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## Article

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# Effect of augmented distributed generation in distribution networks

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## Abstract

This paper aims to study the effect of augmented Distributed Generation (DG) penetration in the basic indices of the distribution network (voltage, angle, power flow, thermal fatigue of cables). For this purpose, a realistic expansion of an existing distribution grid is considered, after looking up theoretically the basic principles of distribution grids and DGs. The case study grid is analyzed as to its basic indices depending on the level of penetration of distributed generation so as to find the necessary but also the optimal penetration. Subsequently, for every different penetration level, the key indices of the grid are discussed and it is estimated whether this specific level is technically sufficient. The optimum penetration level as well as Distributed Energy Resources (DER) hosting capacity is also discussed.

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**Keywords:** Distributed generation; Distribution grids; Voltage; Power flow; Hosting capacity

## 1. Introduction

Electricity grids aim to transfer electrical power from the generation units (power stations) to the final consumer, in other words link generation with consumption [1].

Electricity grids are separated into various categories based on their operating voltage level, each one of which has a particular mission, structure, operation style and protection. In Greece, the 20 kV (Medium Voltage – MV) and the 0.4 kV (Low voltage – LV) voltage levels constitute the distribution network (DN) [2]. The latter begins after a high (150 kV) to medium voltage substation to feed the medium voltage lines that transfer electricity to the local consumption centers. They usually have either radial or looped system structure and can be found either in aerial, underground or underwater forms [1]. The Distribution System Operator – DSO or Distribution Network Operator – DNO is responsible for the proper operation of the DN.

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In the last two decades, the augmented penetration and integration of different technologies of DG units in DN has created many challenges for all stakeholders (Operators, Producers, Consumers, Prosumers etc.). Some of the most known DG units are Photovoltaics (PV), Wind Turbines (WT), Fuel Cells (FC), Microturbines (MT), Small Cogeneration of Heat and Power (CHP), small Hydroelectric plants (mHydro), geothermal power plants etc. [3].

The presence of DG units in DN offers many technical, operational, economical and environmental benefits. The identification and quantification of the benefits of DG has received a great deal of attention from regulators, system operators, public utilities, consumers and society in general. With significant penetration of DGs the power flows may become reversed and the distribution network is no longer a passive circuit supplying loads but an active system with power flows and voltages determined by the generation as well as the loads. The change in real and reactive power flows caused by DGs has important technical and economic implications for the power system [3]. Given that a DG unit is located near load, this will result in reduction of losses and release of network capacity, which can be used to defer future network reinforcement needed to accommodate load growth [4]. Strategically located DG operating during peak load periods can defer or away with the need to undertake expensive network upgrades [5]. Many studies on the interconnection of DG with distribution networks have been carried out, ranging from control and protection to voltage stability and power quality ([6,7] among many others). Some of the benefits are not only technical, such as the improvement of end-user power quality and reliability. In fact, there are a number of economic benefits of DG, the most important of which being the end-user electricity bill reduction, especially for gas-fired technologies (peaking internal combustion engines or microturbines). To fully comprehend the advantages that the penetration of DG units can offer in DN one can refer to [8–15].

In this paper, the effect of increased DG penetration in the basic measures (buses' voltages, power flows, total losses, thermal strain of lines) of a real DN is studied. The considered DN, without the presence of DG, appears to have problems regarding the aforementioned measures due to increased load demand. These problems, as will be proven later on, cannot be addressed with conventional ways which in this case are OLTC (on load tap changer) and in reactive power compensation using capacitor banks. However, the presence of DG units enabling the regulation of the produced reactive power and in combination with the traditional voltage regulation techniques can help in dealing with these issues.

After further analyzing the effect on the basic measures of a DN, the power flow method is presented through its equations. Then, the characteristics of the considered DN, the assumptions that include issues regarding DG units and the different operation scenarios are presented. Finally, in the aforementioned context, the results and the respective conclusions are analyzed. All simulations were carried out using Matlab software.

## 2. Effects on the key elements of the distribution network

Lately, ambitious goals regarding DG penetration in DN have been put into place, especially when it comes to renewable energy sources (RES) mainly through financial motives (Feed-in Tariffs, tax returns etc.). However, this high penetration can affect the operation of the DN in various ways. The main issues, which are presented in [16,17] are:

- The violation of thermal limits in some grid elements
- Voltage regulation. The high penetration of DG units combined with low electricity consumption can lead to overvoltage problems in the remote buses. Although voltage control can be achieved through OLTC and step voltage regulators, things get rather difficult when lines with different characteristics are fed through the same transformer.
- The short circuit level which can cause the excess of the DN tolerance.
- The power quality due to the presence of harmonics in the DN from the power electronics of DG units
- The reverse power flow towards the upstream system under low demand and high DG output. This can affect the operation of certain voltage control modules (and some OLTC) as well as certain safety features.

In light of the above, we have to define a specific measure to set the maximum possible penetration DG without causing technical issues. The latter is defined as DER Hosting Capacity, [18]. There is no common approach for the maximum DER Hosting Capacity. Each operator has its own evaluation criteria to determine the optimal DG power and placement [19].

Although there is no common evaluation approach for determining DER Hosting Capacity, these methods can be classified into 4 main categories [16].

- Category A: Criteria based on the capacity of existing grid infrastructure.
- Category B: Criteria based on the voltage fluctuation tolerance (used as the basic criteria in this paper)
- Category C: Criteria based on the load to production ratio
- Category D: Criteria related to the short-circuit level

The reinforcement of grid's lines (e.g. replacement of cables) as well as the installation of an energy storage system (e.g. batteries) can be considered as alternatives to increase DG penetration while avoiding grid overvoltage phenomena [20].

### 3. Power flow — mathematical formulation

So as to study the effect of increased DG units penetration in a DN, we must solve the power flow (PF) problem.

The PF is the problem of defining the power and the voltage in every bus of a grid as well as the active and reactive power flows through the grid's lines for given conditions. The PF study is the foundation of the analysis and designing of electrical energy systems. It is necessary for designing, operation, unit dispatching as well as the power interchange between the electricity production units. In this paper, the PF refers to steady state and not transitional operation phases. The PF equations can be mathematically formulated with various ways. These are non linear and can be solved using iterative methods. The most common ones are Gauss–Seidel and Newton–Raphson [1]. The non-linear ac form of LF equations are [21,22]:

$$P_i = U_i \sum_{k=1}^n U_k (G_{ik} \cos \theta_{ik} + B_{ik} \sin \theta_{ik}) \quad (1)$$

$$Q_i = U_i \sum_{k=1}^n U_k (G_{ik} \sin \theta_{ik} - B_{ik} \cos \theta_{ik}) \quad (2)$$

From the solution, the power flows in line ik become:

$$P_{ik} = -t_{ik} G_{ik} U_i^2 + U_i U_k (G_{ik} \cos \theta_{ik} + B_{ik} \sin \theta_{ik}) \quad (3)$$

$$Q_{ik} = t_{ik} B_{ik} U_i^2 - B_{ik} U_i^2 + U_i U_k (G_{ik} \sin \theta_{ik} - B_{ik} \cos \theta_{ik}) \quad (4)$$

$$Q_{i(sh)} = U_i^2 B_{i(sh)} \quad (5)$$

where  $P_i$  and  $Q_i$  are the net active and reactive power injection at bus  $i$ ;  $P_{ik}$  and  $Q_{ik}$  are the active and reactive power flows in line  $ik$  at the bus  $i$  side;  $U_i$  and  $U_k$  are the voltage magnitude at bus  $i$  and  $k$ ;  $\theta_{ik}$  is the angle difference between the voltages at bus  $i$  and  $k$ ;  $G_{ik}$  and  $B_{ik}$  are the real and imaginary part of the corresponding term of the admittance Matrix). Also,  $Q_{i(sh)}$ , and  $B_{i(sh)}$  is the reactive compensation power and the transverse conductance capacity of the bus  $i$ , respectively. Finally,  $t_{ik}$  is the transformer tap ratio.

The total injected complex power at bus  $i$ , denoted by  $S_i$ , is given by:  $S_i = P_i + jQ_i = U_i I_i^*$ . The summation of powers over all buses gives the total system losses:

$$P_L + jQ_L = \sum_{i=1}^n U_i \cdot I_i^* = U_{bus}^T \cdot I_{bus}^T \quad (6)$$

where  $P_L$  and  $Q_L$  are the real and reactive power losses of the system,  $U_{bus}$  is the column vector of the nodal bus voltages,  $I_{bus}$  is the column vector of the injected bus currents and  $n$  is the number of buses.

### 4. The considered distribution grid and basic assumptions

The considered distribution grid is presented at Fig. 1, [23]. It is a typical distribution grid of the Greek province where all the buses' voltage can be controlled through conventional means (capacitors and OLTC). On the said network the increasing penetration of dispersed generation (DG) units can as it will be stated later on, further contribute to the dealing of matters of voltage when conventional means are unable to. Due to the area's planning, it was assumed that the dispersed generation (DG) units can be placed only on certain areas (buses) of the network.

The loads of the considered network as well as the characteristics of its lines are presented on Table 1, while the basic assumptions and certain additional data used in the study are presented below:

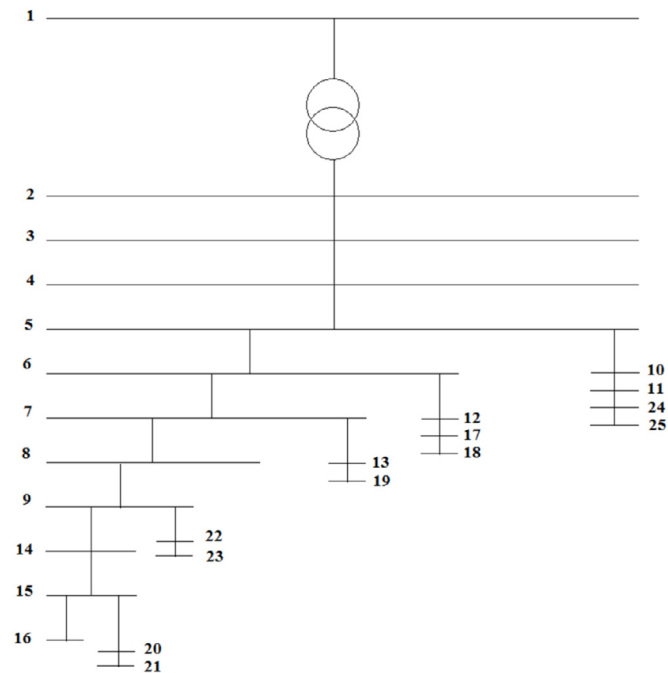


Fig. 1. The examined distribution network.

Table 1. Load demand and characteristics of the grid's lines.

Bus	Load (kW)	Line number	Bus (Start)	Bus (Final)	Distance (km)	R (p.u.)	X (p.u.)
1	0	1	1	2	0	0	0,3
2	0	2	2	3	5	0,2687	0,4175
3	1080	3	3	4	6	0,3225	0,5010
4	720	4	4	5	7	0,3762	0,5845
5	180	5	5	6	4	0,2150	0,3340
6	792	6	6	7	5	0,2687	0,4175
7	180	7	7	8	2	0,1075	0,1670
8	720	8	8	9	3	0,1612	0,2505
9	432	9	5	10	2	0,6340	0,2110
10	576	10	10	11	3	0,9510	0,3165
11	432	11	6	12	3	0,9510	0,3165
12	288	12	7	13	4	1,2680	0,4220
13	204	13	9	14	4	0,2150	0,3340
14	272	14	14	15	3	0,1612	0,2505
15	528	15	15	16	2	0,1075	0,1670
16	444	16	12	17	1	0,0537	0,0835
17	180	17	17	18	2	0,1075	0,1670
18	268	18	13	19	3	0,1612	0,2505
19	336	19	15	20	3	0,1612	0,2505
20	352	20	20	21	1	0,0537	0,0835
21	448	21	9	22	2	0,1075	0,1670
22	200	22	22	23	2	0,1075	0,1670
23	252	23	11	24	2	0,1075	0,1670
24	364	24	24	25	2	0,1075	0,1670
25	224	Base power = $S_b = 100$ MVA for per unit (p.u.) calculations					

(a) The transformer is 150/20 kV, it has 50 MVA nominal power, Dy1 wiring, nominal current 1375 A and 15% short circuit voltage. The iron losses are 42 kW and the copper losses are 174 kW.

- (b) The lines of the network are all 95 ACSR type.
- (c) The Power Factor ( $\cos\phi$ ) is considered common for all the load types and equal to 0,9.
- (d) According to the Distribution Network Operator (HEDNO) the mean value of the voltage can vary from 0,95 to 1,05 p.u. ( $\pm 5\%$ ), and the variation around the mean value of the voltage can be  $\pm 3\%$  [23]
- (e) Moreover, the thermal limits of each line are:  $I_{max} \leq 448$  A. But, due to safety reasons, the operator sets 300 A as the limit [23]. Consequently, the maximum apparent power flow in each line varies between 10,91–16,29 MVA.
- (f) For the penetration of dispersed generation (DG) units, it is assumed that such units can be connected only to buses 3, 8, 10, 16, 19 due to the area's planning. Furthermore, it is assumed that their penetration happens evenly on the buses with a step of 0,5 MW/bus (meaning 2,5 MW). There is no initial dispersed generation units penetration.
- (g) Moreover, it is assumed that the reactive power compensation takes place through 3 0,9 MVA capacitor banks, each located at buses 7, 8, 9 respectively.
- (h) It is considered that reactive power control can be achieved through the power electronics connected to dispersed generation units (e.g. at photovoltaics in combination with their inverters). In other words, the Power Factor of DG units can be controlled.
- (i) DG units are considered to be operating in their nominal power
- (j) Finally, there is the possibility of voltage control through the OLTC. It is assumed that the OLTC setting takes place with a  $\pm 2,5\%$  step within the 85% and 115% boundaries as imposed by the operator regulations [23]. On every level of DG unit penetration the optimal OLTC setting will be selected through test as to fulfill the limits of the voltages.

## 5. Dispersed generation penetration scenarios — results

- **Base Scenario-1:** Without DG, Without compensation, With Nominal OLTC = 1 (0%)

Under these circumstances the limits for the mean value of the voltage are not fulfilled, while the thermal strain of the lines is greater than 300 A, which the value imposed by the operator (even if below the limits of the line - 448 A). We can easily notice that most buses are outside the limits, Fig. 2.

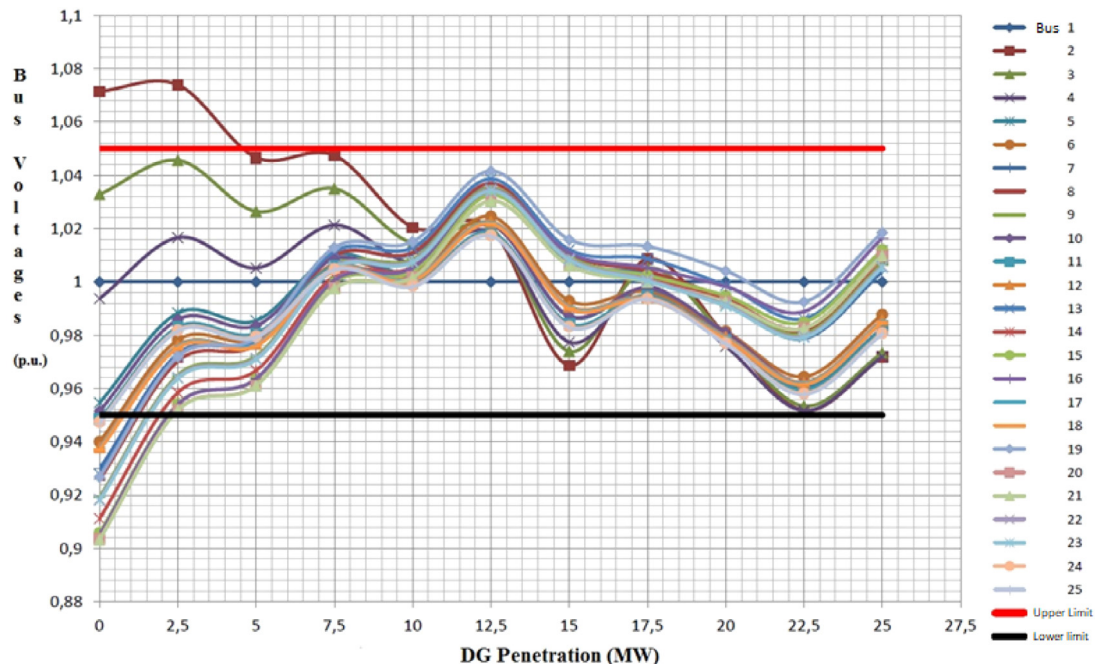


Fig. 2. The buses' voltage variations in the considered distribution network for the various scenarios.



- Scenario-2: Without DG, With compensation, With Nominal OLTC = 1 (0%)  
In this case the voltage mean values are out of limits, Fig. 2. Moreover, the thermal strain of the lines exceeds the limit imposed by the operator, but within thermal strain limits. Both voltages and power flows are in better condition than in Base Scenario-1.
- Scenario-3: Without DG, With compensation, With OLTC  $-5\%$  and  $-7,5\%$   
In neither of these cases, all the buses are situated within limits, Fig. 2. In fact, when we attempt to bring the remote buses within limits by increasing their voltage, the buses which are situated closer to the substation are found outside their limits (overvoltage). So, there is no combination that can bring all buses within limits. Of course, the situation is improved in comparison with the two previous scenarios.

Given the above, it seems that the voltage regulation of the considered distribution network is impossible through its own means. Therefore, the introduction of DG units in order to solve the problems of voltage and power flow is necessary.

- Scenario-4: With DG 0,5 MW/Bus, With compensation, With OLTC  $-7,5\%$   
In this Scenario it is observed that even if almost all of the buses are within limits, in bus 2 there is hyper-voltage, therefore this case is also not acceptable. Moreover, it was observed that there was no OLTC setting that allowed all voltages to be within limits at the same time. However, power flows are within the limits set by the operator.
- Scenario-5: With DG 1 MW/Bus, With compensation, With OLTC  $-5\%$   
Here the mean voltage value is within limits for all buses, Fig. 2. Furthermore, line 2–3 as well as the transformer are “decongested” and have significantly lower power flow due to local generation.
- Scenario-6: With DG 1,5 MW/Bus, With compensation, With OLTC  $-5\%$   
In this case also, all voltages are within limits, Fig. 2. The power flow remains (no inverse power flow is observed) from the upstream network towards the distribution network, but it has a small value.
- Scenario-7: With DG 2 MW/Bus, With compensation, With OLTC  $-2,5\%$   
In this case also, all voltages are within limits, Fig. 2. However, there is an inverse power flow from the network towards the upstream system.
- Scenario-8: With DG 2,5 MW/Bus, With compensation, With OLTC  $-2,5\%$   
In this case also, all voltages are within limits, Fig. 2 and the inverse, at this point, power flow is within thermal limit imposed by the operator. Of course, as the DG units’ penetration is increased, the inverse power flow effect becomes gradually stronger.
- Scenario-9: With DG 3 MW/Bus, With compensation, With OLTC  $+2,5\%$   
Similar conclusions with those of Scenario-8.
- Scenario-10: With DG 3,5 MW/Bus, Without compensation, With OLTC  $+2,5\%$   
Further penetration of DG units, with compensation in operation, cannot be accepted under any OLTC setting, because in every setting there is at least one bus that appears to have either overvoltage or undervoltage. Therefore, there is no setting that satisfies them all. That is why compensation is eliminated from this scenario on. This way, the voltages of all buses are found within the nominal values, Fig. 2.
- Scenario-11: With DG 4 MW/Bus, Without compensation, With OLTC 0%  
Similar conclusions with those of Scenario-10.
- Scenario-12: With DG 4,5 MW/Bus, Without compensation, With OLTC  $+2,5\%$   
Similar conclusions with those of Scenario-11 although the buses’ voltages further diverge from their nominal value, Fig. 2.
- Scenario-13: With DG 5 MW/Bus and Infusion of Reactive Power from these equal to 0,1 MVar/Bus, Without compensation, With OLTC 0%  
There cannot be 5 MW/bus penetrated under the existing circumstances. This is because with OLTC tap 0% (nominal) all the buses are outside limits except bus 13 which presents slight overvoltage, while with OLTC functioning with tap at 2,5% all the buses are outside limits except bus 2 which presents slight undervoltage. Consequently, there cannot be any OLTC regulation that fulfills the voltage criterion for all buses. This way, the last available solution is the control of the DG units’ Power Factor. The results of the voltages at the buses are presented in Fig. 2.

- Scenario-14: With DG 5,5 MW/Bus

The maximum theoretically installed power of the DG units for the considered network is equal to 25 MW. As it has been noted the maximum apparent power flow through the lines is 16,29 MVA. If we install 5,5 MW/bus then the overall installed power of the DG units will be  $5,5 \times 5 = 27,5$  MW. Given the fact that the overall power demand is 9,472 MW the surplus power will be  $27,5 - 9,472 = 18,028$  MW. Therefore, there will definitely be a problem with line 2–3 as well as part of converter’s line since the losses are not significant.

### 5.1. General notes regarding the results

1. The most important of the above is that, based on this procedure, it is technically possible to achieve a maximum 25 MW penetration of DG units (as far as the network data: voltages, power flows, thermal limits are concerned).
2. As is shown at Fig. 2 the most appropriate DG power penetrations with voltage as a criterion are the 10 MW and the 17,5 MW levels, because in these cases the voltages of the buses appear to diverge the least from themselves and from their nominal values (they show the minimal value dispersion). The most “dangerous” buses, meaning the buses that are found outside of limits for at least one DG penetration are the: 2, 6, 7, 8, 9, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25
3. If the criterion of power flow in the grid’s lines is also taken into account, then the technically optimal penetration is 10 MW. In this penetration level, the cables’ thermal strains are minimal. This leads to the minimum possible thermal strain of the transformer and the grids’ main line with significant gains regarding the lifespan of the said equipment. In Figs. 3–5 the power flows are given at the transformer’s line (1–2) for the different levels of power penetration of the DG units. This is about the connection of the considered DN with the upstream network via the power transformer.
4. If we set 300 A as thermal safety limit then the DG units penetration is limited on the 17,5 MW level.

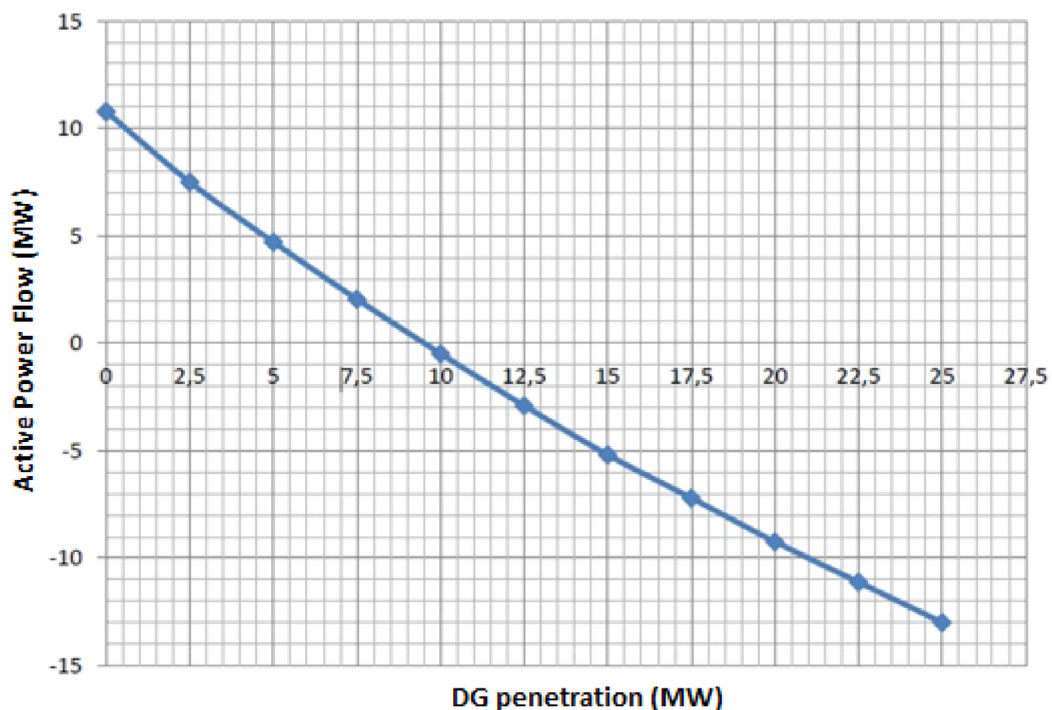


Fig. 3. Active power flow to the transformer (line 1–2) versus the level of DG units penetration (Similar diagrams for the other lines of the examined network).



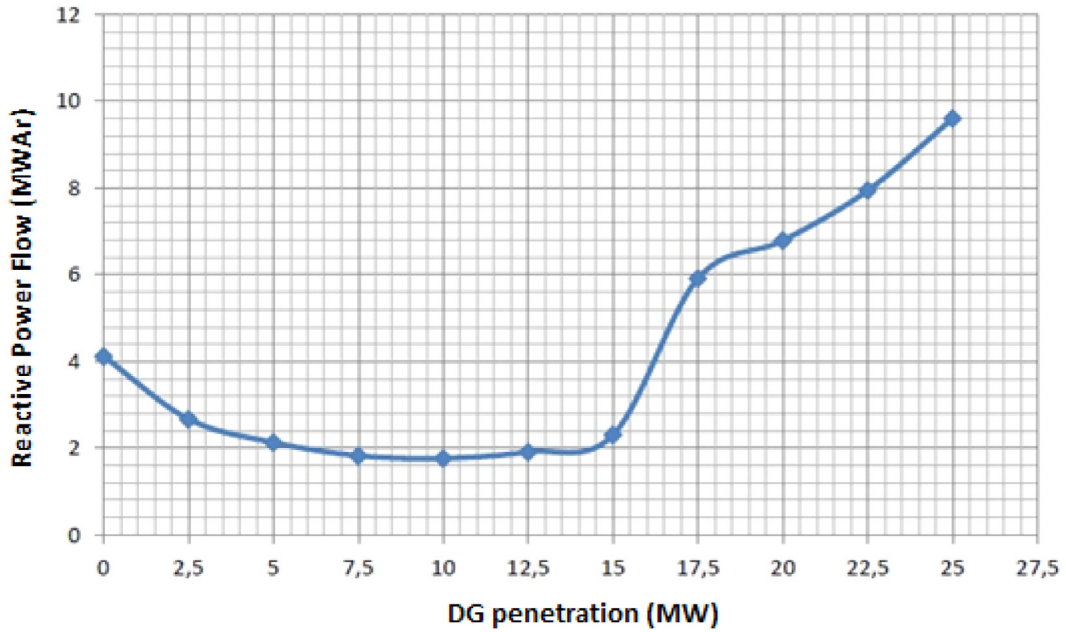


Fig. 4. Reactive power flow to the transformer (line 1–2) versus the level of DG units penetration (Similar diagrams for the other lines of the examined network).

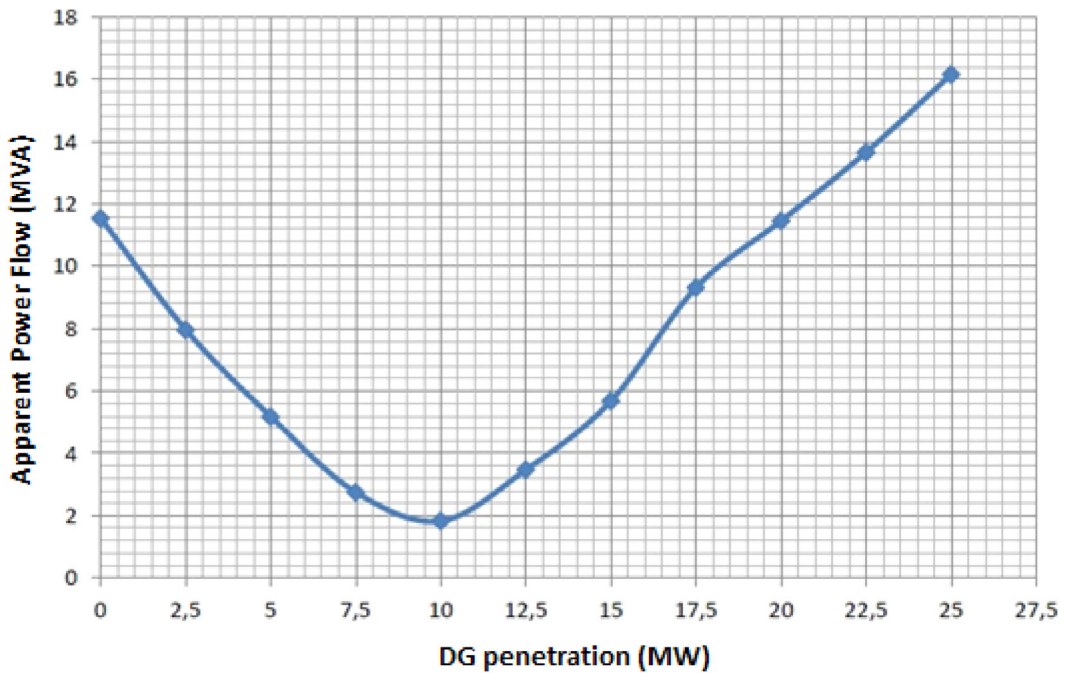


Fig. 5. Apparent power flow to the transformer (line 1–2) versus the level of DG units penetration (Similar diagrams for the other lines of the examined network).

- The effect of the penetration of the DG units on the network's losses is given in Fig. 6. It can be noted that for small DG penetrations, the system losses are decreased in comparison with the baseline while for greater penetrations the opposite happens. The explanation of this phenomenon is simple. At zero DG penetration

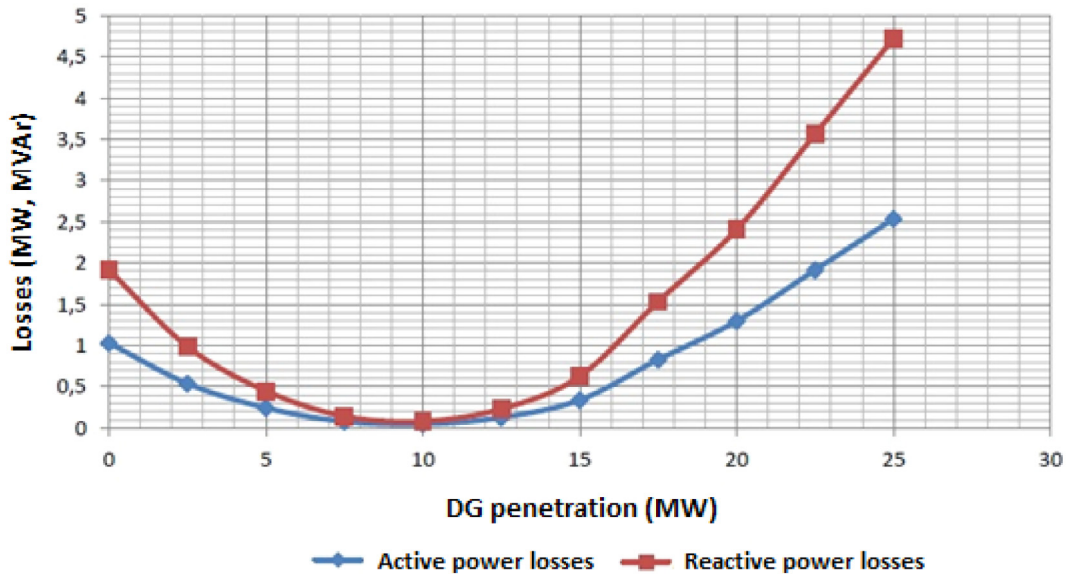


Fig. 6. DG effect on the active and reactive power losses of the grid.

there are losses since the whole power is covered by the upstream network. As the DG penetration increases, certain demand is covered from the local generation resulting in decreased transmission losses. The losses reach their minimum for 10 MW DG unit penetration since there the local generation is roughly equal to the load, therefore the power exchange with the upstream network is minimal. From that point on, there is a phenomenon of inverse power flow resulting in an increase of the transmission losses as it now flows towards the upstream network.

Consequently, from the aforementioned, we can safely conclude that from the network's point of view, the penetration of 10 MW DG units is the optimal.

## 6. Conclusion

In this paper the effect of the increased DG penetration on the DN's basic measures (busses' voltage, power flows, thermal limits in distribution lines) is studied.

For this purpose an actual DN of the Greek province was selected where the voltage regulation of all the buses with conventional means (compensation capacitors and OLTC) is not possible resulting in an obligatory, at his point, DG unit penetration for its proper operation. Due to the area's planning, it was assumed that the DG can be placed in certain only of the DN's areas (buses). The purpose was to examine for each DG level the extent to which the DN's basic measures are found within the defined limits that each Operator sets for the network.

In the study the Voltage Criterion that is related to the limits of the voltage at the DN's various buses was used. For the DN's modeling, appropriate software in Matlab was used, together with DG units and the voltage regulation means. So, the appropriate DG units penetrations were found for the DN's operation, meaning from 5 MW to 25 MW or to 17,5 MW depending on the thermal limit (nominal or set by the operator). In this manner, it was found that the DER Hosting Capacity is 25 MW or 17,5 MW depending on the criterion. For each DG unit penetration, the voltage regulation means (capacitor bank, OLTC and reactive power of the DG units) were set accordingly, so as the DN's voltage would be as close as possible to the nominal value of 20 kV or 1 p.u. Usually, there was only a single combination of these that made voltages in all the buses within the defined limits possible. Indeed, there was also the 2,5 MW case, where it was impossible to find a combination of voltage regulation settings that made this penetration level possible. As for the buses' voltage, they exhibited the lowest disperse around 1 p.u., for the 10 MW and the 17,5 MW penetration levels, respectively. Consequently, if, these two penetrate only voltage is concerned, these levels exhibited the optimum operation of the network.

Moreover, DG units' effect on the power flow between the DN and the upstream network was studied, as well as the DN's total losses. This way, it was found that on 10 MW the active, reactive and apparent power flow between the DN and the upstream network is minimum therefore at this point is the minimum thermal fatigue of the distribution lines. If we also take into account the fact that at 10 MW there is also a small disperse of voltages around the voltage's nominal value, 1 p.u. then this level of the optimal DG units' penetration level from the part of the criteria set for the DN.

These conclusions apply to this particular DN even though the philosophy and the steps to approach the problem, the effort to discover the best and the optimal level of DG penetration is the same regardless of the network's location. In the future, it would be useful to formalize the process of calculating the maximum level of penetration, so as to make it the same for all the countries and all the DN's operators. This would give a great boost to the RES' development and to their integration to the networks. Moreover, an easy to use software could be created with a graphical interface that would take the network's location and its technical characteristics as an input and the maximum and optimum level of penetration of the DG units as an output.

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