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Optimal planning and management of photovoltaic sources and battery storage systems in the electricity distribution networks

***Abstract**. In this paper, the Non-dominated Sorting Genetic Algorithm NSGA-II, accompanied by the Newton Raphson method for power flow calculation, has been applied to an IEEE 33 bus test network to plan locations of photovoltaic power plants and Battery Energy Storage Systems. In addition to the minimization of costs, total losses and the maintain of voltage within acceptable limits (minimize voltage drops), the determination of these optimal locations will make it possible to converge towards a decentralized network with optimized, local energy and close to the consumer.*

Streszczenie.** Przedstawiono wykorzystanie algorytmów genetycznych wspomaganych przez metodę Newton-Raphson do obliczania przepływów mocy. Analizowano szynę zgodną z IEEE 33 w planowanej sieci ze źródłami fotowoltaicznymi i bateryjnym zasobnikiem energii.* ***Optymalne planowanie i zarządzanie siecią rozdzielczą z ogniwami fotowoltaicznymi i magazynami bateryjnymi.

Keywords: Battery Energy Storage System, Decentralization, NSGA-II, Optimal placement, Photovoltaic sources.
Słowa kluczowe: ogniwa fotowoltaiczne, magazyny energii, algorytmy generyczne.

Introduction

Nowadays, the exploitation of renewable energy sources is the best alternative to avoid the energy crisis, especially with the expected extinction of fossil fuel deposits. This is the reason why many countries are adopting this green, non-polluting and intermittent energy solution and are trying to move from centralized fuel production to distributed production.

This intermittent energy has a disruptive and unavoidable effect on the electricity distribution network, since it affects several network parameters; it can cause voltage drops, huge losses and affect the reliability of the power grid. As a result, network managers have started to think about controlling these parameters by planning the position of renewable energy sources in the electricity network.

Determining the optimal locations of renewable energy sources for one or more objectives is part of several optimization problems. This vast field was and remains, to this day, the center of interest of several researchers. The most recently used methods in these kinds of optimization problems are metaheuristics. In [1], Borges presented a methodology for determining the optimal sizing and location of distributed generators DGs to ensure reliability, minimize losses and maintain an acceptable level of voltage profile. The power flow method was applied with the genetic algorithm GA and with the analytical methods to evaluate the reliability indices and optimize the losses and the voltage profile. El-Khattam, in his paper [2], proposed a new heuristic method for planning optimal decisions regarding the location and sizing of the capacity of DGs. He also developed an optimization model, in [3], which aims to minimize the cost of purchasing power of the main network, the maintenance and operating costs of the DG, the investment costs and the payments to compensate for the loss of the system. Pisică [4] compared the genetic algorithm to nonlinear optimization for optimal sizing and allocation of DGs to minimize losses and investment cost. The comparison results, based on the number of DGs, showed that the two methods are similar for a single integrated DG, but for more than two DGs, the GA gives better results. Based on a rural distribution network, Singh [5] dealt with the problem of voltage rise. The paper presents a new approach for optimal allocation of DGs for profit, voltage improvement, and minimization of losses. Raoofat [6] proposed an approach based on the genetic algorithm and tested it on a 33-bus network for simultaneous allocation of DGs and remotely controllable switches. The objective was to achieve a better level of reliability and reduce energy losses. The genetic algorithm was also the choice of Vivek Goyal in his article [7] for a good location and sizing of DGs. This famous genetic algorithm remains, to this day, the preferred algorithm for many researchers [8-13] thanks to its promising results in the field of optimization.

Other researchers have been interested in many other methods. For example, in [14, 15], Shuffled Frog Leaping Algorithm was proposed to determine the optimal location of distributed sources in order to minimize losses and improve the voltage profile. The work presented in [16] consisted in using the Artificial Bee Colony ABC algorithm for minimal production cost and losses, taking into account the installation of a Unified Power Flow Controller for better performance of the system. The authors, in [17] and [18], used a new algorithm called Whale Optimization Algorithm to plan the location of DGs in distribution networks.

Probabilistic and analytical methods have also been used for similar optimization problems as in [19- 22], and Particle Swarm Optimization PSO has in turn proven to be effective when used by many researchers [23- 28]. Not to mention the hybrid methods that combine one or more optimization methods. For example, in [29], a hybridization between the genetic algorithm and PSO was performed (HGAPSO) so that the voltage profile can be improved and the losses in the feeding system reduced for a better configuration of the distribution system.

In this article, an optimization approach, based on the non-dominated sorting genetic algorithm NSGA-II, has been applied in two steps to find the optimal locations of PVs and Battery Energy Storage Systems BESSs for two reasons:

- Minimize losses, voltage drops and investment cost
- Promote the concept of decentralized production

On the one hand, finding the optimal locations will prevent power losses and voltage drops in the network at an optimal cost, and it will, on the other hand, allow to create subnetworks near the consumer.

Depending on the optimal locations found, subnets can be created; each sub-network contains photovoltaic systems PVs and BESSs as energy sources.

This is part of the new 4D trend: Decarbonization, Digitization, Decentralization, and Decrease of demand. This new vision will help manage the electricity grid and make it more reliable, digital and decentralized. Several efforts have been made in these four major parts, for example for the concept of digitization, many articles have been published to make the network remotely controllable, intelligent and digital [30-33]. The same goes for the other concepts. This work will be part of the research carried out in the field of decentralization.

This paper is structured as follows: the second section contains the problem formulation and the working hypotheses. The optimization algorithm is detailed in section III. The fourth paragraph presents the simulation results and discussion. And the last part contains a conclusion.

Problem formulation

In this paper, the optimization problem is multi-objective with three functions to minimize:

- Power losses
- Voltage drops
- Investment cost

The problem has been addressed in two steps:

1. Optimal locations of Battery Energy Storage Systems
2. Optimal locations of photovoltaic power plants

Under a constraint of keeping the voltage between 0.95 and 1.05 pu, the functions to minimize are as follows:

$$(1)\quad \begin{cases} F1 = min\left(\sum Ploss\right) = min\left(\sum_{i=1}^{n} Ri\,|Ii|^2\right) \\ F2 = \min\left(\sum_{i=1}^{n} ||1 - Vi\,||\right) \\ F3 = min(cost) \end{cases}$$

where: $Ploss$ – total power losses, Vi – voltage at bus i, n – number of buses.

This work has been accomplished under the following hypotheses:

- It is assumed that the photovoltaic power plant delivers a power of 1MW (the level of penetration is almost 30% of the load).
- Specific photovoltaic panels and batteries technologies were chosen in order to have the costs of the solutions.
- It is assumed that the solar radiation is almost the same over the entire surface of the network.

Optimization algorithm

Known for its promising results, especially for multi-objective optimization problems, the genetic algorithm is considered to be one of the most powerful optimization methods in the literature.

This algorihtm, based on the natural evolution of the human being, initiates its operation by randomly generating a population containing individuals called chromosomes, each characterized by genes. The best chromosomes are crossed (Crossover) by analogy to genetics. A cross is firstly done between two parents, by exchange of genes (bits), to give a child, and then between the best children to have better ones. The process, translated by random mutations of bits, is repeated until having a child close to the optimal solution.

The resolution by the genetic algorithm is ensured according to the following steps:

1. Creation of N random individuals (initial population)
2. Evaluation of the generation
3. Selection / Elimination: the selection can pass just selected individuals, these individuals can move to the next generation to reproduce.
4. The crossing (Crossover): this is the stage where, from the existing solution, the selected chromosomes share their characteristics and create children with good inherited peculiarities.
5. The mutation: in a chromosome, the gene can be altered depending on a certain probability of mutation.
6. Passage to the new generation

Despite all its promising benefits and results, the genetic algorithm remains limited for multi-objective problems. Therefore, several versions have been developed for this reason, for example the classic NSGA, the micro-GA algorithm, the NSGAII, etc. In this article, the resolution was made using the NSGA-II algorithm which is based on the notion of the optimal pareto front. From the best individuals in the previous population, the algorithm creates offsprings to form a population. Then, depending on the crowding distance comparison operator and the non-dominated sort, the NSGA-II selects the next generation.

Methodology

Known for its vital role of providing energy to consumers, the electricity distribution network is considered as one of the most complex parts of the electricity grid. Its complexity is reflected by its reliability [34] with the multitude of components, its radial structure and its management which remains a challenge for network managers, especially with the new trend towards the integration of renewable energies.

Thanks to its resemblance to a real network, the IEEE 33 bus network has been chosen for test, in this article. However, in real networks, the load's behaviour is changing, it's dynamic and varying. This is the reason why the chosen test network remains not enough for the implementation because of its static state. As a result, we have divided the operation and dynamics of the load into 3 periods to represent its variance:

Period A: 06:00 - 18:00, characterized by the participation of the industrial sector in consumption. The energy demand, in this period, will be ensured by the photovoltaic systems and the main source (in case of insufficient solar radiation), in addition to charging the batteries.

Period B: 18:00 - 23:00, the residential sector accounts for the largest percentage of consumption in this period known as the peak area. In addition to the main source station, the battery systems, charged during period A, will be the sources of energy for this period.

Period C: from 23:00 to 06:00, in this period, consumption is falling sharply and will therefore be ensured by the main source.

This work is divided into two parts:

- Determine the locations of battery energy storage systems that will operate during period B.
- Find the locations of photovoltaic power plants that will supply the grid during period A.

The IEEE 33 bus radial distribution test network, represented in Fig.1, contains 32 lines and 33 buses, a voltage of 12.66 kV, 3.715 MW and 2.3 MVar as the average load size.

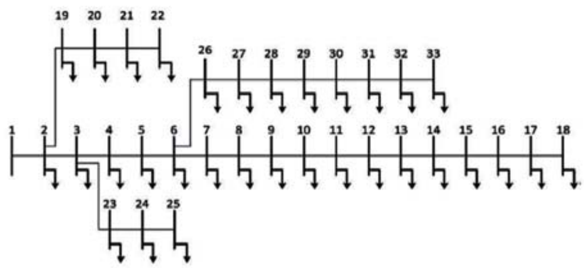

Fig.1. IEEE 33 bus test network

Data from the test network was used to execute the Newton Raphson program, then to run the NSGA-II in MATLAB. The resolution was made according to the steps presented in figure 2.

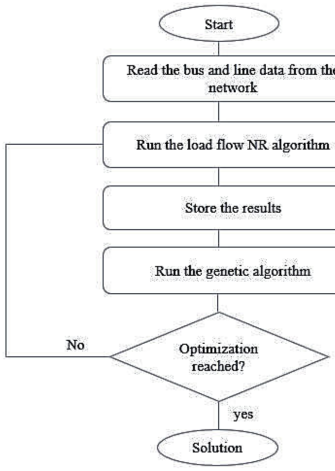

Fig.2. Organizational chart of the problem solution

Battery Energy Storage Systems locations

Battery Energy Storage Systems store energy from PV systems to supply loads when needed. These systems are generally used for different purposes, for example voltage control, frequency regulation, power flow optimization, etc.

A BESS is made up of several racks in parallel, each containing battery modules connected in series and a Battery Management System BMS. The Power Conversion System PCS, of which the inverter is the heart, is also part of the BESS, it converts the energy coming from the network into DC to charge the batteries, and converts the energy coming from the battery, during its discharge, into AC to support the network loads. The BESS also contains an Energy Management System EMS and a Thermal Management System for temperature control. Fig. 3 shows the elements of the battery system:

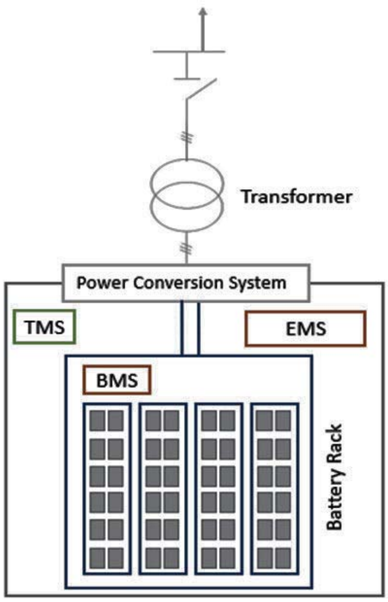

Fig.3. Elements of the Battery Energy Storage System

Battery Energy Storage Systems store energy during period A in order to supply the network during period B (with the main source if necessary). The maximum energy of the system Emax during peak hours has been determined as follows:

(2) $$Emax = P.t.(1+c)$$

where: P – load size, t – operating time of the battery system (from 18:00 to 23:00), c – coefficient of variance of the load during period B.

A value of 25% has been chosen (c = 25%), which means that the load, during the consumption peak, increases by 25% compared to the average load.

The capacity required to ensure the storage of this maximum energy is:

(3) $$BESS\ Capacity\ (kWh) = \frac{Emax}{D \times E}$$

where: D – depth of discharge (80%), E – battery efficiency (95%)

The total energy required during the peak period is: Emax = 23 218.75 kWh. Thus, four battery energy storage systems, each with a capacity of 318.239 kAh at 24 V, can store this energy. Each storage system contains 3183 Lithium-Ion batteries of 100 Ah / 24 V wired and distributed on 8 containers each of 1MWh containing a conversion system of 250 kW, over an area of 1272.582 m^2. The voltage will be converted by a transformer to 12.66 kV.

This dimensioning was carried out for a total load during the consumption peak which is equal to 1.25*the average load. Four battery energy storage systems manage to store energy and supply the total load during this period.

The list of costs is shown in the following table:

Table 1. Cost of a Battery Energy Storage System

Total cost of the installation area (€)	1146.5
Energy Capacity cost (€/kWh)	249.5
Power Conversion System cost (€/kW)	265
Operation & Maintenance (€/kWh-yr)	9.2
Construction & commissioning (€/kWh)	93
	Total: 3 217 341.759 €

As a first step, the test network was simulated under MATLAB and the power flow calculated for the average load and then for the peak load before integrating any BESS. The results found are as follows:

The active and reactive power losses are worth 202.4965 kW and 135.0133 kVar respectively for the average load and 329.8580 kW and 220.0804 kVar for the peak load. Voltage profiles for the two loads are represented in the following figure:

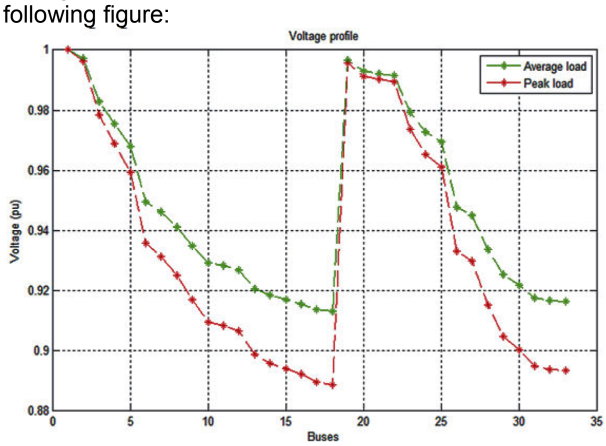

Fig.4. Voltage variation according to the number of buses

The resolution was made using the NSGAII for the objectives already mentioned (minimization of losses, voltage drops and cost). After simulation, the NSGA-II gave 13 optimal scenarios.

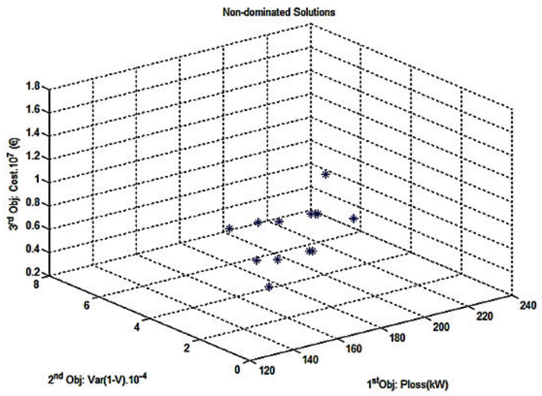

Fig.5. 3D Pareto front for BESS locations

On the pareto front (Fig. 5), the first axis represents the power losses, the second represents the voltage drops and the third displays the cost. The 50 populations were distributed among 13 best scenarios. All the scenarios represented on the pareto front are optimal, but in order to choose a single solution (the best optimum), it is necessary to classify them. In this article, they were classified by giving a weight for each objective function (30% for Ploss, 30% for cost and 34% for voltage drops). The characteristics of the best scenario are represented in the following table:

Table 2. Characteristics of the optimal solution

P (kW)	Q (kVar)	Var(1-V) $\times 10^{-5}$	Cost$\times 10^{7}$ (€)
153.8634	102.3884	2.2257	1.2869

The optimal scenario gave four optimal locations (see Fig. 6), which are sufficient for feeding the system during the peak consumption period.

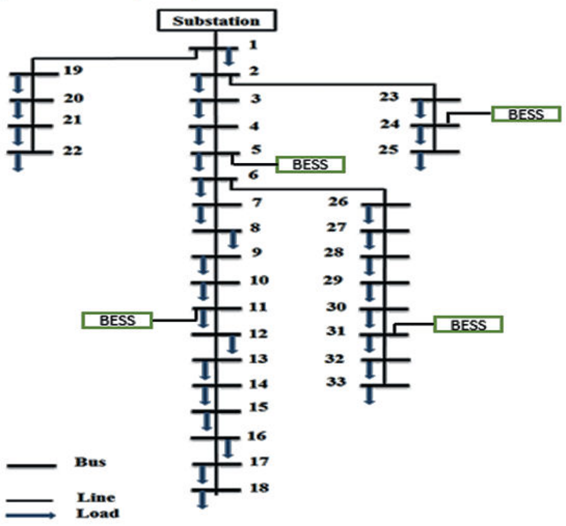

Fig.6. Optimal locations of Battery Energy Storage Systems

For a total cost of 12.869 M€, the insertion of BESSs in the IEEE 33 bus test network, to support it during the peak of consumption, minimized losses to a value of 153.8634 kW for active power losses (reduction of 53.35%) and 102.3884 kVar for reactive power losses (reduction of 53.47%). It had also improved the voltage profile indicated in Fig.7.

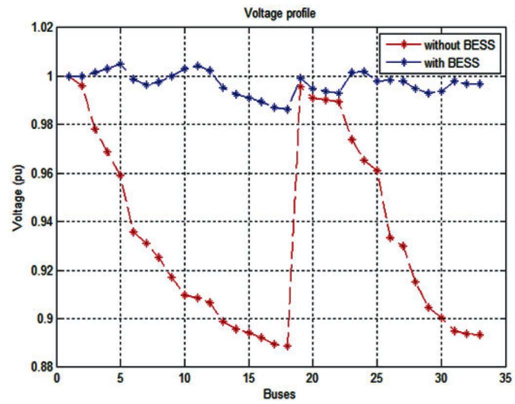

Fig.7. Voltage profile with and without integrated BESSs

Locations of photovoltaic plants

For the location of photovoltaic systems, two cases are possible, the first consists in adding the batteries as loads, in their optimal locations already found, before simulating the locations of PV plants, this means that the PV plant will support the total load and will charge the batteries at the same time. The second scenario is to find the PV locations without adding the batteries as loads and therefore, in this case, the PV system will meet the demand and the surplus of energy will be stored in the batteries.

On the basis of a technical study, 4000 photovoltaic modules of 250 Wp, in each power station, will be needed to provide 1 MW over an area of 1.23 ha. The photovoltaic field is made up of 160 chains in parallel, arranged in 25 rows, each containing 8 strings and each string contains 20 PV modules in series. The inverter connected to the installation has a power of 1MW containing two trackers, each capable of supporting 106 strings. The following table represents the cost of the solution:

Table 3. Total cost of the solution

Total cost of the installation area (€)	14041
Unit cost of a PV module (€)	245.63
Inverter cost (€)	138000
Network Connection Fees (€/MWh)	26
Maintenance & operation cost (€/kW-yr)	12
Design, Engineering & management cost (€)	4800
	Total: 1 439 673 €

A. Case 1

In this case, the four BESSs were added to the load buses, which increased the total load to 9.825 MW and 2.3 MVar (It was assumed that the BESSs do not inject reactive power into the network). As a result, the power losses changed as follows: Ploss= 1454 kW and Qloss=942.9380 kVar.

After updating the system (with BESSs integrated as loads), and running the NSGA-II, the algorithm has converged towards the optimal scenarios (according to the Pareto front). These optimal scenarios have been normalized and classified by weighting in order to obtain the best solution (see table 4).

Table 4. Characteristics of the optimal scenario for the first case

P (kW)	Q (kVar)	Var(1-V) $\times 10^{-4}$	Cost (€)
77.7992	53.5719	1.0501	14396730

From table 4, it is remarkable that the active power losses decreased by 94.64% and the reactive power losses by 94.31% after integrating the PV plants. The voltage profile was also improved as shown in Fig.9.

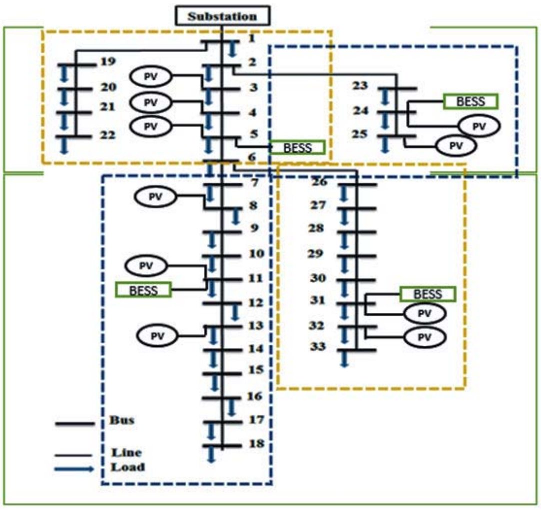

Fig.8. Optimal locations of photovoltaic systems and BESS-case 1

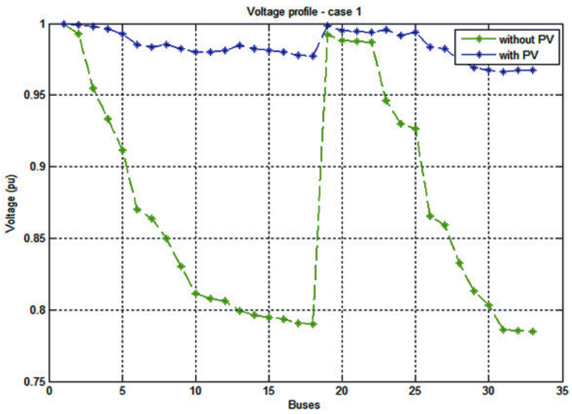

Fig.9. Voltage profile with and without integrated PVs-case 1

B. Case 2

In this part, the simulation was made without adding batteries to the load buses. As a result, the optimal scenarios were selected and classified by weighting, and the best optimal scenario converged towards 4 positions (2,11,24,30) as shown in Fig.10.

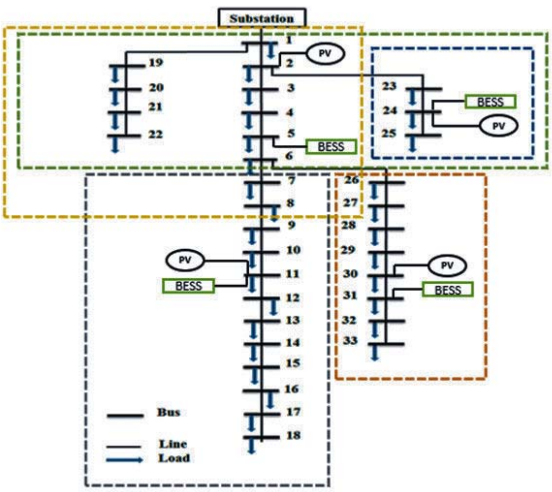

Fig.10. Optimal locations of photovoltaic systems and BESS-case 2

According to these positions, the total losses were reduced by 64.37% for active power losses and 63.28% for reactive power losses compared to the losses of the grid without PV.

Table 5. Features of the optimal scenario for the second case

P (kW)	Q (kVar)	Var(1-V) $\times 10^{-4}$	Cost$\times 10^{7}$ (€)
72.1451	49.5665	1.0103	5758692

At a minimum cost of 5.758 M€, the location of photovoltaic systems in their optimal positions has also improved the voltage profile by comparing it with the voltage profile of the network without PV.

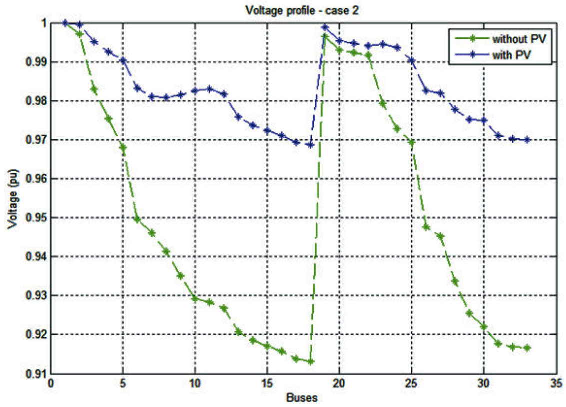

Fig.11. Voltage profile with and without integrated PVs-case 2

In both cases, the concept of decentralization was highlighted; the sources were distributed in the network which makes it decentralized and can be divided into several subnets according to the load. These subnets can be modified with the reconfiguration of the network.

Photovoltaic power plants and BESSs will support part of the electricity grid (in addition to the main source if necessary); they are at the same time close to the consumer, can guarantee the supply of the sub-network and make it possible to limit dependence on the main source station.

Discussion

Based on the results of the first simulation, which consists in finding the optimal placements of battery energy storage systems, their locations have been determined for operation during a period around the peak of consumption. We noticed that to support the energy required during the peak of consumption, the total capacity of the batteries was very large and therefore quite expensive, and just for a short time. For a longer duration, the capacity will be greater and the cost will be multiplied. A thorough financial study is therefore essential.

To avoid the constraint of high cost, we proposed, in this article, to use BESSs only to guarantee security of supply during the peak consumption in order to stabilize the network, to compensate the voltage produced by the PVs and improve the quality of the electrical energy.

For photovoltaic systems, two cases were studied; the first case is to add the batteries to the load buses and the second is to leave the network total load as it is. For the first case, the locations were found after updating the system and adding the batteries as loads so that they could be charged at the same time as the photovoltaic systems support the network. As a result, 10 photofoltaic systems were able to supply the loads (BESS included), while for the second case, 4 photovoltaic systems were sufficient to meet the demand.

For both cases, and taking into account the optimal scenarios, it was concluded that the insertion of photovoltaic panels and BESSs in the network improves the voltage profile and minimizes the total power losses of the system. In addition, the locations found made it possible to converge towards a decentralized network structure promoting the integration of green energies and limiting the dependence on the main source station.

The choice between the two cases can be determined according to the cost, the dynamic state of the load and the dependence on the main source station. In other words, the first case can be used if we want to support the load during periods A and B only by PV and BES systems (during days with sufficient radiation), but the cost remains high (14.396 M€). For the other case, the batteries will be charged only if there is a surplus of PV energy (when there is enough radiation) and therefore the operation of the batteries during period B strongly depends on the load (strong or weak) during period A. More so, the cost for this solution is lower (5.758 M€).

Conclusion

The complexity of the electrical distribution network (voltage drops, faults, power feedback, losses, etc.) and its various challenges make its management and control very difficult. This is the reason for the enormous efforts provided by the network managers to make it more reliable, secure and manageable, especially with the integration of renewable sources. And this goes through the first step which is the optimal location of these sources in the network.

Among the four challenges of the electricity distribution network, its digitization and decentralization remain the most important. Leaving digitization for our next work, decentralization, and implicitly decarbonization (since the reduction in power losses implies the reduction of CO2), forms the subject of this article. A test was carried out, using the non-dominated sorting genetic algorithm NSGA-II, on an IEEE 33 bus network to find the locations of photovoltaic power plants and battery energy storage systems, with the aim of minimizing losses, investment cost and improving the voltage while maintaining it within certain limits, and also allowing decentralization of the network while limiting the dependence on the main source station.

The results showed that there are two possible scenarios; the first consists in opting for sub-networks supplied by a large number of photovoltaic installations which, in addition to supplying the network, will charge the batteries regardless of the variance of the load. In this case, intervention by the main source will be more limited but at a high cost. The second case involves using a limited number of photovoltaic power plants for energy supply and the surplus will be stored to meet demand during the peak period. If there is not enough surplus energy due to the high demand or insufficient solar radiation, the main source will intervene. Consequently, the network will depend more on the main source station. In this case, the cost is lower.

Both scenarios are possible, each with its advantages and disadvantages, the most important is to promote the inclusion of renewable energies in the distribution networks.

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