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RESEARCH ARTICLE

Reduction of the Low Voltage Substation Constraints by Inserting Photovoltaic Systems in Underserved Areas

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Abstract: ***Background:*** The improvement of the voltage in power lines and the respect of the low voltage distribution transformer substations constraints (Transformer utilization rate and Voltage drop) are possible by several means: reinforcement of conductor sections, installation of new MV / LV substations (Medium Voltage (MV), Low Voltage (LV)), *etc*.

Methods: Connection of mini-photovoltaic systems (PV) to the network, or to consumers in underserved areas, is a well-adopted solution to solve the problem of voltage drop and lighten the substation transformer, and at the same time provide clean electrical energy. PV systems can therefore contribute to this solution since they produce energy at the deficit site.

***Results*:** This paper presents the improvement of transformer substation constraints, supplying an end of low voltage electrical line, by inserting photovoltaic systems at underserved subscribers.

Conclusion: This study is applied to a typical load pattern, specified to the consumers region.

Keywords: Transformer utilization rate, Voltage drop, Compensation, Photovoltaic (PV) Systems, Grid Connected PV Systems, Solar Irradiation.

1. INTRODUCTION

The Energy networks role is the transmission of electricity from production centers to places of consumption, often over long distances. However, in many electrical networks, increase in electricity demand is not accompanied by an increase in transmission and generation capacity. The extension of networks to rural areas or the construction of new networks at isolated sites meets significant economic constraints.

The development of new sources of Decentralized Generation (DG) is now a reality in several countries around the world with the technological evolutions of the production means of small power. The DG energy is intended to be produced locally (closer to the consumption centers and therefore intended to be transported over short or medium distances), generally inserted at the distribution network.

One of the DG technologies is the photovoltaic energy PV. The main applications of PV installations are:

- Installations (with storage systems) for isolated users of the network.
- Installations for users connected to the LV network.
- Mini electric photovoltaic central usually connected to the grid MV.

In the literature, studies on the integration of PV systems are carried out to achieve the different objectives. In reference [1, 2] the authors present a way to compensate voltage drops occurring at the end of the feeder, solution based on grid-connected rooftop PV systems taking account technical and economic constraints to determine the best system configurations which significantly reduced the drops. In reference [3], in order to solve the problems of losses in the distribution network of electrical energy, the authors discuss the reconfiguration of Low Voltage (LV) distribution network, by building new High Voltage (HV) lines and also identifying the node of the center of gravity of the loads where the transformer must be connected and then, they suggested the connection of photovoltaic mini-power stations to the network studied to precise nodes. In reference [4], the impact of three different types of distributed generations (diesel generator, wind turbine and photovoltaic (PV)) on distribution networks' voltage profile and power losses was studied. In reference [5, 6], the authors describe the impact of the connection of a mini PV station to the grid (LV) on improving the Voltage Drop. In reference [7], a systematic algorithm is presented to determine the optimal allocation and sizing of Photovoltaic Grid-connected Systems (PVGCSs) in feeders that provide the best overall impact on to the feeder since the installation of PV units at non-optimal places may create a deterioration of feeder technical parameters as well as an

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economical increase in cost; therefore, having an effect opposite to the desired effect. In literature [8], a way to analyze voltage unbalance sensitivity has been described for different maximum sizes of PV systems to get connected to the network.

This paper presents an analysis of the problem of low voltage distribution substation constraints related to peak load in the summer period caused by excessive electricity consumption due to the massive use of air conditioning; the case of the most regions in Algeria which are marked by high temperature in the summer period.

In fact, low voltage distribution stations are managed by constraints concerning principally the transformer utilization rate and the voltage drop admitted for Low Voltage (LV). Exceeding these constraints may constrain the normal operation of the distribution substation (damage of the transformer) and cause problems for the client (power failure and malfunctioning appliances). The improvement of these constraints can be brought by the following means; such as by the reinforcement of the sections of the conductors, and the installation of new transformer station MV/ LV. Photovoltaic Systems (PV) can contribute to resolve this problem by generating energy at the point of the deficit and at the same time, providing clean electrical energy.

The studied case in this work consists of a line end of low-voltage electrical network supplying a set of subscribers dispersed in small groups on dipoles located at respective distances from the transformer substation. The analysis involves calculating and checking by simulation according to the daily load imposed by the consumption of the subscribers if the constraints of the distribution station are respected compared to the allowed limits and thus detecting the dipoles underserved for the purpose of inserting photovoltaic systems at the customers.

The proposed photovoltaic system is a self-consumption system without injection to the grid (currently in Algeria the injection to the network is not possible); self-consumption directly connects photovoltaic system to the electrical equipment of the building. The electricity consumed by the equipment is therefore derived from the photovoltaic system, rather than purchased from the electricity grid: this allows savings on the electricity bill. However, the building remains connected to the electricity grid. If photovoltaic production is not sufficient to fully cover the equipment consumption, electricity is purchased. If there is an excess in production, this one is sold or injected for free in the public network, or it can be stocked and recovered in case of underproduction or at night. If not, a power limiting device is installed to prevent injection into the network, in compliance with the existing legislation [9, 10].

The rest of the manuscript is organized as follows: Section 2 presents the LV transformer substation and the equations governing the transformer utilization rate and voltage drop. Section 3 presents the case studied with the characteristics of the substation with the annual and daily consumption of subscribers in the concerned region. Section 4 illustrates the effect that photovoltaic systems can have on the power consumed. Section 5 presents the sizing of the PV generator to be installed. Simulation results and discussion are given in section 6. Finally, conclusion of the work is given.

2. MATERIALS AND METHODS

2.1. Distribution Substations

The distribution substation is the interface between the medium voltage (MV) and low voltage (LV) networks, by lowering the MV voltage level (usually 30,000 V) to 230 V for single-phase and 400 V for three-phase. The essential characteristic of the distribution station is its nominal power transformer (between a few tens of kilovolt-amperes and several mega volt-amperes), depending on the loads to be served.

2.2. Distribution Substation LV Constraints

The constraints related to the distribution substation LV require respecting the following assumptions [11]:

- Transformer utilization rate:

  50% < Ku <80%

- Permissible unbalance rate at transformer LV terminal: 15%.
- Voltage drop allowed for LV networks: 10%.

If the constraints of the distribution station (load, voltage) exceed the thresholds mentioned above, they can constrain the problems for the distribution companies (transformer damage) and for the customer (power failure and malfunction of household appliances).

2.2.1. Transformer Utilization Rate

The transformer utilization rate is the ratio between the requested power P_c (consumption in kW) and the nominal power of transformer P_n (in kW) [6, 11]:

$$K_u = \frac{P_c}{P_n} * 100 \quad (1)$$

If:

- 50% < k_u < 80% Transformer in normal condition.
- k_u < 50% Underutilized transformer.
- k_u > 80% Transformer overloaded.

The Pc power is the cumulative power consumed by the low voltage customers connected to the substation, it is defined as follows:

$$P_c\,(kW) = \sum_{j=1}^{N} \mathrm{Pj} \quad (2)$$

Where:

- P_j is the power consumed by the customer j.
- N is the total number of consumers

2.2.2. Voltage Drops in the Low Voltage Network

The voltage drops that appear on the line ends are due to RI^2 losses; where I is the network current and R is the line resistance.

These result in the increase in the consumption of LV customers (transited powers). To know the voltage drop of the end customer which is on the dipole n, it suffices to add up the voltage drops that appear from dipole 1 to dipole n.

The cumulative relative voltage drop (%) of the dipole (n) is equal to [2, 6]:

$$\left(\frac{\Delta U}{U}\right)_n = 1 + 10^5 * \left[\frac{R+X*\tan\varphi}{U^2}\right] * \sum_{i=1}^{n} P_i * L_i \quad (3)$$

Where:

- n is the number of dipoles
- P_i(kW) is the cumulative power consumed by m customers connected to the dipole i. It is given by: $P_i = \sum_{j=1}^{m} Pj$
- φ is the phase angle between the voltage and current.
- R(Ω/km) is the linear resistance of a conductor;
- X(Ω/km) is the linear reactance of a conductor;
- L_i(km) is the length of the dipole i.

The voltage drop of the transformer, equal to 1%, is taken into account in equation (3) [2].

3. STUDIED CASE

In this work, power line low voltage was built based on the models of the ends of lines existing in the vicinity of the region of Batna in Algerian eastern. As shown in Fig. (**1**), the end of the line feeds 105 habitations distributed over six dipoles of total length 2.93 km and they are powered by a distribution substation with a nominal power of 160 kVA. The parameters of the line are: resistance equals to 0.69 (Ω/km) and reactance to 0.35 (Ω/km).

The end line characteristics are given in Table **1**.

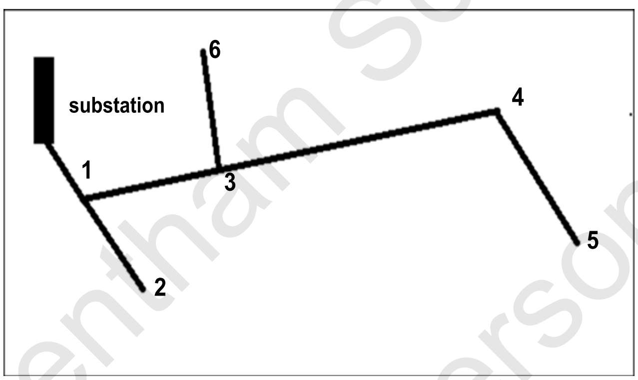

Fig. (1). Architecture of the studied electrical line end.

Table 1. Characteristics of the dipoles connected at the studied electrical line end.

Number of Dipoles	Number of Connected Customers	Length of the Dipole (km)
1	20	0.05
2	25	0.08
3	13	0.1
4	10	1.2
5	15	0.3
6	12	0.2

3.1. Low Voltage Customer Consumption Profile

The evolution of annual consumption of an LV customer depends on the climatological conditions of the region. Fig. (**2**) shows the evolution of annual consumption for the region of Batna in Algerian east [12]. The histogram shows the increased consumption during the summer period. This is due to the use of electric air conditioning.

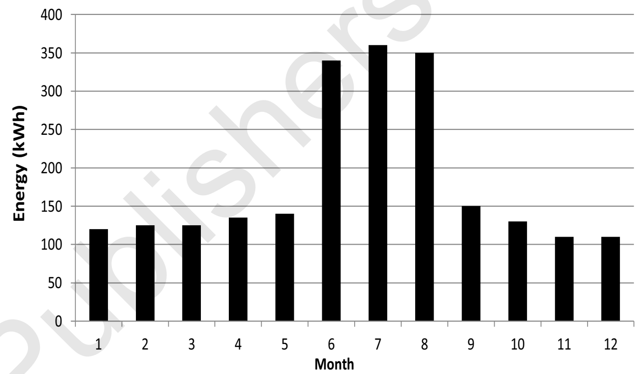

Fig. (2). Annual consumption of a LV subscriber.

Fig. (**3**) presents the hourly load curve of a low-voltage customer, showing variation in the load profile, which is marked by a peak of 1.4 kW between 11:00 and 16:00 [12].

4. EFFECTS OF PV SYSTEMS ON THE POWER CONSUMED

The insertion of PV systems into the electricity network or to the users can compensate the consumption overall or partially, considering the matching of the photovoltaic production with the consumption in peak hours, which suggests that a part of power consumed will be produced locally which reduces the power output of the distribution station during peak periods and alleviates the constraints (overload) of the distribution substation. The power withdrawn from the network by the consumer becomes:

$$P_{J'} = P_j - P_{pv} \quad (4)$$

With: $P_{PV,j}$ is the power produced by the PV system (kW) at the customer j.

The transformer output power with the presence of PV systems becomes:

$$P_c(kW) = \sum_{j=1}^{n} P'j \quad (5)$$

Equations (1) and (3) show that the distribution item constraints depend on the value Pj, so the reduction of this value allows reducing these post constraints

4.1. Coverage Rate of Photovoltaic Energy

The coverage rate of photovoltaic energy corresponds to the percentage of the energy consumed by photovoltaic origin compared to the total energy consumed (energy withdrawn from the electrical network plus that produced by photovoltaic systems). Dependence of the customer on the electrical network decreases with increasing PV coverage rate [2, 5].

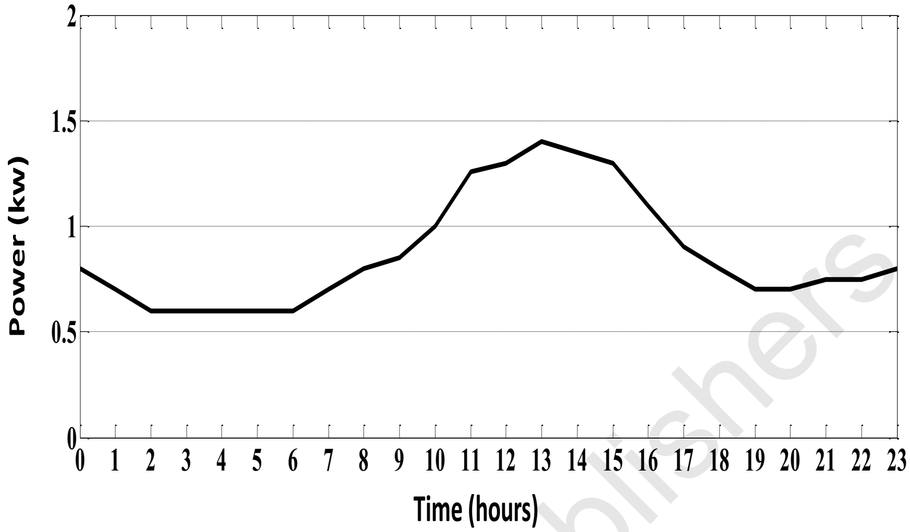

Fig. (3). Hourly load of a low-voltage subscriber

$$T(\%) = \frac{P_{pv.j}(kWh)}{P_j(kWh)} \times 100 \quad (6)$$

With:

$P_{pv.j}$ and P_j are the photovoltaic power and the total power consumed by the client j, respectively.

5. SIZING OF THE PHOTOVOLTAIC GENERATOR

The self-consumption PV installation is simple, it consists of:

- the PV generator built in the building
- the connection box with disconnector and protection
- The inverter transforming the direct current into an alternating current
- The differential circuit breaker and the energy meter to follow the production

The peak power (P_p) of photovoltaic generator is given by [9]:

$$P_p = \frac{E_{elec}}{N_{E_i} \times K} \quad (7)$$

with:

- E_{elec} is the daily electrical energy potentially produced by the photovoltaic system, expressed in kWh/day,
- N_{E_i} is the equivalent number of hours corresponding to the average daily solar irradiation (Ei).
- K is the losses factor due to different losses in the system. It is taken equal to 0.75.

To calculate the peak power Pp, it is appropriate to be placed in the worst case. It is therefore, necessary to take E_{elec} equal to the electrical energy consumed in the most important day of the year), and E_i equals to the lowest daily solar energy of the year.

This study considered the summer period (June, July, and August) where the consumption of customers increases because of the massive use of air conditioning. This is not the case for other months of the year during which the temperature is much lower.

According to Fig. (**2**), the value of E_{elec} considering summer period is:

$$E_{elec} = \frac{360}{31} = 11.61 \text{ kWh/day}$$

5.1. Determination of the Average Daily Solar Radiation

The decision to make a photovoltaic installation in a specific place, its design, installation and monitoring of its operation require knowledge of the incidental solar radiation on the ground. This can be given by solar radiation meters such as the Pyranometers. Many other methods are used to obtain the estimation of the illumination as: the images acquired by meteorological satellites in every point and at any moment. There is also the high-resolution WSIs (whole sky imagers), which can provide more detailed local information of cloud formations. These devices capture the entire sky from the ground at regular intervals with a hemispheric lens. The resulting images are of higher resolution than that obtained from satellites [13]. Solar forecasting can also be estimated by a variety of probabilistic models using real-world data such as Beta, Log-Normal and Normal probability distributions [14].

In this work, the solar radiation data at the considered site (Batna/Algeria) were obtained using the solar radiation calculation interface developed within the research center CDER (Renewable Energy Development Center) in Algeria [15]. The purpose of this application is to simulate the different flows of solar radiation. To do this, two theoretical approaches (Perrin de Brichambaut and Liu & Jordan) have been adopted and chosen, valid for a clear sky.

The average daily solar radiation for each month of the year for the site of Batna is given in Table **2**.

The worst month for solar radiation for the summer periods is the month of August; so we obtain:

E_i= 8.01 kWh/m^2/day, and N_{E_i}=8,01h.

Table 2. Average daily solar radiation for each month of the year for the site of Batna at horizontal area.

Month	Solar Radiation (kWh/m^2)
Jan.	3.82
Feb.	5.1
Mar.	6.57
Apr.	7.94
May	8.76
Jun.	9.02
Jul.	8.73
Aug.	8.01
Sep.	8.83
Oct.	5.41
Nov.	4.08
Dec.	3.46

5.2. Peak Power of Photovoltaic Generator

According to the above data, we obtained the following peak power P_p:

$$P_p = \frac{E_{elec}}{N_{E_i} \times K} = \frac{11.61 \times 1}{8.01 \times 0.75} = 1.93\ kW_p$$

The photovoltaic generator that can satisfy the demand of a subscriber connected to the studied end of the line during peak hours will have a peak power P_p equal to 2kWp.

6. SIMULATION

The simulation is performed under Matlab environment and using Homer software (Hybrid Optimization Model for Electric Renewables) [16], by inserting photovoltaic systems of 1kWp, 1.5kWp and 2kWp for each customer.

Input flows wer characterized by an input time data profile fixing the simulation step. They give rise to powers and it is considered that they are constant on the hour.

Simulation step = Δt = 1 hour.

- The consumption of the user represented by an instantaneous power P(t), considered constant between t and t + Δt.
- The solar irradiation represented by an instantaneous value I(t), considered constant between t and t +Δ t.

7. RESULTS AND DISCUSSION

The establishment of the constraints curves of the substation (overload and voltage drop) showed that constraints occur within the hours of high consumption (peak). As shown in Fig. (**4**), the substation utilization rate reaches 91.87% and the voltage drop exceeds 14% for subscribers located in the two dipoles at the end of line (dipoles 4 and 5) as in Fig. (**5**). The dipoles 1, 2, 3 and 6 do not show non-permissible voltage drops. Then the photovoltaic compensation will be applied on the two dipoles 4 and 5.

Fig. (**6**) shows the matching of photovoltaic electricity production with the daily peak hours consumption confirming the effect that PV systems can have on the power withdrawn from the network.

Table 3. PV power coverage rate.

PV power (kWp)	0	1	1.5	2
PV coverage rate %	0	28.89	49.73	63.85

Table **3** shows that PV systems can cover a significant portion of LV subscribers' electricity consumption by up to 63%.

After inserting photovoltaic systems at the customers of dipoles 4 and 5, the results are:

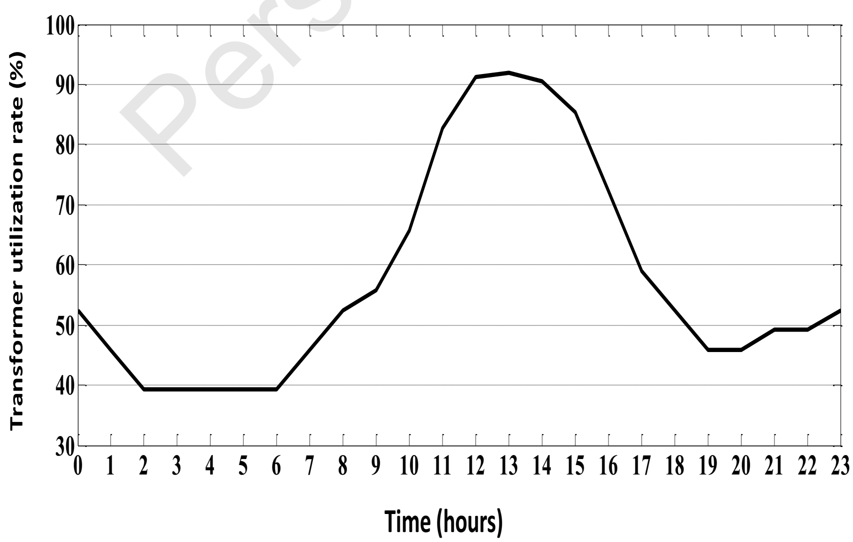

Fig. (4). Evolution of the daily utilization rate of the substation (%) before PV compensation.

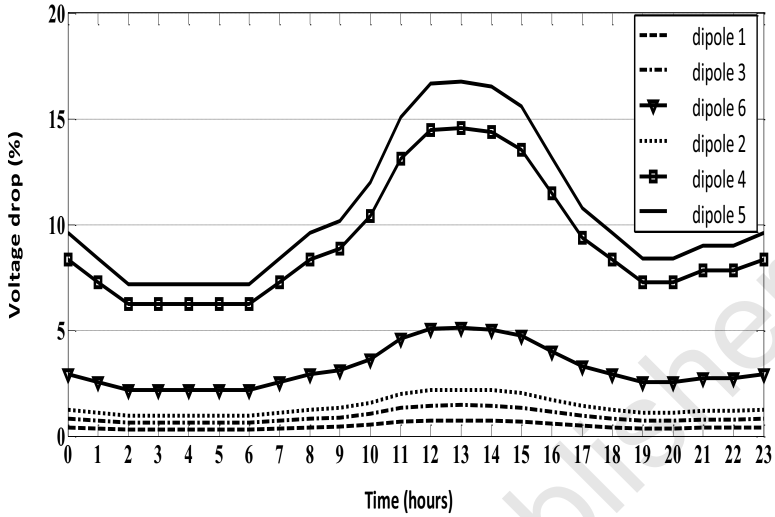

Fig. (5). Evolution of the voltage drop for the LV customers for six dipoles (%) before PV compensation.

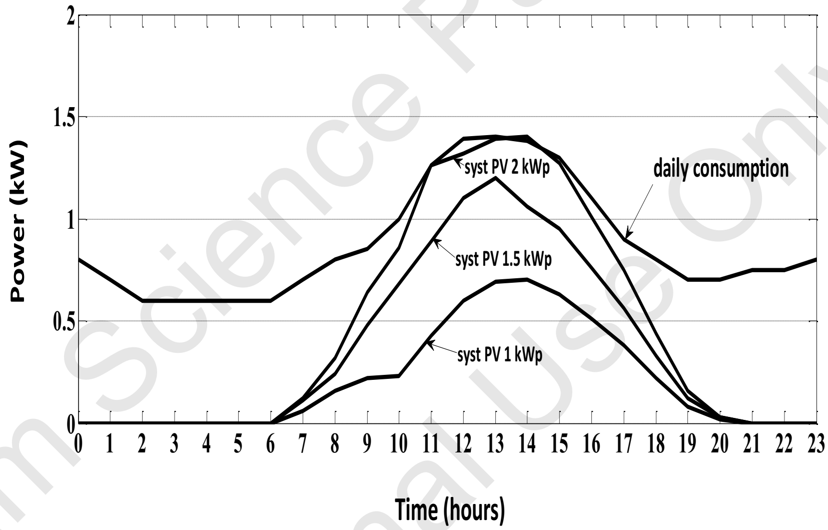

Fig. (6). Matching of PV production with peak hour consumption.

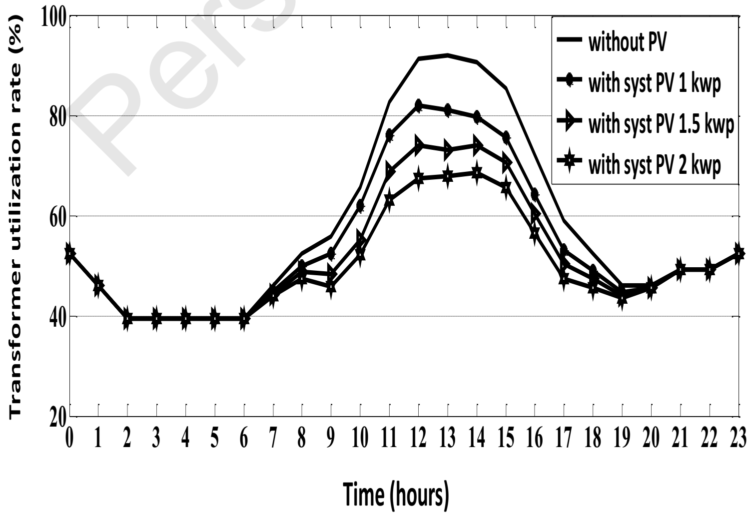

Fig. (7). Transformer utilization rate after PV compensation.

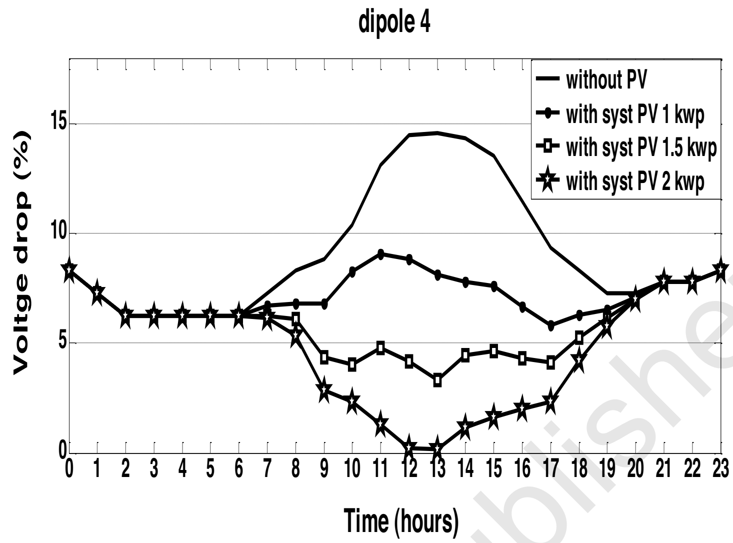

Fig. (8). Voltage drop in section 4 after compensation.

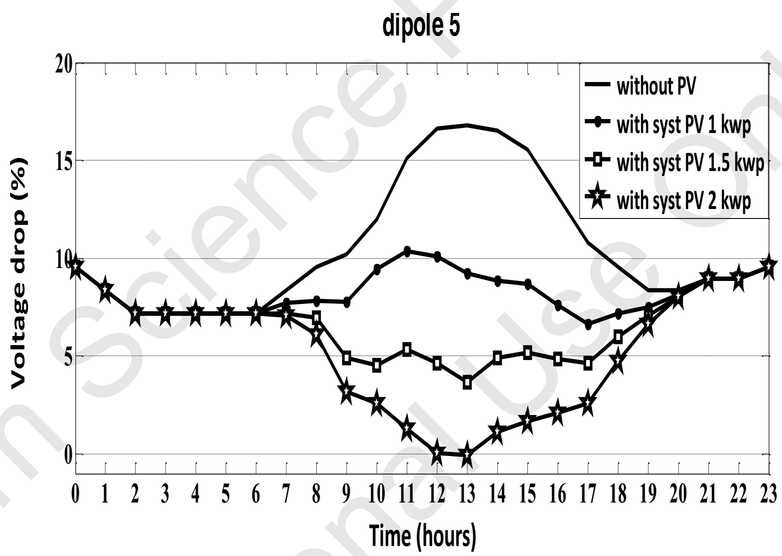

Fig. (9). Voltage drop in section 5 after PV compensation.

Figure (**7**) shows that the station utilization rate decreased from 91.87 to 70%, and voltage drops were improved and almost eliminated for peak hours 13h and 14h for end-of-line sections 4 and 5 in the case of insertion of systems PV 2kWp as shown in Figs. (**8** and **9**).

Thus, the installation of a PV system makes it possible to act even on the power withdrawn from the network in the evening hours and this happens by the insertion of a storage system (batteries) which makes it possible to increase the photovoltaic coverage rate.

Taking into account that the PV systems in self-consumption without injection to the networks do not pose any constraint on the Low Voltage network, this solution seems very interesting for the network manager, but from the point of view of the Low Voltage customers in Algeria, the self-consumption is an approach that seems complex because they are accustomed to be served energetically by the state in a continuous, inexpensive and cheaper way. The idea of investing in the long term to reduce its energy bill is not worthwhile unless the state switches to subsidize self-consumption instead of consumption.

CONCLUSION

The study done in this work shows that rooftop photovoltaic systems can provide a very efficient solution to address the constraints of transformer stations and thus reduce the number of transformers damaged by overload and avoid or postpone investments for strengthening the network.

CONSENT FOR PUBLICATION

Not applicable.

CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

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Declared none.

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