unwilling to see an important PV integration in the grid [5]. As a result, other solutions which should be cheaper and more flexible will be needed. Energy storage systems are a solution that could be used in the near future [4] [6]. Hence, this paper focuses on the implementation of two main solutions (reinforcement and energy storage systems) in a low voltage (LV) network with an important PV integration.

In order to compare the technical and economic aspects of these different solutions, the electrical network considered is a rural low voltage network and the study is carried over thirty years.

MODEL DESCRIPTION

Network characteristics

The network has the following characteristics: 20 clients spread in the network whose total subscription is 156 kW have been considered (see Figure 1). According to ERDF (the French distribution network operator), it is possible to place from 15 to 35 clients in this sort of network (it is equivalent to 100 kW to 255 kW). Consumption is considered constant and the rate of installation of PVs is set to 3% per year. Finally, 208 kW of PVs has been installed at year 30 producing half of all clients' consumption.
Concerning the energy storage systems, lithium-ions batteries were considered for the economic aspect of the study.

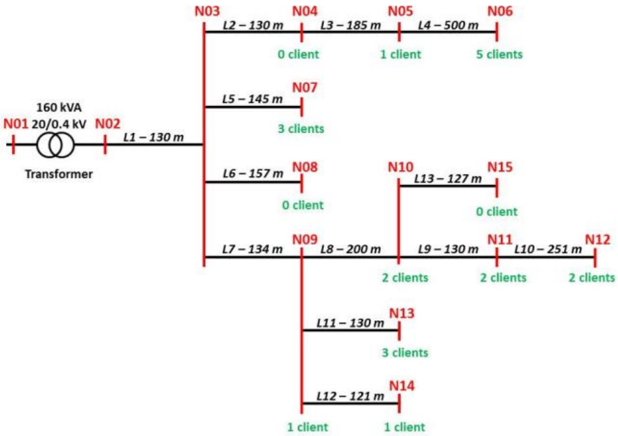

Figure 1 - Single line diagram of the electrical network used in simulations

Tool implemented

In the model described, a Matlab algorithm has been developed which calculates the probability of overvoltage for each year and each node. The distribution network operator considers that overvoltage must not occur more than 3 hours annually [7]. It has been considered that when the algorithm calculates a 1% probability, it means that there is 10s of disconnection per day for a client. Therefore, if the calculated ratio in the model is higher than 3%, the situation is not acceptable and solutions should be applied.
This algorithm combines a Monte-Carlo method, which

simulates PV production and clients' consumption and a load-flow, which calculates steady state variables of the grid [8]. More specifically, PV production and clients' consumption were modelled based on 2 years measurements data. In one hand, PV production is considered as a combination of a uniform distribution with a normal distribution for peak production. On the other hand, consumption is based on a mean consumption specific for each client with asymmetrical noise and a normal distribution. Moreover, as mentioned before, some clients are "one tariff" and others are "2 tariffs". The "One tariff" consumption is modelled following the method described above. The "2 tariffs" consumption uses also the method described but it adds the consumption of specific equipment (ie water heater, etc) which is launched during off-peak hours. Finally, the load-flow implemented uses the method described in [9].

Solutions implemented

As mentioned before, different solutions are considered in order to prevent overvoltage in the grid: reinforcement and energy storage systems.

In the model described, lines are modelled with its impedance which is modified when the decision of reinforcement is made (reinforcement includes also parallelization). The decision for reinforcing a line is taken when at least 10% of the tests need to reinforce this particular line.

The energy storage systems are considered to deliver either active or reactive power only. As a result, its power is available immediately. Moreover, this study does not take into account the state of charge of the batteries. Finally, the tool determines the maximum power needed from the energy storage systems to prevent overvoltage to occur in the grid.

The solutions succeed to prevent overvoltage in the grid when voltage at each node is within the contractual limits (+/-10% with 1.5% margin [10]).

RESULTS AND DISCUSSIONS

Description of the different scenarios

In this study, an important share of PV is fixed and the period of the simulation is set to 30 years. This period is similar to the one used by the grid operators.

As the model uses a Monte-Carlo approach, the number of iterations has been set to 1000.

Two different scenarios were studied:

(1) Scenario "2 nodes": PV production located in node 6 and 10;

(2) Scenario "Clients": each client own a PV panel.

For each scenario, 3 different cases were compared:

(a) Reinforcement only;

(b) Storage only: 2 batteries are located in node 6 and 10.

Different assumptions were made for the different cases:

- reinforcement is made every 10 years. For example, at year 0 all lines which need to be reinforced during the next 10 years will be reinforced.

- Energy storage systems last also 10 years and their implementation starts immediately when power in charge is needed.

Results

Case (a) – Reinforcement only

Reinforcing the lines cannot help to integrate all the PV production at year 30 in both scenarios (see Figure 2). Indeed, the probability of overvoltage exceeds the 3% limit during the 7th year for scenario 1 as shown in Figure 2 (a).

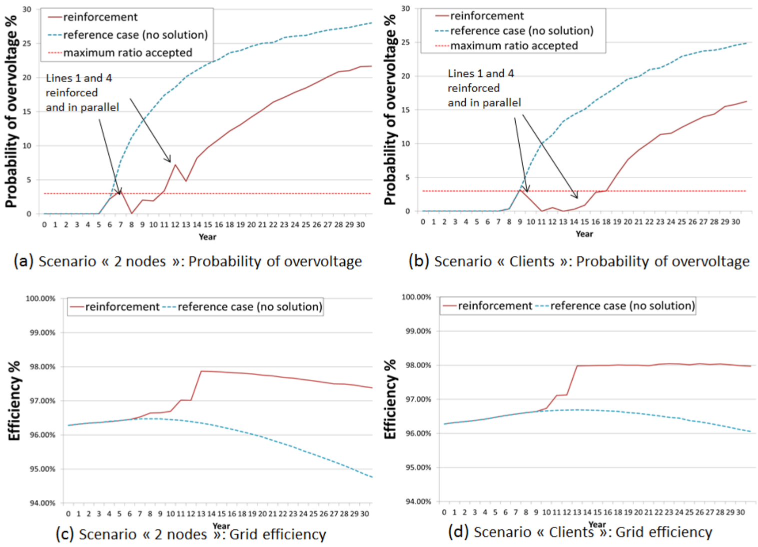

Figure 2 - Impact of reinforcement works into the network

However in this particular scenario, reinforcement helps to maintain the probability of overvoltage under the limit during year 8 to year 11. Then the probability increases to reach 21% at year 30 which is lower than with no solution implemented (28%).

For scenario 2, the observations are similar but reinforcement helps to keep the probability of overvoltage until the 17th year. Then it reaches a maximum of 16% against 25% in the reference case where no solutions are implemented.

One can also see that the reinforcement helps to increase significantly the annual grid efficiency up to 98% (see Figure 2 (c) and (d).

Case (b) – Storage only

In both scenarios, the power needed from the batteries to prevent overvoltage appears before overvoltage occur (see Figure 3). Indeed, the tool takes into account a 1.5% margin. Therefore there is a need for power as soon as the voltage exceed 1.085 pu (per unit).

As shown in Figure 3, when PVs are diffused in the network, the power needed from the batteries starts when 34.8 kW of PVs are installed and then for each new kW of PVs installed, 0.7 kW of storage is needed.

Similarly when PVs are located in two nodes, the power needed from the batteries starts when 20.9 kW of PVs are installed and then for each new kW of PVs installed, 1 kW of storage is needed.

Case (c) – Reinforcement with storage
In this particular case, the power needed from the energy storage systems are determined once the planning of reinforcement for year 0, year 11 and year 21 has been made.

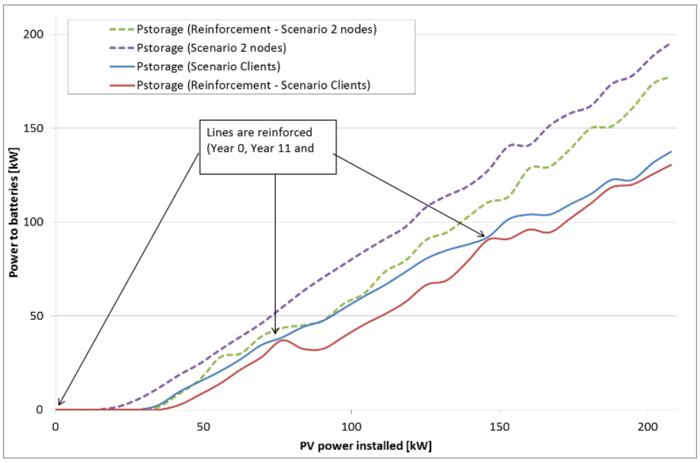

Figure 3 - Power needed from the batteries for the 2 scenarios in the 2 cases

As shown in Figure 3, the power needed has been reduced for each scenario between 10% and 4%. Moreover, one can see that when lines are being reinforced, the power needed decreases the year after.

Cost analysis
All costs are calculated in k€ and it uses a discount rate α equals to 8%. The different costs were taken from [4].
The cost of the different solutions described can be broken down as:

$$C^{30\,years} = C^{30\,years}_{storage} + C^{30\,years}_{reinfor} + C^{30\,years}_{loss\,lines} \qquad \text{(Eq. 1)}$$

where

- $C^{30\,years}_{storage}$ is the total cost for using storage systems over 30 years and is calculated as in Eq. 2.
- $C^{30\,years}_{reinfor}$ is the total cost for reinforcing the grid over 30 years and is calculated as in Eq. 3.
- $C^{30\,years}_{loss\,lines}$ is the total cost for grid losses over 30 years and can be calculated as in Eq. 4.

$$C^{30\,years}_{storage} = C^{30\,years}_{inv\,storage} + C^{30\,years}_{conv\,stor} + C^{30\,years}_{loss\,storage} \qquad \text{(Eq. 2)}$$

where

- $C^{30\,years}_{inv\,storage}$ is the investment cost and replacement cost of lithium-ion batteries over 30 years.
  $C^{30\,years}_{inv\,storage} = \sum_{batt,year\,p} C^{energy}_{lithium-ions} * E_{batt,p} * \frac{1}{(1+\alpha)^p}$
  (Eq. 2 (a))
  with *batt* the batteries which need to be added or invested at year *p*.
  $C^{energy}_{lithium-ions} = 400 \frac{€}{kWh}$, the energy cost for lithium-ions batteries
  $E_{batt,p}$, the mean energy use during the battery lifetime from year p in kWh.
- $C^{30\,years}_{conv\,stor}$ is the conversion cost with the maintenance cost of lithium-ion batteries over 30 years.
  $C^{30\,years}_{conv\,stor} = \sum_{batt,year\,p} C^{power}_{lithium-ions} * P_{batt,p} * \frac{1}{(1+\alpha)^p}$
  (Eq. 2 (b))
  with *batt* the batteries which need to be added or invested at year *p*.
  $C^{power}_{lithium-ions} = 145 \frac{€}{kWh}$, the power cost for lithium-ions batteries
  $P_{batt,p}$, the battery power at year p in kW.
- $C^{30\,years}_{loss\,storage}$ is the total cost of loss in batteries lithium ions over 30 years.
  It has been assumed that 20% of total energy transferred to the batteries is being lost:
  $C^{30\,years}_{loss\,storage} = 0.2 * \sum_{year\,n} C_{loss} * P_{batt,n} * T_{batt} * \frac{1}{(1+\alpha)^p}$ (Eq. 2 (c))
  with $C_{loss} = 0.06 \left[\frac{€}{kWh}\right]$, cost for energy losses
  T_{batt}, the number of hours per year when the battery is being used

$$C^{30\,years}_{reinfor} = \sum_{n=0,11,21} C^{line}_{renfor} * L^{year\,n}_{renfor} * \frac{1}{(1+\alpha)^p} \qquad \text{(Eq. 3)}$$

where

- $C^{line}_{renfor} = 100[\frac{€}{m}]$, linear reinforcement cost
- $L^{year\,n}_{renfor}$ is the total length of the lines which are being reinforced at year n

Concerning the grid losses, it has been assumed that losses can be calculated using the peak power losses which occur 1500 hours per year in winter and 1000 hours per year in summer.

$$C^{30\,years}_{loss\,lines} = C_{loss} * \sum_{year\,n} (1500[h] * P^{year\,n}_{loss\,winter} + 1000[h] * P^{year\,n}_{loss\,summer}) \frac{1}{(1+\alpha)^p} \qquad \text{(Eq. 4)}$$

Where

- $P^{year\,n}_{loss\,winter}$, is the peak power in winter at year n.

Finally these equations help to calculate the costs for each case described above.
The main hypothesis are that the energy storage systems last 10 years and are then replaced with the power in charge needed 10 years later so that it helps to maintain the voltage.
Overall costs for each case and each scenario have been placed in Figure 4 versus overall grid efficiency in 30 years. It can be observed that batteries are the cheapest solutions (between 89.4k€ and 124.7k€) for the 2 scenarios ("PVs located in 2 nodes" and "PVs located at all clients"). However grid efficiencies are lower: around 96.5%.
As the lines in the grid are very long and as PV integration rate is very high, only reinforcing the grid is a very expensive solution (between 175k€ and 194k€) and the probability of overvoltage is above the limit. However the grid efficiency increases and reaches 97.4%.
When energy storage systems are being added to the reinforcement; total costs is two times higher than reinforcement alone (between 377k€ and 404k€) while grid efficiency is 97.7%.
When each solution is being compared for each scenario ("PVs located in 2 nodes" and "PVs located at all clients"), the solution implemented in "PVs located at all clients" is cheaper and more efficient.
Finally, for the grid operator, in this particular grid, energy storage systems seems to be have more benefits than reinforcing

cables.

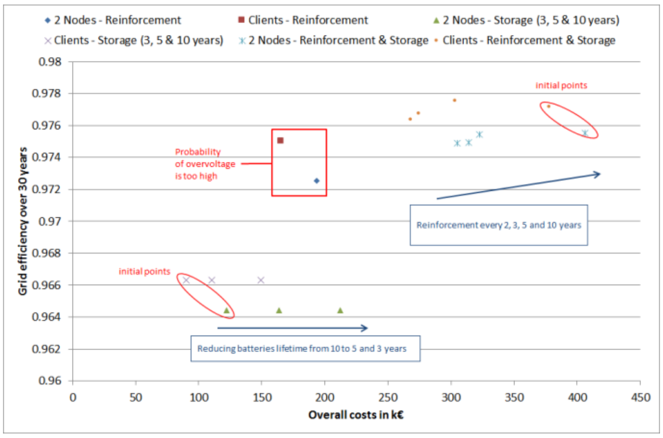

Figure 4 - Costs over 30 years (in k€) versus the overall efficiency for the 3 cases.

Sensitivity analysis

These results show that energy storage systems are cheaper than reinforcing the grid. However the PV integration is very important and the lines are long. For these reasons, a sensitivity analysis has been performed on these different parameters:

- Batteries lifetime which is reduced from 10 years to 5 years and 3 years;
- Planning of reinforcement which is made every 2, 3 5 or 10 years
- Length of some lines in the grid
- Total of PV power output installed at year 30.

Batteries lifetime and planning of reinforcement

The hypothesis of batteries lifetime is been fixed to 10 years. However this variable depends on many parameters (temperature, number of cycles, etc.) which can reduce this lifetime. The study has been done for a lifetime of 3 years, 5 years and 10 years as shown in Figure 4. Hence reducing the lifetime increases the total cost of the solution. For example, reducing the batteries lifetime from 10 to 3 years increase the costs by 70% in both scenarios while the grid efficiency is constant.

Concerning the planning of reinforcement, instead of reinforcing every 10 years, the planning of reinforcement is made every 2, 3 or 5 years. The batteries lifetime is kept to 10 years. The results are also shown in Figure 4. Increasing the planning of reinforcement increases the total costs and also the grid efficiency. Finally, reinforcing the lines many years before it is needed costs more than the reduction of losses it implies.

Length of the lines in the grid

Three lines are being analysed:

1. Line n°4: the longest line in the grid
2. Line n°8: the line which is connected to many nodes
3. Line n°10: the line with the least clients and the second longest one in the grid

The results for the 2 scenarios and the 2 solutions (reinforcement only and reinforcement with storage) are presented in Figure 5.

The method described has been repeated 20 times when the lines are equal to 50%, 100% and 150% of their initial length.

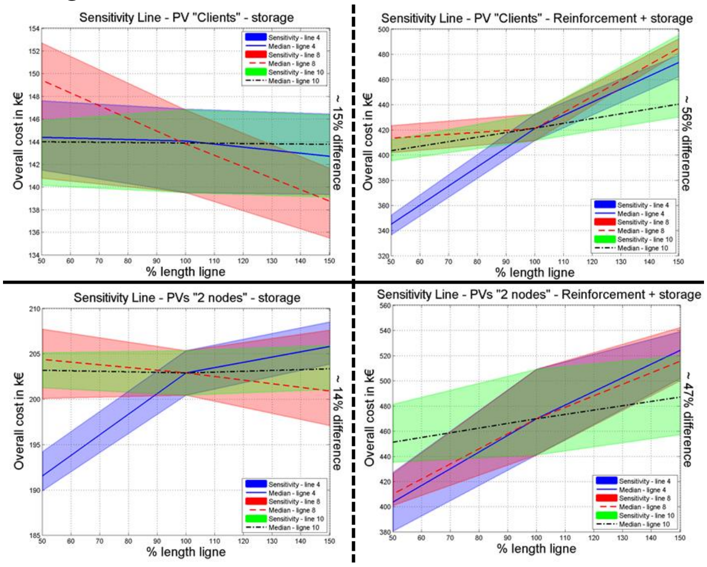

Figure 5 - Sensitivity analysis for length of 3 lines

It can be observed that if energy storage systems are used alone, the total cost of the solution is not sensitive to the length of the lines. However, the costs are very sensitive when reinforcement is considered. In particular, length of lines 4 and 8 is very sensitive in both scenarios.

PV power output at year 30

In this study, it seems that the rate of PV installation is very high and thus energy storage systems are more advantageous. Indeed, the grid has to be reduced very quickly. Therefore Figure 6 shows the total costs for each scenario and for each solution when the rate of PV integration rate increases.

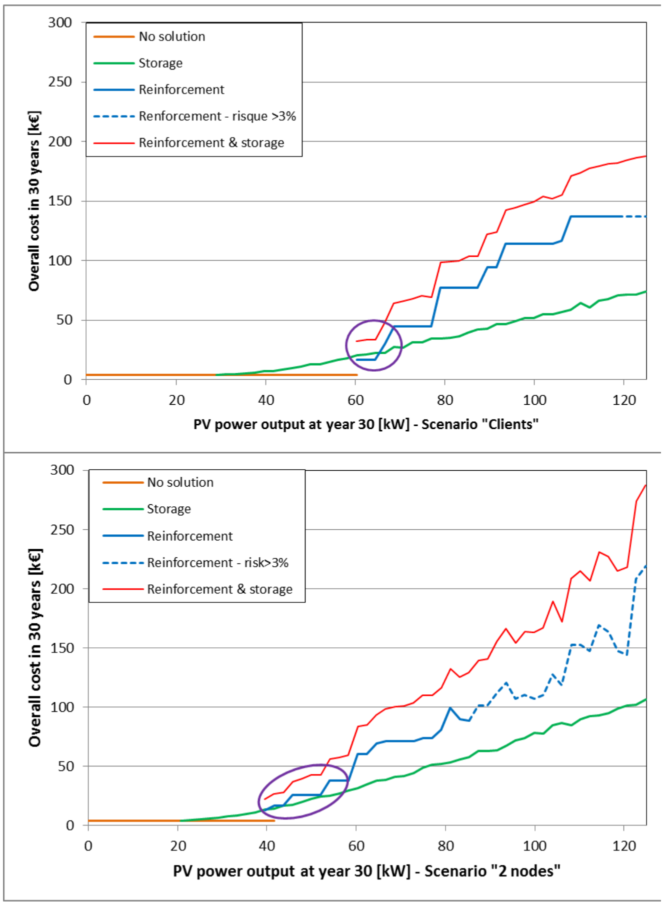

Figure 6 - Sensitivity analysis for PV power output installed at year 30

It can be observed that from 60 and 65 kW for scenario “Clients” and from 40 and 55 kW for scenario “2 nodes”, reinforcement solution and storage solution have the same costs.

CONCLUSIONS

In the situation described, the energy storage systems have more benefits than reinforcing cables. They can prevent effectively overvoltage in LV grid. Hence, a sensitivity analysis on different parameters have been performed: batteries lifetime, planning of reinforcement, length of different lines and rate of installation solar panels. The results show that the reduction of batteries lifetime increases significantly the overall cost. They also indicate that with a lower rate of installation, reinforcing can compete with energy storage systems. Finally, the design of the LV grid used in this paper seems to benefit to energy storage systems: lines are quite long and there are few customers while PV production is very important. In future, the study could be expanded by including other solutions such as the management of reactive power by solar panels.

Acknowledgments

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