Electric Power Systems Research 80 (2010) 1421–1427

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Optimum allocation of the maximum possible distributed generation penetration in a distribution network

G.N. Koutroumpezis*, A.S. Safigianni

Electrical and Computer Engineering Department, Democritus University of Thrace, University Campus (Kimmeria), GR 67100 Xanthi, Greece

ARTICLE INFO

Article history:
Received 9 November 2009
Received in revised form 21 April 2010
Accepted 8 June 2010
Available online 15 July 2010

Keywords:
Distributed generation
Maximum penetration
Medium voltage power distribution networks
Optimum allocation
Thermal rating
Voltage profile

ABSTRACT

In this paper a method is proposed to determine the optimum allocation of the maximum distributed generation penetration in medium voltage power distribution networks. The method is based on an already-known but suitably modified and optimized method. Technical constraints, such as thermal rating, transformer capacity, voltage profile and short-circuit level are considered. A real network with already installed distributed generation resources is examined as a case study. The type, locations and ratings of these resources are predetermined. The satisfaction of the aforementioned technical constraints is examined initially in the framework of the existing network situation. The problems observed are solved by applying the required modifications in the network structure. Next, the proposed method is used to determine the optimum allocation of the maximum distributed generation penetration either in the predetermined network buses or in other random buses, in order to overcome the technical problems, without changing the network structure. Finally, the results are suitably estimated and extended in order to allow for more general conclusions concerning real power distribution networks.

1. Introduction

During the last few years, the deployment of distributed generation (DG) resources has been growing steadily. A general definition for DG was suggested in [1], which is now widely accepted, as follows: "Distributed generation is an electric power source connected directly to the distribution network or on the customer site of the meter". The above definition of DG does not define the rating of the generation source, as the maximum rating depends on the local distribution network conditions, e.g., voltage level. Furthermore, this definition does not cover the area of the power delivery, the penetration, the ownership or the treatment within the network operation. It also does not define the used technologies, as they can vary widely. Renewable and non-renewable DG resources are suggested as possible categories.

The DG is now being connected at distribution level, which, in turn, changes the characteristics of the distribution networks [2]. Existing distribution networks are passive, in that they were designed and built purely for the delivery of electricity to the customers. The introduction of DG has led to increased and bidirectional active and reactive power flows, along with wider variation in voltage levels, both of which affect the operation of equipment on the network and the extent of losses. Distribution networks are also characterized by a design short-circuit capacity. As the level of installed capacity increases, in the case of DG penetration, it is a fundamental requirement that the maximum short-circuit rating for all equipment is not exceeded.

The above changes to the use of the network together with the potentially high penetration of DG have led to the need for an effective and easily used technique to optimize both the rating and positioning of these generators within an established network. The issues that need to be considered in the choice of rating and positioning of DG include both technical and commercial factors [3–11]. The technical issues include the adequacy of the network's and associated plant's thermal rating, fault levels and sufficient voltage support to insure both the security and quality of electricity supply. The commercial issues include the cost of the DG, installation charges, operating costs, revenue expectations and the value of reduced losses in the network. Specifically in [3], the authors employ an optimal power flow technique to maximize DG capacity with respect to voltage and thermal constraints. In [4], genetic algorithms were used to place generation such that losses, costs, and network disruption were minimized and the rating of the generator maximized. A determination of the allowable DG penetration level is carried out based on harmonic limit consideration in [5], which is restricted to radial distribution feeders with uniform, linearly increasing or decreasing load pattern. The methodology of [6] determines the optimal DG allocation with respect to specific technical constraints. The basis for this methodology is in exploit-

* Corresponding author. Tel.: +30 2541079527; fax: +30 2541079526.
E-mail addresses: gkoytroy@ee.duth.gr (G.N. Koutroumpezis), asafig@ee.duth.gr (A.S. Safigianni).

0378-7796/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.epsr.2010.06.005

ing the interdependence, if any, of the buses with regard to the constraints. The constraints all have either linear or approximately linear characteristics with respect to increasing power injections, or they place a fixed and independent limit on the power injection. Nara et al. [7] apply tabu search techniques to locate DGs and minimize overall power losses. Celli and Pilo [8] present a genetic algorithm approach that, for a defined planning horizon, minimizes the cost of network investment and losses whilst meeting feeder thermal, voltage profile and fault-level constraints. In [9], a combination of fuzzy non-linear goal programming and genetic algorithm techniques is used to locate DGs and minimize overall power losses. In [10], El-Khaltam et al. use a heuristic approach to determine the optimal DG size and site from an investment point of view. In [11], a multi-objective procedure for the optimal DG sitting and sizing is proposed.

The results of an existing DG penetration in a weak medium voltage Greek network were first investigated in [12]. The connected DG resources are in their entirety small hydroelectric plants. Their locations and ratings are predetermined. Specifically, the DG influence on the network branch currents and voltage profile as well as on the short-circuit level (SCL) at the medium voltage busbars of the infeeding substation were examined. The arising technical problems were explored and solutions (alternative DG connection, reconductoring) were proposed.

As an extension of the work described in [12], this paper proposes an optimum allocation of the maximum possible DG penetration initially at the network buses, which have already been selected as DG connection points, in order to avoid technical problems, but without changing the network structure. It is based on the method given in [6], but it faces problems arising from the application of this method in real networks with many buses. It takes into account the technical constraints of [6] and an additional technical constraint concerning the thermal rating for all the network branches. It also examines the effect of the connected DG units on the voltage profile, for maximum load conditions not considered in [6]. Furthermore, different groups of network buses are investigated as possible DG connection points, in order to arrive at general conclusions concerning real power distribution networks.

2. Technical constraints

The following technical constraints are taken into account throughout the investigation of the DG penetration:

(1) Thermal constraint: it means that the rated current of the lines, I_{irated}, must not be exceeded:

$$I_i < I_{\text{irated}} \tag{1}$$

where I_i is the current flowing at each network branch.

(2) Transformer capacity: the amount of generation connected minus the minimum load must not exceed the rating of the transformer at the higher voltage.

(3) SCL constraint: a basic requirement for permitting the interconnection of DG is to insure that the resulting SCL remains below the network design value ($\text{SCL}_{\text{rated}}$). The SCL is highest at the medium voltage busbars of the infeeding substation, (SCL_{max}). The following relation gives the constraint:

$$\text{SCL}_{\text{max}} < \text{SCL}_{\text{rated}} \tag{2}$$

(4) Voltage variation constraint: when DG units are connected at the distribution network, the generator voltage will be the load/bus voltage plus some value related to the impedance of the line connecting them and the power flows along that line [6,13]. The increased active power flows on the distribution network have a great impact on the voltage level because the resistive element of the lines on distribution networks is higher than other lines. The following relation gives the voltage variation constraint:

$$\left|\varepsilon_i\% = \frac{U_i - U_{\text{T}}}{U_{\text{mean}}} \times 100\right| \le \left|\varepsilon_{\max}\%\right| \; i\forall N \tag{3}$$

where ε_i is the i_{th} bus voltage variation, U_i is the voltage value at the i_{th} bus, U_{T} is the voltage value at the substation busbars (U_{Tmin} for minimum load and U_{Tmax} for maximum load), U_{mean} is the mean voltage value at the substation busbars, $\varepsilon_{\max}$ is the permissible voltage variation and N is the number of buses. The constraint is usually examined for minimum load conditions, as this is supposed to be the worst-case scenario for voltage rise [6], but here it will also be examined for maximum load conditions which cause maximum voltage drop, in order to provide a solution for a network with acceptable voltage profile for any load case.

3. Existing situation

In case that DG units are already interconnected to a distribution network, it becomes necessary to evaluate primarily the existing situation, in view of potential technical problems. In order to make this procedure clear, a real power distribution network with DG resources is considered as a case study.

Fig. 1 shows the examined distribution network with the existing DG resources. This network is situated in West Macedonia, Greece. It is one of the main medium voltage lines (named line 23) fed by a 25 MVA, 150/20 kV substation. There are also three other main lines stemming from this substation. Line 23 is a radial network with mainly overhead lines. The main feeder consists mostly of 95 mm^2 ACSR conductors but there are also many lateral branches consisting of 16 mm^2 ACSR conductors. The main buses such as lateral branch origins or load positions are marked with the letter P in Fig. 1, whilst the letter S is used for secondary buses. DG resources of a total power of about 11.52 MW are connected in four network positions (P6, P19, P29 and P31). The already existing DG resources are small hydroelectric plants.

Also given in Fig. 1, except for the conductor sizes, are the branch lengths and the installed maximum loads in Amperes, all coincident to the maximum load of the main feeder, which is equal to 110 A (or equally about 4 MVA). Other network data are: $\text{SCL}_{\text{rated}}$ = 250 MVA, U_{Tmax} = 21.4 kV, U_{Tmin} = 20.4 kV, $U_{\text{mean}} \approx$ 21 kV, load power factor $\cos\varphi$ = 0.9 inductive, permissible voltage variation $\varepsilon_{\max}\% = \pm 3\%$ (according to the Greek Public Power Corporation (PPC) requirements).

Taking into account that the total DG penetration is 11.52 MW or about 11.52/0.95 = 12.12 MVA and that the minimum network load is about 20 A or equally 0.706 MVA, their difference is about 11.5 MVA, which is smaller than the substation rating (25 MVA). There is no DG penetration in the other feeders stemming from the 25 MVA substation, so the second constraint of Section 2 (transformer capacity) is not breached.

The other constraints concerning the conductor rated currents, the voltage profile of the network and the SCL_{max} are examined using the NEPLAN software package. Especially for the SCL computation the IEC 60909 [14–16] is used.

First, power flow analysis is realized to calculate the branch currents and the bus voltages for minimum and maximum load and voltage supply, with and without the existing DG penetration. The results of this analysis according to the branch currents are that the first constraint (thermal constraint) of Section 2 is not breached [12]. From the same analysis the permissible voltage drop (−3% of the nominal voltage) is not exceeded for minimum load but it is exceeded (it is over −5% of the nominal voltage in several buses) for maximum load, without DG penetration, as the cells in dark

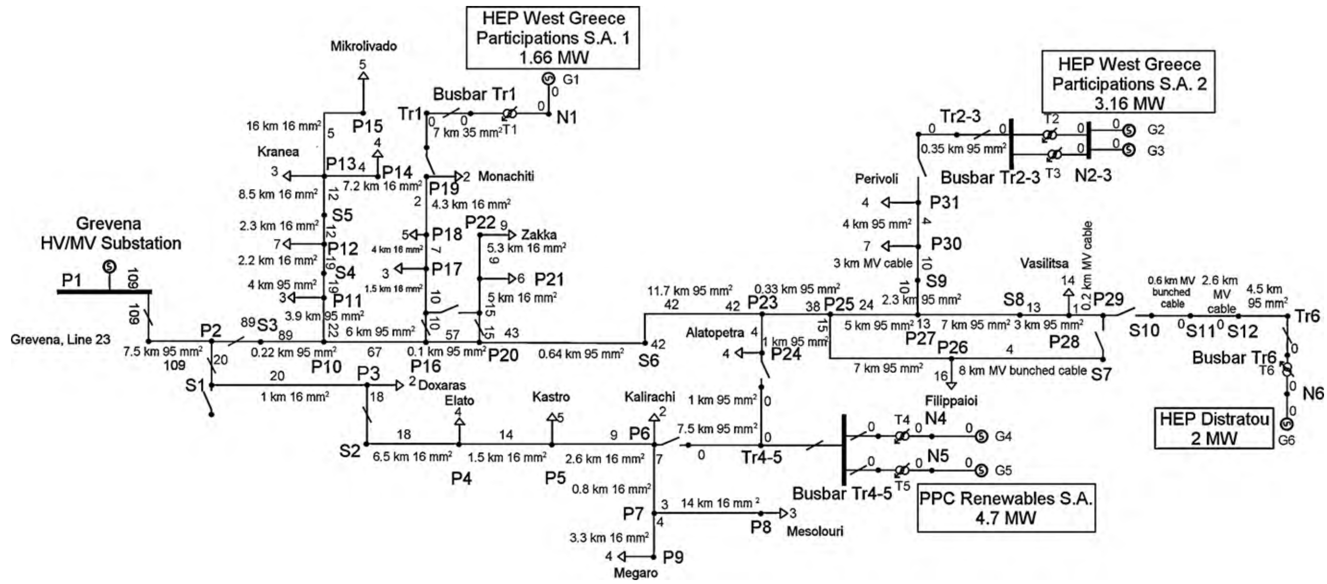

Fig. 1. Network diagram.

grey scale in the third column of Table 1 show. This is because the network has many branches consisting of 16 mm^2 ACSR conductors. When all the DG units are connected to the network, there is an impermissible voltage rise at the buses of the route P4–P8, P9 and a marginally impermissible voltage rise at the bus P19, for minimum load, as the cells in light grey scale in the forth column of Table 1 show. The problem is significant at the route P4–P8, P9 and taking into account that the fourth constraint (voltage variation constraint) of Section 2 is breached, the question is whether the connection of the DG units of PPC Renewables S.A. to the bus P6 is possible without using a voltage regulator. The voltage drop problem for maximum load is improved with this DG penetration, as a comparison between the third and fifth columns of Table 1 shows.

The results of the analysis concerning the third constraint (SCL constraint) of Section 2, for maximum supply voltage, are that the DG penetration causes a significant increase in SCL_{max} (Table 2) but without exceeding SCL_{rated} = 250 MVA. Therefore this constraint is not breached.

The following two alternative proposals were examined in [12] in order to solve the above-mentioned voltage rise problem for minimum load in order to accommodate the units of PPC Renewables S.A. that is a total DG injection of 11.52 MW instead of the 6.8 MW, which correspond to the power of the remaining units under the condition that the network structure is not modified:

- First proposal: connection of the DG units of the PPC Renewables S.A. to the bus P24 instead of the bus P6.
- Second proposal: conductor replacement at the route P2–P6 with ACSR 95 mm^2 conductors.

Both the proposals solve the voltage rise problem for minimum load and improve significantly the voltage drop problem for maximum load. The selection of one of them is a matter of economic evaluation, possibility of implementation and general PPC policy.

4. Optimization process and results

The subject of this section is, firstly, the development of a method for the determination of the optimum allocation of the maximum possible DG penetration at network buses, which have already been selected as DG positions, in a way that the technical constraints of Section 2 are satisfied. The buses P6, P19, P29 and P31 of the network given in Fig. 1 are examined as a case study. Furthermore, the same problem is examined for other groups of network buses, such as possible DG locations, in order to arrive at general conclusions. For this reason the method of [6] is exploited but with suitable modifications, remarks and extensions.

Specifically, Keane and O'Malley [6] examine all the technical constraints given in Section 2 except the thermal constraint, which, in some cases, may be the crucial criterion for the optimum DG penetration, as will be shown later. They examine this constraint only with regard to the current flow in the line between each DG unit and its corresponding bus. The accurate calculation of the branch currents requires power flow analysis, but Eq. (4) may give an approximate estimation:

$$I_i = \frac{\sqrt{P_{ti}^2 + Q_{ti}^2}}{\sqrt{3}U_i} = \frac{\sqrt{(P_{tGi} - P_{tLi})^2 + (Q_{tGi} \pm Q_{tLi})^2}}{\sqrt{3}U_i} \tag{4}$$

where I_i is the current flowing to the bus i from the previous upstream bus, P_{tGi} and Q_{tGi} are the total DG active and reactive powers correspondingly downstream of the bus i, P_{tLi} and Q_{tLi} are the total load active and reactive powers correspondingly downstream of the same bus and U_i is the voltage at this bus.

An investigation of Eq. (4) for different load power factors has proved that the divergence between these approximate values and the accurate current values is not significant. Therefore Eq. (4) can be used as a first test for the satisfaction of the thermal constraint. In any case, power flow analysis follows to verify the final result.

The contribution of the DG connected to the individual buses to SCL_{max} is determined by short-circuit analysis. These contributions are combined and formalized into an algebraic equation expressing the SCL constraint [6]:

$$\sum_{j=1}^{N} \delta_{jTx} P_{Gj} + \alpha_{Tx} \le SCL_{rated} \tag{5}$$

where δ_{jTx} is the slope of the SCL_{max} versus power injection characteristic of the j_{th} bus, P_{Gj} is the power injection at the j_{th} bus, and α_{Tx} is the initial SCL_{max} with no generation present.

Table 1
Voltage variation.

Bus	Voltage variation ε_i%							
	Without DG		With DG (existing situation)		Optimum-maximum DG penetration			
					Voltage constraint for minimum load		Voltage constraint for minimum and maximum load	
	Min load	Max load	Min load	Max load	Min load	Max load	Min load	Max load
P1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
P2	−0.43	−2.31	−0.03	−1.57	−1.37	−2.82	−0.40	−1.90
P3	−0.48	−3.65	0.77	−0.94	−1.22	−2.84	−0.25	−1.76
P4	−0.67	−3.86	6.19	3.46	−0.22	−2.83	0.74	−0.67
P5	−0.71	−4.09	7.49	4.57	0.02	−2.77	0.98	−0.36
P6	−0.76	−4.15	9.80	6.64	0.47	−2.53	1.42	0.31
P7	−0.76	−4.56	9.80	6.59	0.46	−2.59	1.41	0.27
P8	−0.86	−4.27	9.72	6.22	0.38	−3.00	1.33	−0.13
P9	−0.81	−2.37	9.78	6.47	0.43	−2.72	1.39	0.14
P10	−0.43	−2.60	−0.02	−1.60	−1.40	−2.89	−0.41	−1.95
P11	−0.48	−3.22	−0.07	−1.83	−1.44	−3.12	−0.45	−2.18
P12	−0.57	−4.50	−0.18	−2.44	−1.56	−3.74	−0.57	−2.79
P13	−0.81	−4.78	−0.42	−3.71	−1.81	−5.03	−0.81	−4.07
P14	−0.90	−5.30	−0.47	−3.99	−1.87	−5.31	−0.87	−4.35
P15	−1.00	−3.51	−0.57	−4.51	−1.97	−5.84	−0.97	−4.87
P16	−0.67	−3.67	0.28	−2.21	−1.95	−4.20	−0.50	−2.84
P17	−0.67	−3.95	0.76	−2.35	−1.43	−3.83	−0.17	−2.72
P18	−0.71	−4.03	2.06	−2.62	0.00	−2.71	0.73	−2.30
P19	−0.76	−2.37	3.51	−2.71	1.60	−1.29	1.75	−1.63
P20	−0.67	−3.54	0.29	−2.22	−1.96	−4.22	−0.50	−2.85
P21	−0.81	−4.28	0.15	−2.94	−2.10	−4.96	−0.64	−3.58
P22	−0.86	−4.75	0.06	−3.41	−2.19	−5.44	−0.73	−4.05
P23	−0.95	−5.07	1.13	−2.50	−2.16	−5.51	−0.39	−3.85
P24	−0.95	−5.08	1.13	−2.51	−2.16	−5.52	−0.39	−3.86
P25	−0.95	−5.11	1.16	−2.50	−2.15	−5.52	−0.38	−3.87
P26	−1.00	−5.42	1.10	−2.80	−2.21	−5.83	−0.44	−4.17
P27	−1.00	−5.45	1.64	−2.29	−1.82	−5.46	−0.17	−3.95
P28	−1.10	−5.84	2.34	−1.91	−1.39	−5.33	0.06	−4.09
P29	−1.10	−5.84	2.35	−1.89	−1.38	−5.31	0.07	−4.08
P30	−1.05	−5.57	1.89	−2.15	−1.42	−5.18	0.03	−3.86
P31	−1.05	−5.61	2.05	−2.02	−1.15	−4.96	0.16	−3.76
S01	−0.43	−2.31	−0.03	−1.57	−1.37	−2.82	−0.40	−1.90
S02	−0.48	−2.51	0.77	−0.94	−1.22	−2.84	−0.25	−1.76
S03	−0.43	−2.32	−0.03	−1.57	−1.37	−2.82	−0.40	−1.90
S04	−0.52	−2.81	−0.10	−2.03	−1.48	−3.33	−0.49	−2.38
S05	−0.67	−3.49	−0.23	−2.71	−1.61	−4.01	−0.62	−3.06
S06	−0.67	−3.62	0.32	−2.23	−2.00	−4.31	−0.50	−2.91
S07	−1.00	−5.42	1.10	−2.8	−2.21	−5.83	−0.44	−4.17
S08	−1.05	−5.72	2.13	−2.02	−1.53	−5.39	−0.02	−4.05
S09	−1.00	−5.52	1.72	−2.27	−1.70	−5.41	−0.11	−3.95
S10	−1.10	−5.84	2.35	−1.89	−1.38	−5.31	0.07	−1.90
S11	−1.10	−5.84	2.41	−1.83	−1.38	−5.31	0.14	−1.76
S12	−1.10	−5.84	2.56	−1.69	−1.38	−5.31	0.27	−0.67

The individual sensitivity of the SCL_{max} to power injections at the buses P6, P19, P29 and P31 is calculated, resulting in Fig. 2. The values for δ_{jTx} (MVA/MW) used in Eq. (5) are calculated from the slopes of the curves given in Fig. 2. These curves were plotted taking into account that the DG units are connected to the network buses via a very short 95 mm^2 ACSR line, which restricts the maximum possible DG penetration to 13.6 MVA. DG injection is realized by connecting successively identical DG units in parallel to each bus. These units are represented by their rated power and power factor and may be resources of any kind (renewable, modular, combined production of heat and power).

The voltage variation constraint may be formalized into algebraic equations, giving the U_i of Eq. (3) for each bus [6]:

$$\mu_i P_{Gi} + \beta_i + \sum_{j=1}^{N} \mu_{ji} P_{Gj} = U_i i \forall N, \quad i \neq j \tag{6}$$

where μ_i is the slope of the voltage versus power injection characteristic for the i_{th} bus. β_i refers to the initial voltage level at the i_{th} bus with no generation, and μ_{ji} refers to the dependency of the voltage level at the i_{th} bus on power injections at bus j (slope of the voltage U_i versus power injection in the j_{th} bus characteristic).

Table 2
Maximum short-circuit level.

SCL_{max} (MVA)			
Without DG	With DG (existing situation)	Optimum-maximum DG penetration	
		Voltage constraint for minimum load	Voltage constraint for minimum and maximum load
197	229	224.784	219.531

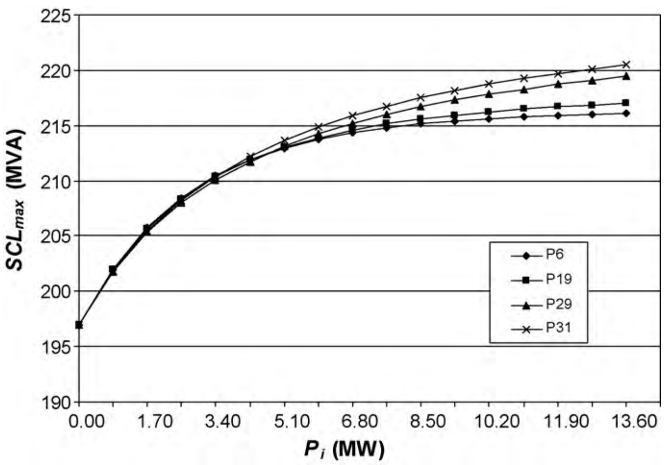

Fig. 2. SCL_{max} versus power injections at individual buses.

The dependence of the voltage U_i at each bus on power injections at the buses P6, P19, P29 and P31, for minimum load, was first calculated, resulting in a graph for each bus. The graph for bus P29 is shown in Fig. 3a. Fig. 3b shows more clearly the dependence of the voltages U_{29} and U_9 at buses P29 and P9, respectively, on power injections at bus P29. The values for μ_{29} and μ_{929} (kV/MW) in Eq. (6) are determined from Fig. 3b. The values for μ_{j29} (kV/MW) are determined from the other relevant curves shown indicatively in the graph of Fig. 3a. The corresponding graphs for the buses P6, P19 and P31 have similar form to that given in Fig. 3. The graphs for the buses P29 and P31 present the greatest similarity. This is to be expected, as these buses are at about the same distance from the main feeder, they are connected via conductors of the same type

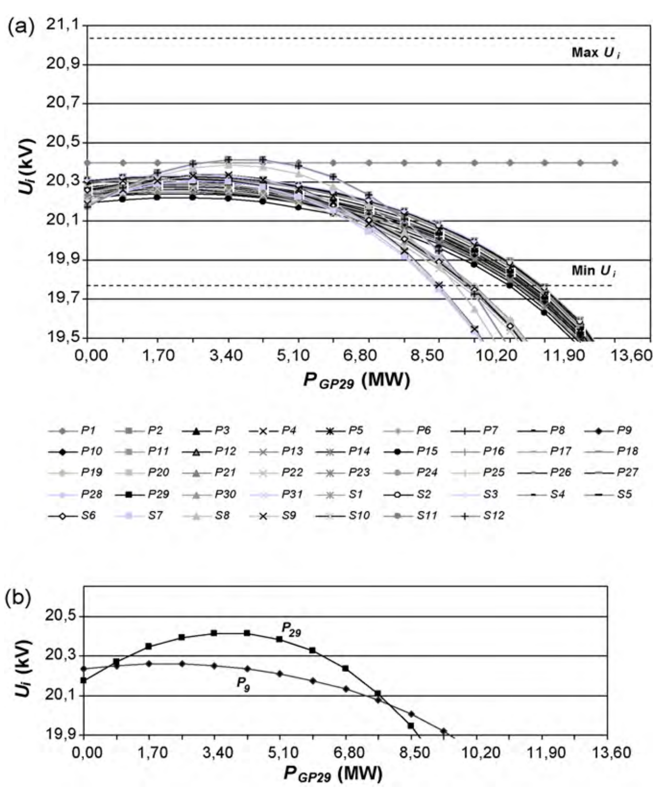

Fig. 3. (a) Dependence of the voltage U_i at each bus on power injections at bus P29, for minimum load, (b) dependence of the voltages U_{29} and U_9 at buses P29 and P9, respectively, on power injections at bus P29.

(95 mm^2 ACSR) to the main feeder and they are the ends of lateral branches with almost the same load. These buses can accept the highest DG penetration as opposed to the buses P6 and P19, which are the ends of weak lateral branches (16 mm^2 ACSR conductors) and therefore they can accept a smaller DG penetration because of the voltage variation constraint. From all the voltage graphs the generalized conclusion is that the power injections at each bus affect the voltage of the other buses around in groups, depending on their relative distance, resulting in groups of curves having the same shape.

The analysis for maximum load is quite relevant. Generation capacity should be allocated across all or particular network buses such that none of the above-mentioned technical constraints is breached and the capacity is maximized. Therefore, the proposed objective function is:

$$J = \max \sum_{i=1}^{N} P_{Gi} \tag{7}$$

where P_{Gi} is the DG capacity at the i_{th} bus and N is the number of buses supposed as possible DG positions.

The basic criterion for the determination of the optimum allocation of the maximum possible DG penetration in the selected buses of the examined network of the present case study is the voltage variation rather than the short-circuit capacity. This is because the network short-circuit capacity without DG is far from the SCL_{rated}.

In order to solve Eq. (7) subject to the technical constraints (1), (2) and (3), it is necessary to determine, as accurately as possible, the coefficients $\delta_{j\text{T}x}$, μ_i and μ_{ji} from the slopes of the relative curves. The calculation of the coefficients $\delta_{j\text{T}x}$ from the curves of Fig. 2 is relatively easy, because these curves have a positive slope that is relatively regular along their total range. Unlike this, the voltage curves, like those of Fig. 3, present areas with either positive or negative slopes, thus making difficult the calculation of the coefficients μ_i and μ_{ji} for minimum and maximum load. This is a problem not considered in [6], where the examined network presents voltage curves with solely positive slopes. In order to address this problem for voltage curves presenting areas with either positive or negative slopes and to define the suitable range of the curves for the determination of the final μ_i and μ_{ji} used in Eq. (6) (slopes of the relevant curves) an iterative solution process of Eq. (6) was performed. This resulted in a range which is just less than the maximum value of the voltage curve for each examined bus (e.g., about 4.5 MW for bus P29, according to Fig. 3b). The selection of the above range is absolutely justified by the fact that a maximum DG penetration, subject to the acceptable voltage rise constraint for minimum load, is searched out.

Taking into account the above finding, first the coefficients $\delta_{j\text{T}x}$, μ_i and μ_{ji} were calculated and then Eq. (7), subject to constraints (1), (2) and (3) examined only in relation to the voltage rise effect, was solved, with the help of the software package Mathematica. During the solution process small changes in the initial range selection for the calculation of the slopes may be necessary, in order to improve the accuracy of the dependencies and insure an accurate determination of the optimum DG allocation. The resulting optimum-maximum DG penetration for the selected network buses is given in the first line of Table 3.

The resulting total DG penetration (11.9 MW) is now slightly higher and its distribution at the pre-selected buses is quite different from the existing one (11.52 MW) that requires network modifications within the technical confines detailed in Section 3. However, the power injection of 11.9 MW is much higher than the power of 6.8 MW that remains connected to the network in the case that the PPC Renewables S.A. units are dispatched in order to meet the adopted constraints without performing any network modifications. There is an almost equal DG capacity interconnected with the

Table 3
Optimum-maximum distributed generation penetration in the buses P6, P19, P29 and P31.

Bus	P6	P19	P29	P31	Total
DG penetration (voltage constraint for minimum load) (MW)	0.85	1.7	4.25	5.1	11.9
DG penetration (voltage constraint for minimum and maximum load) (MW)	0.85	1.7	2.55	2.55	7.65

buses P29 and P31. As mentioned above, these buses present a great similarity and the resulting balanced DG allocation, instead of an unequal distribution of the same total capacity between the above two buses, provides for a better voltage profile. The network voltage profile for this DG penetration, for minimum and maximum load, is also shown in the sixth and seventh columns of Table 1 correspondingly, for reasons of direct comparison. It is obvious that no voltage rise problems exist for minimum load, whilst this DG penetration does not make the voltage drop problem worse, for maximum load, compared to the situation without DG. If an improvement of the network voltage profile for maximum load is desirable, then a new network study (not carried out in [6]) providing new voltage curves and coefficients μ_i and μ_{ji} for this load case is necessary, in order to meet the voltage drop constraint. This analysis, carried out in the context of this paper, led to the optimum-maximum DG penetration given on the second line of Table 3. The network voltage profile for this DG allocation is also shown in the eighth and ninth columns of Table 1, for minimum and maximum load, respectively.

The resulting total DG penetration when the voltage drop constraint for maximum load is taken into account is smaller (as a comparison of the two lines of Table 3 shows). The voltage drop problem is significantly improved, as a comparison of the last column with all the relative columns of Table 1 shows, but it is not completely resolved. This is due to the fact that the examined network had serious voltage drop problems before the DG connection. Another provision, for example the use of capacitors, would have been made for maintaining the voltage, since the main DG goal is to supply the network with power whilst the optimization of the network voltage profile is a secondary benefit. The DG positioning within the network makes its character less inductive up to a certain limit, corresponding to the best possible network voltage profile, which however does not mean that the achieved voltage drop is less than ε_{max}% for all network buses. An additional DG penetration increases the voltage drop instead of decreasing it further. This is due to the form of the voltage curves (positive and negative slopes on the same curve) determining the coefficients μ_i and μ_{ji}. When DG resources exceeding the above limit are added, these coefficients are determined from the negative slope (voltage drop) area instead of the positive slope (voltage rise) area of the voltage curve.

With regard to SCL_{max}, it remains smaller than SCL_{rated} for the determined optimum-maximum DG penetration (with or without the voltage constraint for maximum load), as the relative columns of Table 2 show.

Another group of buses was selected as possible DG connection points in order to arrive at general conclusions. The selected buses are P6, P10, P19, P20 and P24. The dependence of the voltage U_i at each bus on power injections at the bus P20, for minimum load, is shown in Fig. 4a whilst Fig. 4b shows more clearly the dependence of the voltages U_{20} and U_9 at buses P20 and P9, respectively, on power injections at bus P20. The corresponding graphs for the buses P6, P10, P19 and P24 are similar. All these graphs show that the DG penetration in these buses leads almost exclusively to voltage rise (the curves have solely positive slope). Only in cases of high DG penetration is there a voltage drop.

The results of the optimum-maximum DG penetration investigation in this case with and without the thermal constraint are shown in Table 4. The basic criterion for the first results is the short-circuit capacity instead of the voltage variation constraint, but this first DG allocation causes an excess of I_{irated} in the routes P1–P2, P2–P10, P10–P16 and P16–P20. The second line of Table 4 shows the optimum-maximum DG penetration when the thermal constraint is additionally taken into account. In the last case the total DG capacity is smaller and the SCL_{max}, which is equal to 249.892 MVA, remains marginally smaller than the SCL_{rated}. By comparison of the results given in the two lines of Table 4 it is clear that the thermal constraint introduced in this paper determines the final optimum-maximum DG allocation for this group of buses.

In general the DG penetration is higher when the prospective buses are not predetermined but the entire network buses are possible DG locations. The solution procedure becomes more laborious and time-consuming in this case, because a large number of graphs, like those of Figs. 2 and 3, must be plotted and an accurate determination of the ranges for the calculation of the coefficients δ_{jTx}, μ_i and μ_{ji} is needed for all these graphs. This is one of the weaknesses of the applied optimization process but it must be noted that in most cases someone can not arbitrarily locate the DG for any technology on very many buses and so the problem is rather hypothetical and it does not constitute a big limitation. The second serious weakness is because the SCL and the voltage variation constraints have the form of linear equations, as magnitudes instead of vectors are added in Eqs. (5) and (6). With this approximation the optimum-maximum DG penetration can be determined with sufficient accuracy only for

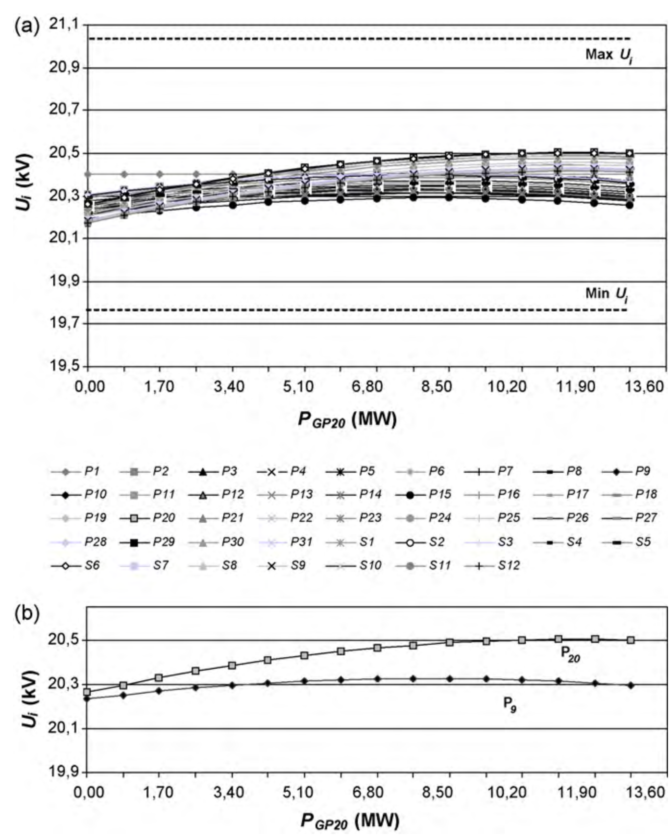

Fig. 4. (a) Dependence of the voltage U_i at each bus on power injections at bus P20, for minimum load, (b) dependence of the voltages U_{20} and U_9 at buses P20 and P9, respectively, on power injections at bus P20.

Table 4
Optimum-maximum distributed generation penetration in the buses P6, P10, P19, P20 and P24.

Bus	P6	P10	P19	P20	P24	Total
DG penetration without thermal constraint (MW)	0.0	0.0	0.0	6.8	12.75	19.55
DG penetration with thermal constraint (MW)	0.0	4.25	0.0	9.35	0.0	13.6

networks where the DG penetration causes voltage rise, which is beneficial during the maximum load hours and controllable under the minimum load hours. In cases of inductive relatively high DG penetration, however, voltage drop instead of voltage rise appears and so the method leads to wrong results or perhaps will not give a solution at all. The final result depends also on the selection of the DG connection points, i.e. if they are end buses or belong to the main feeder.

5. Conclusions

The DG interconnection to the distribution networks causes changes to their characteristics. These changes are often not acceptable, as basic technical constraints do not apply.

This paper first examines the results of a concrete DG penetration, considering a real medium voltage power distribution network as a case study. Technical constraints such as thermal rating, transformer capacity, voltage profile and short-circuit level are taken into account. The arising problems can be possibly solved by modifying the network structure. If this is not desirable, then the method proposed here allows for an optimum distribution of the maximum possible penetration of any type of DG resources, which are represented by their rated power and power factor, in predetermined or in random network buses. This method exploits further an existing method however, it extends it with additional technical constraints. By applying the enhanced method in real networks the paper highlights real problems that arise, such as complicated voltage profiles, and proposes appropriate solutions.

The application of the method analysed in this paper, in the context of the sample network, led to important general conclusions. Specifically, it resulted that the DG penetration is higher and best allocated when the prospective buses are not predetermined but the entire network buses are possible DG locations. In case the buses or the rating of DG penetration in some of them are predetermined the maximum DG penetration is restricted. Furthermore it is not obvious from the beginning which of the technical constraints will finally determine the optimum distribution of the maximum possible DG penetration. Therefore, all the technical constraints have to be examined. In any case a method such as the one proposed is necessary to specify the optimum allocation of the maximum DG penetration. The described method gives satisfactory results for small distribution networks but requires labor and time resources for networks with many buses, since these networks require more time for the power flow and short-circuit analysis. This tradeoff can be balanced by the modern software tools for power network simulation and planning, such as NEPLAN, that includes functions to access data and calculation algorithms through advanced programming language user written programs. The main disadvantage of the present form of the proposed method is that it adopts some necessary simplifications, that may occasionally compromise precision or result in dubious solutions. Therefore, a semi-analytical approach, that uses the aforementioned equations but which handles them by an analytical optimization method, is under investigation by the authors in order to minimize the involvement of their parameters and the uncertainty they import into the whole process. In this way, a more accurate and flexible method, that works for various sizes of distribution networks, and permits a more reliable solution for the optimum DG allocation, will be completed soon.

References

[1] T. Ackermann, G. Andersson, L. Soder, Distributed generation: a definition, Electr. Power Syst. Res. 57 (3) (2001) 195–204.
[2] P.P. Barker, Determining the impact of distributed generation on power systems: Part 1. Radial distribution systems, in: Proc. IEEE PES Summer Meeting, 2000, pp. 1645–1656.
[3] A.R. Wallace, G.P. Harrison, Planning for optimal accommodation of dispersed generation in distribution networks, in: CIRED 17th Int. Conf. Elect. Distrib., Barcelona, Spain, 2003.
[4] B. Kuri, M. Redfern, F. Li, Optimization of rating and positioning of dispersed generation with minimum network disruption, in: Proc. IEEE Power Eng. Soc. Gen. Meeting, Denver, CO, 2004, pp. 2074–2078.
[5] A. Bhowmik, A. Maitra, S.M. Halpin, J.E. Schatz, Determination of allowable penetration levels of distributed generation resources based on harmonic limit considerations, IEEE Trans. Power Deliv. 18 (2) (2003) 619–624.
[6] A. Keane, M. O'Malley, Optimal allocation of embedded generation on distribution networks, IEEE Trans. Power Syst. 20 (3) (2005) 1640–1646.
[7] K. Nara, Y. Hayashi, K. Ikeda, T. Ashizawa, Application of tabu search to optimal placement of distributed generators, in: Proc. IEEE Power Engineering Society Winter Meeting, 2001, pp. 918–923.
[8] G. Celli, F. Pilo, Optimal distributed generation allocation in MV distribution networks, in: Proc. 22nd IEEE PES Int. Conf. on Power Industry Computer Applications PICA, Sydney, Australia, 2001, pp. 81–86.
[9] K.H. Kim, Y.J. Lee, S.B. Rhee, S.K. Lee, S.K. You, Dispersed generator placement using fuzzy-GA in distribution systems, in: Proc. IEEE Power Engineering Society Summer Meeting, Chicago, IL, 2002, pp. 1148–1153.
[10] W. El-Khaltam, K. Bhattacharya, Y. Hegazy, M.M.A. Salama, Optimal investment planning for distributed generation in a competitive electricity market, IEEE Trans. Power Syst. 19 (3) (2004) 1674–1684.
[11] G. Celli, E. Ghiani, S. Mocci, F. Pilo, A multi-objective evolutionary algorithm for the sizing and siting of distributed generation, IEEE Trans. Power Syst. 20 (2) (2005) 750–757.
[12] A.S. Safigianni, G.N. Koutroumpezis, G.S. Demetzos, J.G. Kendristakis, Investigation of the distributed generation penetration in a medium voltage distribution network, in: Proc. Medpower '08, Thessaloniki, Greece, 2008.
[13] N. Jenkins, R. Allan, P. Crossley, D. Kirschen, G. Strbac, Embedded Generation, IET Publications, London, 2000.
[14] Short-circuit currents in three-phase a.c. systems: Part 0. Calculation of short-circuit currents, IEC 60909-0, 2001.
[15] Short-circuit currents in three-phase a.c. systems: Part 1. Factors for the calculation of short-circuit currents according to IEC 60909-0, IEC 60909-1, 2002.
[16] Short-circuit currents in three-phase a.c. systems: Part 2. Electrical equipment – data for short-circuit currents calculation in accordance with IEC 909 (1988), IEC 60909-2, 2002.