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Optimum Distributed Generation Penetration In a Distribution Network

G. N. Koutroumpezis and A. S. Safigianni, *Member, IEEE*

Abstract--**This paper investigates the results of distributed generation penetration in a medium voltage power distribution network. The network is located in West Macedonia, Greece. The connected distributed generation resources are in their entirety small hydroelectric plants. Their locations and ratings are predetermined. Only technical constraints such as thermal current, transformer capacity, voltage profile and short-circuit level are taken into account. The arising problems concerning the network voltage profile are first solved by changing the network structure. Afterwards an already known but suitably modified and optimized method is used to determine an optimum distribution of the maximum distributed generation penetration either in the predetermined network buses or in other random buses, in order to avoid the technical problems, without changing the network structure.**

Index Terms--**Distributed generation, maximum penetration, medium voltage network, optimum distribution, short-circuit level, thermal current, voltage profile.**

I. 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 distinction between distribution and transmission networks is based on the legal definition. 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. The categories of renewable and non-renewable DG are suggested as possible.

The DG is now being connected at distribution level. 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 is changing the characteristics of the distribution networks. It 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 in the network and the level 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 [2]-[6]. 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.

The results of an existing DG penetration in a weak medium voltage Greek network were first investigated in [7]. The connected DG resources are in their entirety small hydroelectric plants. Their locations and ratings are predetermined. Specifically in [7], 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 [7], this paper proposes an optimum distribution of the maximum DG penetration at the network buses, which have already been selected as DG connection points, in order to avoid the resulting technical problems without changing the network structure. It is based on the method given in [2], but it faces problems arising from the application of this method in real networks with many buses. It also takes into account more technical constraints than [2]. The investigation is extended to other random network buses, in order to arrive at general conclusions.

II. Technical Constraints

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

This work was produced in the Electrical and Computer Engineering Department, Democritus University of Thrace, Greece.

The authors are with the Electrical and Computer Engineering Department, Democritus University of Thrace, Xanthi, GR-67100, Greece (e-mail: asafig@ee.duth.gr, gkoytroy@ee.duth.gr)

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

$$I_i < I_{irated} \quad (1)$$

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: distribution networks are characterized by a design short-circuit capacity, i.e. a maximum fault current never to be exceeded, related to the rating of switchgear and the thermal and mechanical endurance of all equipment and standardized constructions [8]. Hence, a basic requirement for permitting the interconnection of DG is to insure that the resulting SCL remains below the network design value (SCL_{rated}). The SCL is highest at the medium voltage busbars of the infeeding substation, (SCL_{max}). The following relation gives the constraint:

$$SCL_{\max} < SCL_{rated} \quad (2)$$

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 [2], [9]. 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:

$$\left| \varepsilon_i \% = \frac{U_i - U_T}{U_{mean}} \times 100 \right| \le \left| \varepsilon_{\max} \% \right| \quad i \forall N \quad (3)$$

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, ε_{max} is the permissible voltage variation and N is the number of buses. The constraint is usually examined for the minimum load conditions, as this is the worst-case scenario for voltage rise.

III. Network Data And Existing Situation

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 25MVA, 150/20kV 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 95mm^2 ACSR conductors but there are also many lateral branches consisting of 16mm^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 11.5MW are connected in four network positions (P6, P19, P29 and P31). All these 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 110A (or equally about 4MVA). Analytical data for all the network components are given in Table I.

Taking into account that the total DG penetration is 11.52MW or about 11.52/0.95=12.12MVA and that the minimum network load is about 20A or equally 0.706MVA, their difference is about 11.5MVA, which is smaller than the substation rating (25MVA). There is no DG penetration in the other feeders stemming from the 25MVA substation, so the second constraint of section II (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 by using the NEPLAN software package. Especially for the SCL computation the IEC60909 [10]-[12] 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 II is not breached, [7]. From the same analysis the permissible voltage drop (-3%) is not exceeded for minimum load but it is exceeded (it is over -5% in several buses) for maximum load, without DG penetration, as the cells in dark gray scale in the seventh column of Table II show. This is because the network has many branches consisting of 16mm^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 gray scale in the third column of Table II show. The problem is significant at the route P4-P8, P9 and taking into account that the fourth constraint (voltage variation constraint) of section II 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 seventh and eighth columns of Table II shows.

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

Two alternative proposals were examined in [7] in order to solve the above-mentioned voltage rise problem for minimum load:

- First proposal: connection of the DG units of the PPC Renewables S.A. to the bus P24 instead of the bus P6. This connection can be realized via an existing line with an ACSR 95mm^2 conductor and 7km in length.

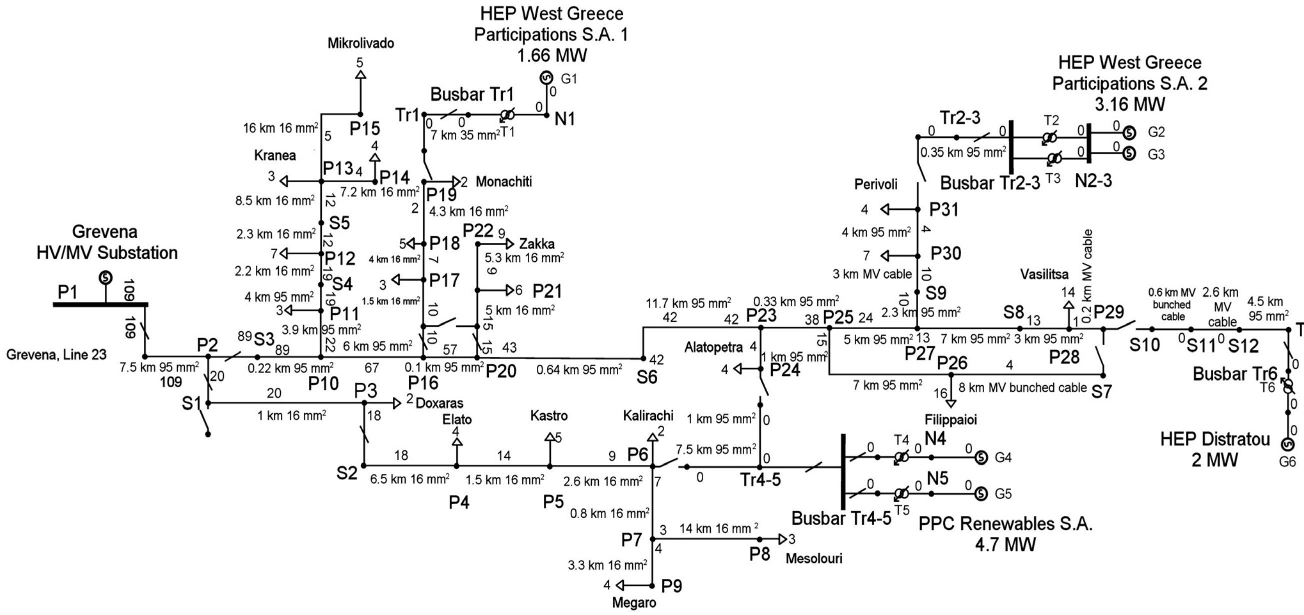

Fig. 1. Network Diagram

TABLE I
NETWORK DATA

Network Feeder Q	Network Transformer
U_{nQ}=150kV, SCL_Q=197MVA, R_Q/X_Q=0.1	SCL_{rated} =250MVA, S_{rT}=25MVA, t_r=150/20kV, U_{Tmax}=21.4kV, U_{Tmin} =20.4kV, U_{mean}≈21kV
HEP West Greece Participations S.A. 1, 1.66 MW	
Generator G1	Synchronous, PELTON, P_{rG1}=1.66MW, U_{rG1}=660V, x''_{d1}=0.131 p.u., x_{d1}=2.39 p.u., $cos\varphi_{rG1}$=0.95 (inductive)
Transformer T1	S_{rT1}=2MVA, t_{rT1}=20/0.66kV, u_{krT1}=5.66%, u_{RrT1}=1%
HEP West Greece Participations S.A. 2, 2 × 1.58MW	
Generators (G2, G3)	Synchronous, PELTON, P_{rG2-3}=1.58MW, U_{rG2-3}=660V, x''_{d2-3} =0.133 p.u., x_{d2-3}=2.4 p.u., $cos\varphi_{rG2-3}$ =0.95 (inductive)
Transformers T2,T3	S_{rT2-3}=2MVA, t_{rT2-3}=20/0.66kV, u_{krT2-3} =6.25%, u_{RrT2-3}=1%
PPC Renewables S.A., 1.5MW + 3.2MW	
Generator G4	Synchronous, PELTON, P_{rG4}=1.5MW, U_{rG4}=660V, x''_{d4}=0.14p.u., x_{d4}=1.5 p.u., $cos\varphi_{rG4}$ =0.95 (inductive)
Generator G5	Synchronous, FRANCIS, P_{rG5}=3.2MW, U_{rG5}=6.3kV, x''_{d5}=0.23p.u., x_{d5}=2.5 p.u., $cos\varphi_{rG5}$=0.95 (inductive)
Transformer T4	S_{rT4}=2MVA, t_{rT4}=20/0.66kV, u_{krT4}=6.0%, u_{RrT4}=1%
Transformer T5	S_{rT5}=4MVA, t_{rT5}=20/6.3kV, u_{krT5}=6.0%, u_{RrT5}=1%
HEP Distratou, 2MW	
Generator G6	Synchronous, P_{rG6}=2MW, U_{rG6}=690V, x''_{d6}=0.133p.u., x'_{d6}=0.24p.u., x_{d6}=1.77 p.u., $cos\varphi_{rG6}$=1
Transformer T6	S_{rT6}=2MVA, t_{rT6} =20/0.69kV, u_{krT6}=5.0%, u_{RrT6}=1%
Medium Voltage Lines	
Overhead lines	ACSR 16mm^2: $R_{L20°C}$=1.098 Ω/ km, X_L=0.393 Ω/ km, I_{rated}=127 A
	ACSR 35mm^2: $R_{L20°C}$=0.52 Ω/ km, X_L=0.369 Ω/ km, I_{rated}=197 A
	ACSR 95mm^2: $R_{L20°C}$=0.192 Ω/ km, X_L=0.336 Ω/ km, I_{rated}=400 A
	Bunched cable 3×150mm^2: $R_{L20°C}$=0.2375 Ω/ km, X_L=0.125 Ω/ km, I_{rated}=280 A
Underground cable	XLPE (3×240+25)mm^2: $R_{L20°C}$=0.127 Ω/ km, X_L=0.115 Ω/ km, I_{rated}=410 A
Additional data	
Minimum Network Load: 20 A, Maximum Network Load: 110 A, Load power factor: cosφ=0.9, inductive, Permissible voltage variation: ε_{max}% =±3%	

- Second proposal: conductor replacement at the route P2-P6 with ACSR 95mm^2 conductors (about 12km). The implementation of this proposal gives to the route P2-P6 the possibility of supplying increased loads.

Table II shows the voltage variation for minimum and maximum load and Table III the maximum network short-circuit level for the entire network situations mentioned above, according to the DG penetration.

TABLE II
VOLTAGE VARIATION

Bus	Voltage Variation ε_i% for Minimum Load					Voltage Variation ε_i% for Maximum Load				
	Without DG	With DG-existing situation	With DG-first proposal	With DG-second proposal	Optimum DG penetration	Without DG	With DG-existing situation	With DG-first proposal	With DG-second proposal	Optimum DG penetration
P1	0.00	0.00	0.00	0.00	0	0.00	0.00	0.00	0.00	0.00
P2	-0.43	-0.03	-0.62	0.06	-1.37	-2.31	-1.57	-1.97	-1.48	-2.82
P3	-0.48	0.77	-0.66	0.08	-1.22	-3.65	-0.94	-2.16	-1.50	-2.84
P4	-0.67	6.19	-0.88	0.28	-0.22	-3.86	3.46	-3.30	-1.54	-2.83
P5	-0.71	7.49	-0.91	0.33	0.02	-4.09	4.57	-3.51	-1.52	-2.77
P6	-0.76	9.80	-0.96	0.45	0.47	-4.15	6.64	-3.74	-1.45	-2.53
P7	-0.76	9.80	-0.97	0.44	0.46	-4.56	6.59	-3.79	-1.51	-2.59
P8	-0.86	9.72	-1.05	0.37	0.38	-4.27	6.22	-4.21	-1.91	-3.00
P9	-0.81	9.78	-1.00	0.42	0.43	-2.37	6.47	-3.92	-1.63	-2.72
P10	-0.43	-0.02	-0.63	0.07	-1.40	-2.60	-1.60	-2.01	-1.52	-2.89
P11	-0.48	-0.07	-0.68	0.02	-1.44	-3.22	-1.83	-2.24	-1.75	-3.12
P12	-0.57	-0.18	-0.79	-0.09	-1.56	-4.50	-2.44	-2.86	-2.36	-3.74
P13	-0.81	-0.42	-1.03	-0.33	-1.81	-4.78	-3.71	-4.13	-3.62	-5.03
P14	-0.90	-0.47	-1.08	-0.38	-1.87	-5.30	-3.99	-4.41	-3.90	-5.31
P15	-1.00	-0.57	-1.18	-0.48	-1.97	-3.51	-4.51	-4.94	-4.43	-5.84
P16	-0.67	0.28	-0.54	0.37	-1.95	-3.67	-2.21	-2.71	-2.12	-4.20
P17	-0.67	0.76	-0.06	0.85	-1.43	-3.95	-2.35	-2.85	-2.27	-3.83
P18	-0.71	2.06	1.25	2.15	0.00	-4.03	-2.62	-3.12	-2.54	-2.71
P19	-0.76	3.51	2.71	3.60	1.60	-2.37	-2.71	-3.21	-2.62	-1.29
P20	-0.67	0.29	-0.54	0.38	-1.96	-3.54	-2.22	-2.71	-2.13	-4.22
P21	-0.81	0.15	-0.68	0.24	-2.10	-4.28	-2.94	-3.44	-2.86	-4.96
P22	-0.86	0.06	-0.77	0.15	-2.19	-4.75	-3.41	-3.91	-3.32	-5.44
P23	-0.95	1.13	0.63	1.22	-2.16	-5.07	-2.50	-2.61	-2.41	-5.51
P24	-0.95	1.13	0.70	1.22	-2.16	-5.08	-2.51	-2.56	-2.43	-5.52
P25	-0.95	1.16	0.66	1.25	-2.15	-5.11	-2.50	-2.61	-2.42	-5.52
P26	-1.00	1.10	0.60	1.20	-2.21	-5.42	-2.80	-2.91	-2.71	-5.83
P27	-1.00	1.64	1.14	1.73	-1.82	-5.45	-2.29	-2.40	-2.20	-5.46
P28	-1.10	2.34	1.85	2.43	-1.39	-5.84	-1.91	-2.01	-1.82	-5.33
P29	-1.10	2.35	1.86	2.44	-1.38	-5.84	-1.89	-2.01	-1.80	-5.31
P30	-1.05	1.89	1.39	1.98	-1.42	-5.57	-2.15	-2.25	-2.06	-5.18
P31	-1.05	2.05	1.55	2.14	-1.15	-5.61	-2.02	-2.13	-1.93	-4.96
S01	-0.43	-0.03	-0.62	0.06	-1.37	-2.31	-1.57	-1.97	-1.48	-2.82
S02	-0.48	0.77	-0.66	0.08	-1.22	-2.51	-0.94	-2.16	-1.50	-2.84
S03	-0.43	-0.03	-0.62	0.06	-1.37	-2.32	-1.57	-1.97	-1.48	-2.82
S04	-0.52	-0.10	-0.71	-0.01	-1.48	-2.81	-2.03	-2.44	-1.95	-3.33
S05	-0.67	-0.23	-0.84	-0.14	-1.61	-3.49	-2.71	-3.13	-2.63	-4.01
S06	-0.67	0.32	-0.51	0.41	-2.00	-3.62	-2.23	-2.73	-2.15	-4.31
S07	-1.00	1.10	0.60	1.20	-2.21	-5.42	-2.8	-2.91	-2.71	-5.83
S08	-1.05	2.13	1.63	2.22	-1.53	-5.72	-2.02	-2.13	-1.94	-5.39
S09	-1.00	1.72	1.22	1.81	-1.70	-5.52	-2.27	-2.37	-2.18	-5.41
S10	-1.10	2.35	1.86	2.44	-1.38	-5.84	-1.89	-2.00	-1.80	-5.31
S11	-1.10	2.41	1.92	2.50	-1.38	-5.84	-1.83	-1.94	-1.74	-5.31
S12	-1.10	2.56	2.06	2.65	-1.38	-5.84	-1.69	-1.80	-1.61	-5.31

TABLE III
MAXIMUM SHORT-CIRCUIT LEVEL

SCL_{max} (MVA)				
Without DG	With DG-existing situation	With DG-first proposal	With DG-second proposal	Optimum DG penetration
197	229	225.7	231.55	224.784

There is no problem according to SCL_{max} (SCL constraint), as Table III shows.

From the results of Table II it is obvious that both the proposals solve the voltage rise problem for minimum load. In addition, the first proposal improves significantly the voltage drop problem for maximum load whilst the second proposal solves it almost comprehensively. The selection of one of them is a matter of economic evaluation, possibility of implementation and general Public Power Corporation (PPC) policy.

IV. Optimization Process

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

Specifically, the authors of [2] examine all the technical constraints given in section II 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 (4) may give an approximate estimation:

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

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 (4) for different load power factors has proved that the divergence between these approximate values and the accurate current values is not significant. Therefore (4) can be used as a first test for the satisfaction of the thermal constraint. In any case, power flow analysis must follow 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, [2]:

$$\sum_{j=1}^{N} \delta_{jTx} P_{EGj} + \alpha_{Tx} \le SCL_{rated} \quad (5)$$

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

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 (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 95mm^2 ACSR line, which restricts the maximum DG penetration to 13.6MVA. The total DG penetration is realized by connecting step by step to each bus identical DG units of a particular type. Specifically, they are synchronous generators with the data: P_{rG}=0.85MW, U_{rG}=690V, x''_d=0.129 p.u., x_d=1.9 p.u. and $cos\varphi_{rG}$=0.95 (inductive). Each DG unit is connected to a bus via a transformer with the data: S_{rT}=1MVA, t_{rT} =20/0.69kV, u_{krT}=6.0%, u_{RrT}=1%.

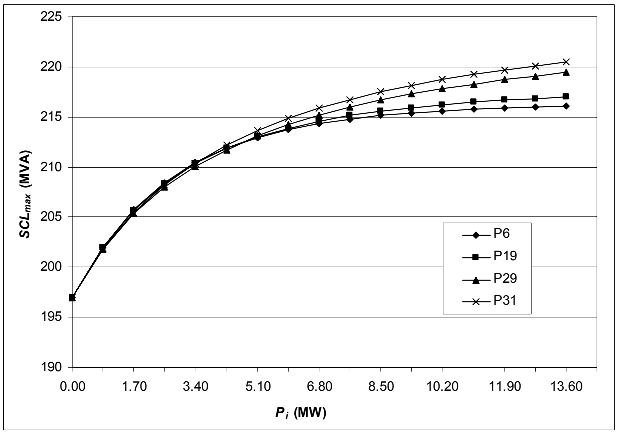

Fig. 2. SCL_{max} versus power injections at individual buses.

The voltage variation constraint may be formalized into algebraic equations, giving the U_i of (3) for each bus [2]:

$$\mu_i P_{EGi} + \beta_i + \sum_{j=1}^{N} \mu_{ji} P_{EGj} = U_i \quad i \forall N, \quad i \ne j \quad (6)$$

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.

The dependence of the voltage *Ui* at each bus on power injections at the buses P6, P19, P29 and P31, for minimum load, was calculated, resulting in a graph for each bus. The graph for bus P29 is shown in Fig. 3. The values for μ_{29} and μ_{j29} (kV/MW) in (6) are determined from this graph. The data for the DG units and their connective lines are the same as in Fig. 2. 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 (95mm^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 (16mm^2 ACSR conductors) and therefore they can accept a smaller DG penetration because of the voltage variation constraint.

From the graphs of Fig. 3 and the other related graphs it is obvious 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.

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:

$$J = Max\sum_{i=1}^{N} P_{EGi} \tag{7}$$

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

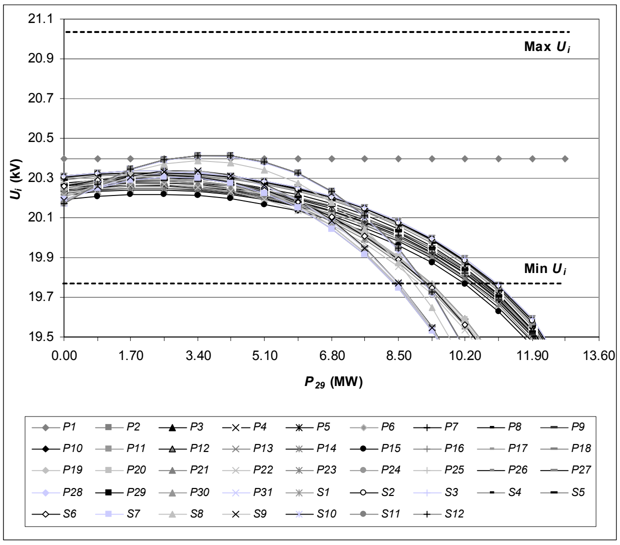

Fig. 3. Dependence of the voltage U_i at each bus on power injections at bus P29, for minimum load.

From the curves of Fig. 2 and Fig. 3 it is obvious that the basic criterion for the determination of the optimum DG penetration in the selected buses 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 (7) subject to the technical constraints (4), (5) and (6), it is necessary to determine, as accurately as possible, the coefficients δ_{jTx}, μ_i and μ_{ji} from the relative curves. The calculation of the coefficients δ_{jTx} 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}, which constitute, as mentioned, the basic criterion for the determination of the optimum DG penetration in the examined network. A relative investigation concerning the determination of the range of the curves which gives the final μ_i and μ_{ji} showed that this range is around the maximum value of the voltage curve for each examined bus (about 4.5 MW for the bus P29, according to Fig. 3). The selection of the above range is absolutely justified by the fact that a maximum DG penetration, subject to the acceptable voltage rise constraint, is revealed.

Taking into account the above finding, first the coefficients δ_{jTx}, μ_i and μ_{ji} were calculated and then (7), subject to constraints (4), (5) and (6), 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 DG penetration for the selected buses is given in Table IV.

TABLE IV
OPTIMUM DISTRIBUTED GENERATION PENETRATION INTO THE BUSES P6, P19, P29 AND P31

Bus	P6	P19	P29	P31	Total
DG Penetration (MW)	0.85	1.7	4.25	5.1	11.9

The resulting total DG penetration is a little higher and its distribution at the selected buses is quite different from the existing one. There is an almost equal DG capacity interconnected with the buses P29 and P31. As mentioned above, these buses present a great similarity and the resulting 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 penetration, for minimum and maximum load, is shown in the sixth and eleventh columns of Table II 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, without DG. If an improvement of the network voltage profile in the last case is desirable, then a new network study giving new voltage curves and coefficients μ_i and μ_{ji} for maximum load is necessary, in order to meet the voltage drop constraint.

With regard to SCL_{max}, it remains smaller than SCL_{rated} for the determined optimum DG penetration, as the last column of Table III shows.

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 *Ui* at each bus on power injections at the bus P20, for minimum load, is shown in Fig. 4. The corresponding graphs for the buses P10 and P24 are similar. All these graphs show that the DG penetration in these buses leads almost exclusively to voltage rise. Only in cases of high DG penetration is there a voltage drop.

The results of the optimum DG penetration investigation in this case with and without the thermal constraint are shown in Table V. 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 (538A, 540A, 542A and 544A correspondingly). The second line of Table V shows the DG distribution when the thermal constraint is additionally taken into account. The total DG capacity is smaller and the SCL_{max},, which is equal to 249.892MVA, remains marginally smaller than the SCL_{rated}. By comparison of the results given in the two lines of Table V it is clear that the thermal constraint determines the final DG allocation for this group of buses.

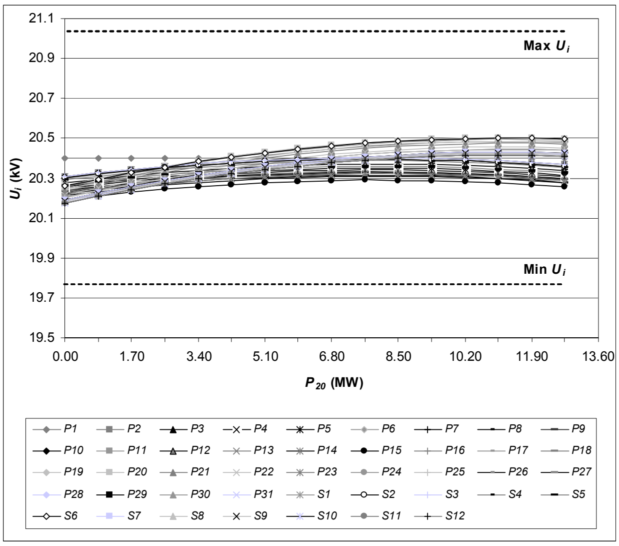

Fig. 4. Dependence of the voltage U_i at each bus on power injections at bus P20, for minimum load.

TABLE V
OPTIMUM DISTRIBUTED GENERATION PENETRATION INTO THE BUSES P6, P10, P19, P20 AND P24

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

In general the DG penetration is higher when the prospective buses are not predetermined but the entire network buses are possible DG locations, as a relative investigation proves. The solution procedure becomes more laborious and time-consuming in this case, because a large number of graphs, like those of Fig. 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. 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 (5) and (6). With this approximation the optimum DG penetration can be determined with sufficient accuracy only for 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 and 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.

V. CONCLUSIONS AND FUTURE WORK

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 in a medium voltage power distribution network. Technical constraints such as thermal current, transformer capacity, voltage profile and short-circuit level are taken into account. The arising problems are solved by changing the network structure. Then, an already known method is exploited but with suitable modifications, remarks and extensions, in order to determine an optimum distribution of the maximum penetration of particular type DG units in accidentally selected network buses, without changing the network structure. Although the applied method gives satisfactory results for small distribution networks, it is laborious and time-consuming for networks with many buses. It also adopts some simplifications, which in some cases may lead to wrong results or perhaps to failure in thinking out a solution. Therefore the development of a new, more accurate, fast and flexible method, working for every size of distribution network, and giving a solution for the optimum DG allocation without fail, is necessary.

The used methodology determines the optimal DG allocation without considering commercial factors such as cost of the DG units, installation charges, operating costs, revenue expectations, cost of losses, redesign cost of the protection system, etc. It is not easy to integrate all these factors into the applied methodology. Therefore, further research is required regarding the analysis of the impact of DG on the economic operation of distribution systems. In addition it has been assumed that all the generators are synchronous generators with particular data. A mix of generator technologies could alter some of the constraint characteristics and this also requires further research.

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VII. Biographies

George N. Koutroumpezis received both his Dipl.-Eng. degree and his M.Sc. degree from the Electrical and Computer Engineering Department of the Democritus University of Thrace, Greece, in 2002 and 2004, respectively. He is currently working towards his Ph.D. in the Power Systems Laboratory of the same Department. His research interests include power systems planning and distributed generation.

Anastasia S. Safigianni (M' 1997) received her Dipl.-Eng. degree and Ph.D. degree from the Electrical Engineering Department of the Democritus University of Thrace, Greece, in 1981 and 1988 correspondingly. She is currently Associate Professor in the Electrical and Computer Engineering Department of the Democritus University of Thrace, Greece. Her teaching interests include power systems and electrical installations. Her research interests include short-circuit losses and forces in metal enclosed arrangements, power systems planning and optimization, lighting systems, influence of extra low frequencies electric and magnetic fields on human being and distributed generation.