I. RENEWABLE ENERGY SOURCES AND ENVIRONMENTAL PROTECTION

OPTIMAL INTEGRATION OF DISTRIBUTED ENERGY STORAGE AND SMALL GENERATORS INTO AN ISLANDED MICROGRID WITH RENEWABLE SOURCE

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ОПТИМАЛНА ИНТЕГРАЦИЯ НА РАЗПРЕДЕЛЕНИ ЗАПАСЯВАЩИ ЕНЕРГИЯТА УСТРОЙСТВА И МАЛКИ ГЕНЕРАТОРИ В АВТОНОМНА СИСТЕМА С ВЪЗОБНОВЯЕМИ ЕНЕРГИЙНИ ИЗТОЧНИЦИ

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Abstract: The purpose is to study how best to integrate distributed energy storage and small thermal generators in a Microgrid mainly powered by renewable sources. Optimal placing and capacity sharing of distributed energy storage helps to reduce Joule losses and voltage drops. Small generators give same advantages at optimal location. Optimal capacity sharing of Distributed energy storage is based on Droop mode control of specific inverter. Storage units are guided to behave homogenously to have the same evolution of State of Charge, so the same life cycle. By minimizing the Joule losses, the decentralization of storage allows to reduce the conductor section or the size of renewable power sources at design phase. For existed grid, it could delay distribution grid's upgrade investment. It should be therefore financially interesting.

Keywords: Distributed Energy Storage, Optimal placing, Droop mode

INTRODUCTION

More than 25% of the population doesn't have any connection to the electrical network. Unfortunately, because of the economic and technical problems, several areas are not connected. An interesting and economical solution is to use autonomous systems powered by renewable sources. To balance between production and consumption, it is necessary to add diesel generators or energy storage units (batteries) to ensure the continued service, regardless of the renewable source's intermittency. It is worth noticing that energy storage can introduce additional benefits to the whole electric system: enhance power quality, reduce peak load…

Usually, most energy storage systems centralize their batteries and use a single inverter. It seems worthwhile to consider the decentralization of storage, in particular to estimate the impact and the gain on the reduction of Joule losses and voltage drops on the grid. Indeed, without adding any complex energy management system, it is possible to split centralized energy storage unit into two (or more) units which are located at different nodes on the microgrid. If storage units are well located at critical points in the electrical network, additional benefits can be achieved such as Joule losses reduction.

The objective of this paper is to validate and generalize the concept of distributed energy storage (DES) units in low voltage (LV) network. By assuming energy storage units can operate in droop mode control, a tool is developed to define the optimal localization and sharing/splitting capacity ratio of DES units. This tool can also apply for optimal localization of small thermal generators if their production schedules are already determined.

HYPOTHESIS FOR OPTIMAL INTEGRATION OF DES UNITS AND GENERATOR

Predetermined load/generation profile

The concerned microgrid is on islanded operation mode powered by renewable sources. We consider that the load consumption curve and generation profile of renewable sources are known for a simulation period. It could be a result of a good prediction. For generators, we assume that their production profiles are fixed by the operator, i.e. in our case, the generator start only at peak hours.

Control strategy of battery inverter (droop mode)

In order to decentralize energy storage unit without adding any complex energy management system, it require battery inverters could work in parallel independently. Each inverter can provide own voltage and frequency reference based only on information available locally at the inverter – voltage and current. Such inverter is called VSI (Voltage source inverter). According to a specific control strategy-for example the power frequency droop control as described in the next paragraph, VSI define real and reactive power output. Thus it is possible to control voltage and frequency of microgrid by means of inverter control.

The concept of "droop mode control" is based on variation of active power/frequency. At first it is only applicable for high voltage grid. But [1] has demonstrated it can be applied to low voltage grid as well.

If the power supply (production) is greater than the power demand (consumption), the frequency is increased, and vice-versa if the power supply is lower than the power demand, the frequency is reduced. In the same way, the control of the voltage is provided by controlling the reactive power. This dependence can be expressed in the following linear equations:

(1) $$f - f_0 = -k_P(P - P_0) .$$

(2) $$U - U_0 = -k_Q(Q - Q_0) .$$

This primary control act locally on each group of production and provides an automatic correction between production and demand. It would lead to a new equilibrium in the entire network. Droop control characteristic is shown graphically in (Fig.1).

Droop mode inverters are already commercialized such as Sunny Island 4500 by SMA Solar Technology [2]. The main advantage of droop mode control is that no (complex) communication between inverters is required. With droop parameters, frequency variation in the microgrid provides an adequate way to define power sharing among VSI.

Proposed method to minimize power losses with optimal allocation of DES and generator

Instead of one centralized storage unit with capacity C, we try to split it into 2 or more storage units C_1, C_2… C_n (called as DES units). The sum of DES unit's capacity must be equal to C:

(3) $$C_1 + C_2 + C_3 + ... = C .$$

The number of generator and their profile are fixed as input data. The main question is how we split centralized storage to DES unit? What amount? Where we place them in microgrid topology? The allocations of DES units and generators have to be precisely calculated because their installations in optimal locations help to decrease power losses.

The optimal allocation of DES units requires simultaneously solving two problems: the identification of the optimal placing of DES unit, and the estimation of their optimal capacity. With a predetermined production profile, generators only require identifying their optimal placing.

Genetic algorithm (GA) can be a potentially useful approach for optimal placing problem of both DES and generator. During the GA optimization process, to estimate the optimal capacity of each DES unit, we use a simple but reasonable and effective method called "Approximated capacity" (cf. 4.3). Nevertheless, a more accurate method for optimal DES capacity is described at later section (cf. 5).

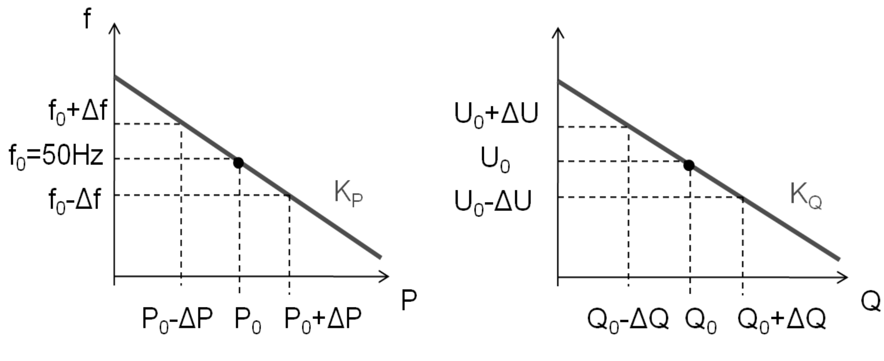


Fig.1. Droop parameters.

GENETIC ALGORITHM FOR THE OPTIMAL PLACING

Introduction of Genetic Algorithms

Genetic algorithms are implemented as computer simulation in which a population of abstract representations (chromosomes) of candidate solutions (individuals) to an optimization problem evolves toward better solutions. The evolution usually starts from a population of randomly generated individuals and happens in generations. In each generation, the fitness of every individual in the population is evaluated, multiple individuals are stochastically selected from the current population (based on their fitness), and modified (recombined and possibly randomly mutated) to form a new population. This new population is then used in the next iteration of the algorithm. The algorithm commonly terminates when either a maximum number of generations has been produced or a satisfactory fitness level has been reached for the population. If the algorithm is terminated due to a maximum number of generations, a satisfactory solution may or may not have been reached.

GA implementation

The number of desired DES unit and generator is classified as input to determine the size of the solution vector. Each solution vector contains only one type of information: the location of DES units and generators. The next figure shows an example GA coding of 3 DES units and 2 generators.

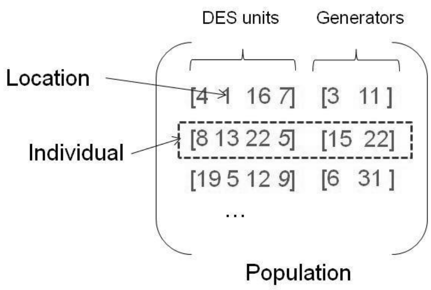


Fig.2. GA coding.

In reproduction phase, we use two-point crossover technique. The location information between the two points is swapped between the parents, rendering two children (Fig.3).

To maintain genetic diversity, mutation operator chooses randomly a point, then change from its original state to random value (location) (Fig.4).

Individual evaluation by power losses

The objective function to evaluate an individual refers to the total Joule losses in microgrid which is the sum of Joule losses at every branch of grid.

$$F_{OF} = \sum_{i=1}^{N-1} P_i \quad (4)$$

In this paper, the Joule losses (Eq. 4) are calculated by JPelec software [3]. This tool provides an accurate grid simulation in steady state. JPelec requires not only the location of DES units for simulation but also their capacity; therefore, an approximated capacity calculus (cf. 4.3) must take place. Generator locations are also needed for grid simulation. The next figure sums up the whole process to obtain individual score.

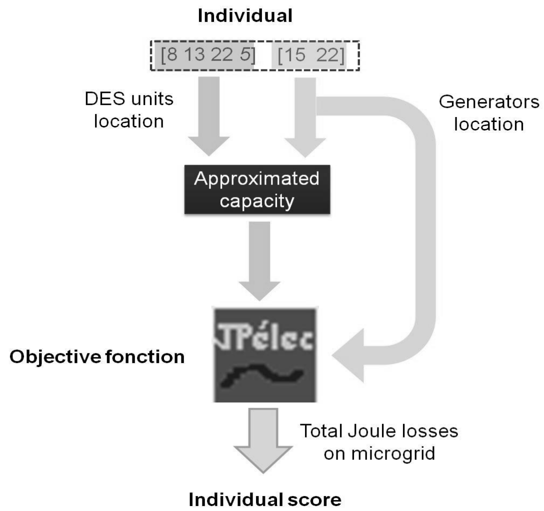


Fig.5. Individual evaluation process.

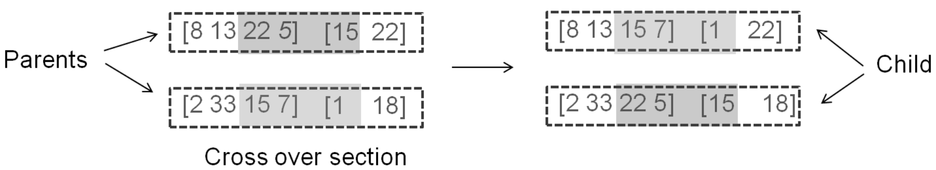


Fig.3. Crossover reproduction.

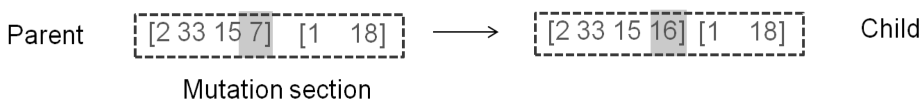


Fig.4. Mutation phase.

APPROXIMATED CAPACITY OF DES UNIT

At first we begin by modeling a simplified system and finding an optimal DES capacity's sharing by means of inverter's droop value. In the case of one central energy storage unit, the droop value for inverter control of whole system is K (kW.Hz-1) and energy storage capacity is C (kWh).

2-nodes microgrid with two DES unit

The micro grid has 2 nodes linked by a power line AB. Instead of only one energy storage unit (size C) located at A or B, two separated energy storage units C_A and C_B ($C_A + C_B = C$) are located at A and B (Fig.6).

Let K_A and K_B be the droop of storage inverter A and B:

(5) $$K_A = \frac{-dS_A}{df} = \frac{-S_A(t)}{f(t) - f_0}$$
$$K_B = \frac{-dS_B}{df} = \frac{-S_B(t)}{f(t) - f_0}.$$

(6) $$K_A + K_B = K.$$

The Joule losses are proportional to the power (or current) transmitted in AB line from A to B:

(7) $$P_J = 3RI^2 = 3R\frac{P_{line}{}^2}{3^2(\cos f)^2 V^2}.$$

In the article [4], in order to minimize Joule losses in power line for a considered period T, $a = \frac{K_B}{K_A}$ must be equal to $\frac{b_2}{2b_1 - b_2}$, with β_1 and β_2 are defined by these equations:

(8)
$$b_1 = \int_t^T (L_A(t) + L_B(t) - G_A(t) - G_B(t))^2.dt$$
$$b_2 = \int_t^T (L_A(t) + L_B(t) - G_A(t) - G_B(t)).(L_B(t) - G_B(t)).dt$$

This α represents the optimal droop's ratio between two inverters that minimizes the power transmitted in line AB, thus Joule losses for the considered time period. Most of the time, this ratio is positive, meaning that signs of both droop values are the same, so an energy storage unit never charges the other. The authors also state that the condition to have the same state of charge evolution in both batteries is:

(9) $$\frac{K_A}{K_B} = \frac{C_A}{C_B}$$

This means that the capacity ratio of energy storage is the same as the droop values ratio for inverters.

N-nodes microgrid with N- DES units

Let's consider a microgrid with N nodes. At each node, we place a DES unit. By considering that the network topology is fixed, that production and load profile are perfectly identified and [4] have already solved these questions:

- What should be the droop value K_i at each node i in order to minimize Joule losses in the whole network?
- What should be the optimal capacity of DES units?

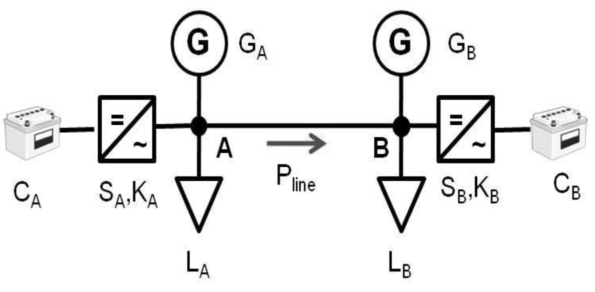
It means that all the variable $K_1 \ldots K_N$; $C_1 \ldots C_N$ are identified, and these equations are satisfied:

(10) $$\begin{cases} K_1 + K_2 + K_3 + \ldots + K_N = K \\ \frac{K_1}{C_1} = \frac{K_2}{C_2} = \ldots = \frac{K_N}{C_N} \end{cases}$$

Approximated capacity

Now we place on the N-nodes network only p units of storage (p <N). The location of p DES units is known. We try to identify C_{DES1}, $C_{DES2} \ldots C_{DESp}$ subject to:

(11) $$C_{DES_1} + C_{DES_2} + \ldots + C_{DES_p} = C$$



G_A, G_B: total generation at A or B
L_A, L_B: total load at A or B
C_A, C_B: storage capacity
S_A, S_B: inverter power output
K_A, K_B: inverter's droop
P_{line}: power flow in line AB

Fig.6. 2 storage units at each node.

At first, we take the result of the previous paragraph 4.2. For each node having a storage unit, we determine among other nodes (without storage units installed) all R nodes closest (relative to other nodes with DES unit). A node *i* is considered closer to a node *j* than node *k* where the line resistance between *i* and *j* is less than that between *i* and *k*. Dijkstra algorithm is used for this research. The DES capacity at this node is the sum of capacity of all R nodes.

For example, in Fig. 7, we place 3 DES units on microgrid at nodes 10, 16 and 21. The droop value to split between them is K.

Nodes from 1 to 11 are closer "electrically" to node 10 than the others. Therefore, capacity for DES units located at node 10, 16 and 21 are:

$$C_{DES1} = \sum_{1}^{11} C_i, C_{DES2} = \sum_{12}^{18} C_i, C_{DES3} = \sum_{24}^{19} C_i \tag{12}$$

with C_i calculated at paragraph 0. The C_{DES1}, C_{DES2}, C_{DES3} are not optimal capacity, but very close to the optimal ones.

OPTIMAL CAPACITY OF DES UNITS

This method is more accurate than the previous one. Because this method is time consuming, we didn't use it in GA process. Once the location of DES is determined, we try refining the DES capacity in order to minimize the Joule losses. The first constraint is the total capacity of DES fixed by the user's configuration (C). Other constraints are: the capacity of each DES must be greater than 0 and lower than the total capacity.

The function to be optimized is the total Joule losses on microgrid. The DES unit's locations determined by GA algorithm described above are used as input parameter. The problem is a Constrained Optimization with equality and inequality constraints.

$$\begin{cases} \min F_{OF}(C_{DES1}, C_{DES2}, ..., C_{DESp}) \\ \sum_{1}^{p} C_{DESi} = C \\ C_{DESi} - C < 0, i = 1..p \\ C_{DESi} > 0, i = 1..p \end{cases} \tag{13}$$

To solve this problem, analytical methods are not suitable because JPelec calculations do not give the derivative of the objective function. We must use optimization algorithms that require only the evaluation of the objective function.

The zero-order methods are useful because in practice, a large number of functions to optimize are not differentiable, even non-continuous. Most common zero-order methods are the Direct Search methods. They can adapt to nonlinear, non convex or non differentiable problems. These methods deal the optimization problem as a black box, given an input value x, the black box calculate and returns the value of the objective function f(x) (Fig.8).

The Pattern Search (PS) is one method of Direct Search Optimization. In general, the PS has the advantage of being very simple in design, easy to implement and the computation is efficient. Unlike other heuristic algorithms such as genetic algorithms, the PS are adapted to global search [5].

The Pattern Search algorithm is done by computing a sequence of points that approach an optimal point. At each step, the algorithm searches a set of points, called a mesh, around the current point – the point computed at the previous step of the algorithm. The mesh is formed by adding the current point to a scalar multiple of a set of vectors called a pattern. If the pattern search algorithm finds a point in the mesh that improves the objective function at the current point, the new point becomes the current point at the next step of the algorithm.

"Approximated capacity" (cf. 4.3) value are used as the initial point for the algorithm. Within about 20 iterations, the algorithm finds optimal capacity for each DES unit.

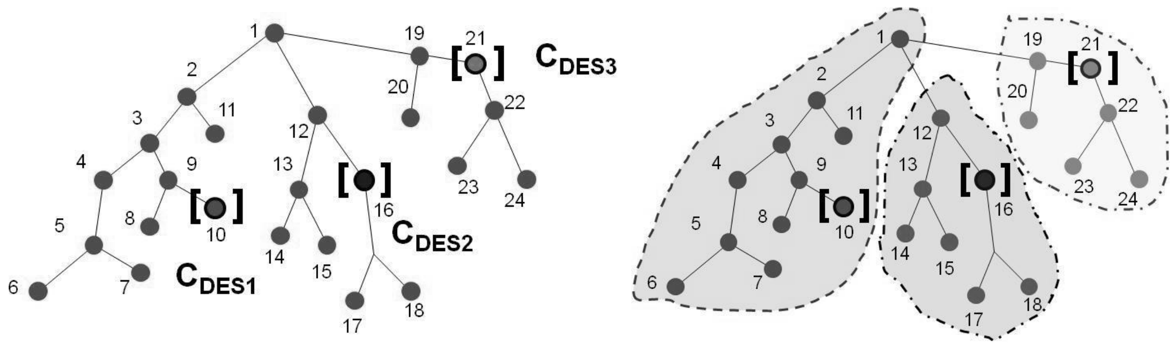


Fig.7. Approximated capacity illustration.

RESULTS AND DISCUSSION

In order to validate the methodology described previously, a test case on a microgrid built according to the real distribution network of Saül village in French Guyana is examined. The microgrid typology, load consumption and PV production are shown in Fig. 9.

The village has two generators. Generator G1 gives 5kW at 20h and 6kW at 21h (Fig.10). The second one G2 has the same profile but one hour later (it means 5kW at 21h and 6kW at 22h).

The simulation period of the whole system is 24 hour. The Joule losses of the microgrid with only one energy storage unit located at node 1 are about 10% of the total load consumption.

We try to split one centralized storage unit into 2, 3 or 4 DES units. In the case of 3 DES units, optimal location for energy storage units are node n^0 5, 18 and 38 with the capacity ratio between DES units is 34.4: 48.8: 16.8 (Fig.11). Two generators are best placed at node n^0 11 (G1) and 32 (G2).

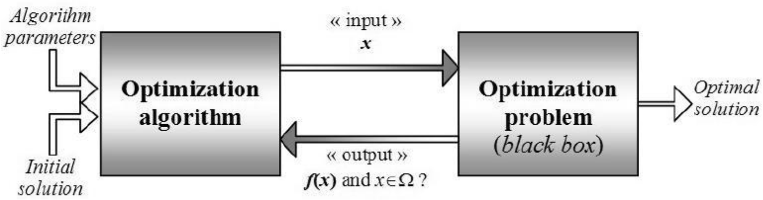
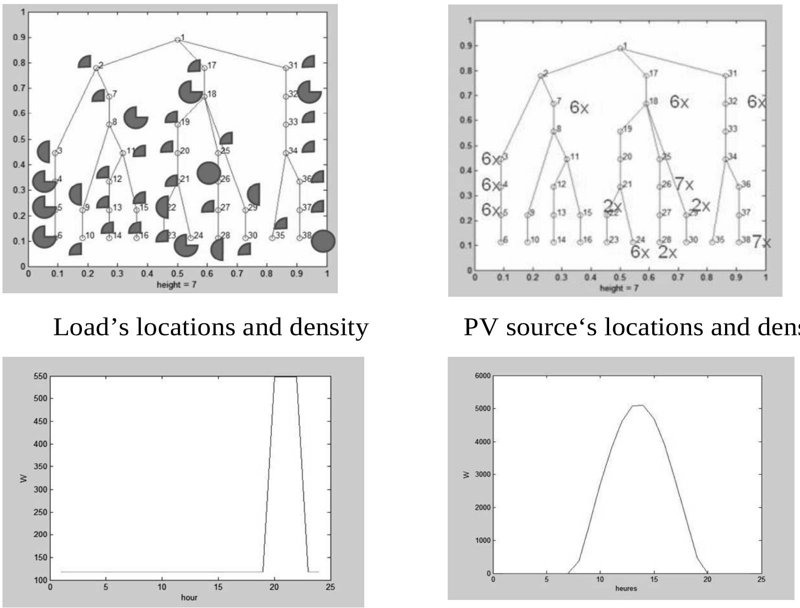


Fig.8. Direct search optimization.



Load's locations and density

PV source's locations and density

Daily load curve

Daily PV production curve

Fig.9. Saül-village microgrid configuration.

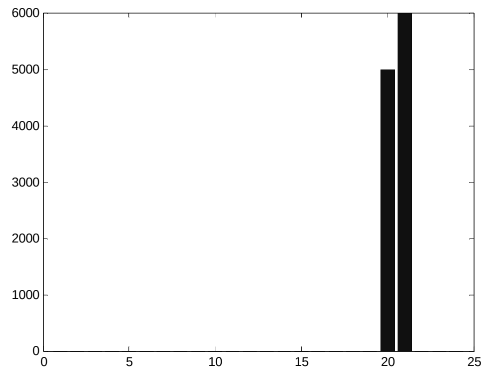


Fig.10. Generator G1 production profile.

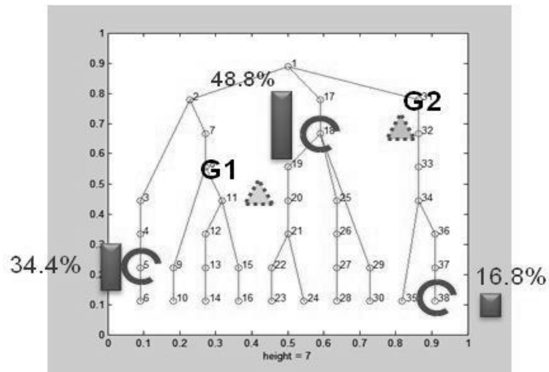


Fig.11. Optimal DES and generators allocation.

With inverter in droop mode control, if energy storage units have the same starting conditions, the evolutions of their state of charge (SOC) are identical (Fig.12). Energy storages are charging when PV production exceed load consumption and are discharging at low or without PV production.

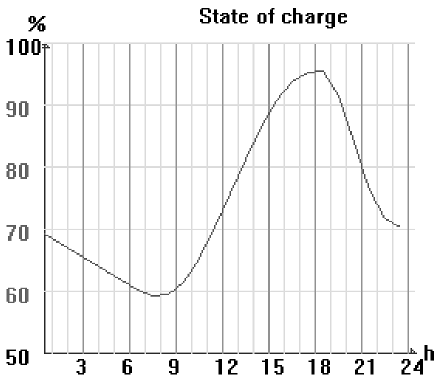


Fig.12. State of Charge Evolution of DES.

The Joule losses are reduced by increasing the number of energy storage units. In the case 3 DES, the Joule losses are reduced 4 times in comparison with the case with only one energy storage unit located at node n^0 1 (Fig.13). This means more energy can be stored or the power source's size can be reduced.

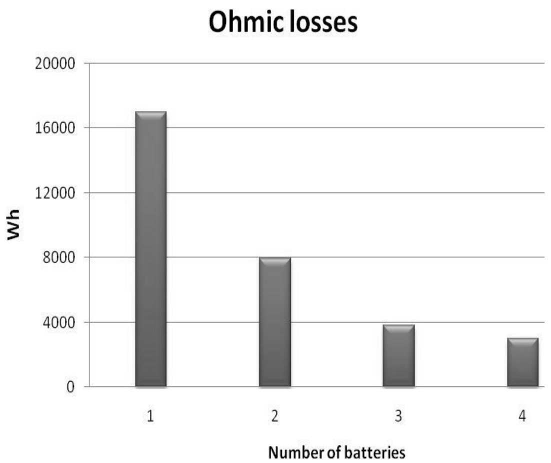


Fig.13. Joule losses reduction with increased number of DES units.

However the reduction is less significant from 3 DES to 4 DES (only 5% difference). To determine what number of DES units is the best fit for a microgrid, we must compare the economic and technical benefits (further work).

The voltage profile at each node of the microgrid is improving with more DES installed. With power flow simulations performed using JPelec software; we observe that voltage quality improvement is most significant at the farthest node. The difference between maximum and minimum voltage decrease from 36V to 15V with three energy storage units installed instead of only one storage at node n^0 1 (Fig.14).

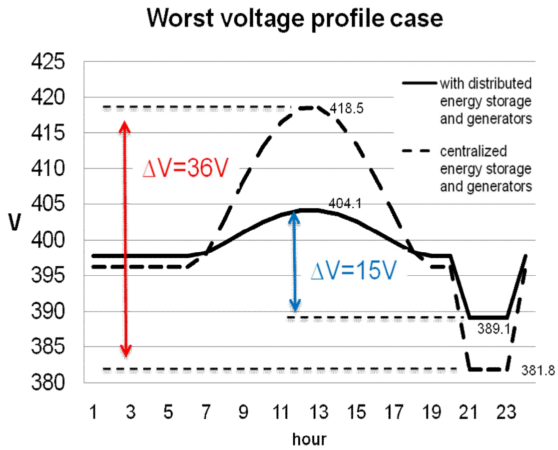


Fig.14. Worst voltage profile.

The voltage profile in the worst case is less fluctuating with distributed energy storage than the centralized energy storage case. It means more PV production can be added without breaking voltage limit rules (max 420V, min 360V). So more load consumption can be allowed without needing a distribution grid upgrade (bigger power lines for example).

CONCLUSION

In this paper, a method based on Genetic Algorithm is proposed to find the optimal placing for DES units and small generator in a microgrid. With inverters running in droop mode, it is possible to locate the optimal location and determine the optimal sharing capacity ratio of DES that minimizes the Joule losses and thus improves network efficiency. By doing so, the optimization procedure can help to determine the number of DES units that fits at best with the microgrid typology. In case of load consumption growth, optimal placing of DES units may help to avoid distribution grid's upgrade.

By increasing the number of energy storage units, microgrid quality and reliability are improved. Without any (complex) energy management, storage units running in "droop mode" behave homogeneously, which facilitate planning and maintenance.

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