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Observing the performance of distribution systems with embedded generators

Rade M. Ciric[1], Antonio Padilha-Feltrin[2,*,†] and Iara Fernanda E. D. Denis[2]

[1]*University of the West of England—Bristol, Frenchay Campus, Coldharbour Lane, Bristol BS16 1QY, U.K.*
[2]*Department of Electrical Engineering, Universidade Estadual Paulista—Campus de Ilha Solteira, Av. Brazil 56, P.O. Box 31, 15385-000 Ilha Solteira-SP, Brazil*

SUMMARY

In this paper, a multi-objective approach for observing the performance of distribution systems with embedded generators in the steady state, based on heuristic and power system analysis, is proposed. The proposed hybrid performance index describes the quality of the operating state in each considered distribution network configuration. In order to represent the system state, the loss allocation in the distribution systems, based on the Z-bus loss allocation method and compensation-based power flow algorithm, is determined. Also, an investigation of the impact of the integration of embedded generators on the overall performance of the distribution systems in the steady state, is performed. Results obtained from several case studies are presented and discussed. Copyright © 2004 John Wiley & Sons, Ltd.

KEY WORDS: distribution networks; dispersed generators; distribution management system; performance indices

1. INTRODUCTION

Various investigations conducted by industry and research institutions have shown that embedded generators (EGs) could affect the host distribution networks (DNs) in a number of ways [1–13]. One of the interesting issues about EGs in the de-regulated power energy market is the question of optimal, or rather 'the best feasible', placement of the EGs in the DNs. Another important issue is the distribution management system (DMS) in the presence of the EGs. Since the DNs with embedded generators are not passive, all issues about the DNs planning, building, maintainance and operation become very interesting and need a re-investigation. Previous experience has shown that the integration of EGs into DNs could create safety and technical problems. They may contribute to fault currents, cause voltage flickers, interfere with the process of voltage control, increase losses, etc. Actually, the overall model

*Correspondence to: Antonio Padilha-Feltrin, Department of Electrical Engineering, Universidade Estadual Paulista—Campus de Ilha Solteira, Av. Brazil 56, P.O. Box 31, 15385-000 Ilha Solteira-SP, Brazil.
†E-mail: padilha@dee.feis.unesp.br

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of the DNs should be reconsidered, since the impact of EGs on the DNs planning and operation is significant [8,11,13,14].

In this paper, a tool for observing performances of the distribution system with EGs in the steady state, based on heuristic and power system analysis, is proposed. Also, loss allocation in the distribution systems with EGs based on the Z-bus loss allocation method [12] and compensation-based power flow algorithm [15,16], is determined. An investigation of the impact of the integration of EGs on the overall distribution system performance in the steady state, is performed. Results obtained from several case studies using an IEEE 34 node test network, are presented and discussed.

2. PROBLEM DEFINITION

The distribution management system (DMS) power applications such as state estimation, power flow calculation, network reconfiguration, supply restoration, short circuits analysis, relay setting, Q–U regulation etc. are significantly affected by the EGs in the distribution system. Most of the DMS applications should be reconsidered and probably modified in order to properly respect the presence of the EGs in the DN [14]. For example, the presence of EGs in the DN will improve the quality of state estimation in the DN, since the voltages in the PV nodes are known. Power flow calculation is of course affected by the EGs, as well as the network reconfiguration in order to minimize the power losses. Supply restoration after faults of the feeder or supply transformer, should respect the presence of the EGs in the DN as well, since alternate variants of power supply could be quite different compared to those in the passive DN. Similarly, the EGs affect the node voltages and reactive power flow in the DNs and consequently Q–U regulation should be reconsidered as well. Obviously, the greatest changes are happening in the DN expansion planning and operation. The main question is: '*Where is the best place to install the EG?*' When the EGs are installed, the next question is: '*What is the best way to operate the DN with the EGs?*' The determining optimal operating state in the DN with EGs is the combinatorial, non-linear, large-scale optimization problem with constraints. The aim of this research is not to find the optimal problem solution but to develop a tool for observing the system performances in the DN with EGs and to help the engineers to answer these questions.

Another interesting issue about EGs in the de-regulated power energy market is the loss allocation to the loads and EGs in the DN. Although the loss allocation issue is naturally more addressed to the transmission systems, after introducing EGs and open access distribution networks in the last decade, the distribution system loss allocation is becoming a more interesting problem. Moreover, in the de-regulated power industry, loss allocation in the DNs is becoming a very important issue since the losses in the medium-voltage distribution networks are in the range of 2–5%, while the losses in the low-voltage network sometimes exceed 10–15%. The main difficulty in allocating losses, regardless of the approach, is that the final allocation always contains a degree of arbitrariness [12,13]. This is the consequence of the fact that distribution system losses are non-linear functions of the node injections.

In the proposed multi-objective approach for observing the performances of the DNs with EGs, the following issues are investigated: active power losses, reactive power losses, reactive power injection, voltage drop, sum of the squared voltage deviation, current balance of the feeders, as well as, current balance of the supply transformers. Finally, the hybrid index, which describes the quality of the operating state in each considered DN configuration, are calculated based on the single indices. Loss allocation in the DNs with EGs based on the Z-bus loss allocation method [12] is also determined, and the contribution of each node, load or generator, to the overall system losses is determined.

3. HANDLING PV NODES IN POWER FLOW

Since the power flow analysis is the basic tool in the proposed methodology for observing the system performance, as well as for the loss allocation procedure, in this part some issues are given about power flow techniques in the DN with EGs. If the source controls the voltage magnitude at the corresponding node, then the node is referred to as a PV node. In the last decade, different procedures for handling PV nodes have been proposed [15–19]. Special power flow methods have been developed for radial and weakly meshed network analysis. Experience shows that good results in handling PV nodes in large DNs are obtained using the backward/forward procedure, i.e. branch-orientated methods. These methods may be classified as follows: current summation methods [15,16], power summation methods [17,18] and admittance summation methods. In the proposed multi-objective approach for observing the system performance in the DNs with EGs, the compensation-based power flow method from Reference [15] is applied.

4. MODEL DESCRIPTION

The proposed multi-objective approach for observing the system performance in the distribution networks (DNs) with embedded generators (EGs) is based on the calculation of the various system indices that describe the performance of the system. Namely, after the power flow solution in the DN with EGs is determined, the following indices are calculated: active and reactive power losses, reactive power injection of the EGs, maximum voltage drop, sum of the squared voltage deviation, current balance of the feeders, as well as, current balance of the supply transformers. Finally the multi-objective system performance index is calculated which represents the system state in the DN with EGs. The above-mentioned indices of the distribution system with EGs are defined as follows [14].

4.1. Active power losses

Active power losses in the h-th DN configuration-variant of placement the EGs in the DN are defined by Equation (1):

$$ILP^h = \mathrm{Re}\left\{\sum_{i=1}^{NF}\sum_{j=1}^{NFSi} Z_{ij} I_{ij}^{h^2}\right\} \tag{1}$$

The meanings of all the symbols used are explained in the List of Symbols at the end of the paper. Equation (1) is defined as the total active power losses in the DN. Lower values of the index ILP^h indicate lower active power losses, meaning better system performance.

4.2. Reactive power losses

Reactive power losses in the h-th configuration are defined by Equation (2):

$$ILQ^h = \mathrm{Im}\left\{\sum_{i=1}^{NF}\sum_{j=1}^{NFSi} Z_{ij} I_{ij}^{h^2}\right\} \tag{2}$$

Equation (2) is defined as the total reactive power losses in the DN. Lower values of the index ILQ^h indicate lower reactive power losses, meaning better system performance.

4.3. *Reactive power injection*

Reactive power injection in the *h*-th configuration is defined by Equation (3):

$$IQ^h = \frac{\sum_{k=1}^{NG} Q^h_{\text{gen } k}}{\sum_{k=1}^{NG} Q_{\text{gen max } k}} \tag{3}$$

Index IQ^h is defined as the relative value of the total reactive power injection of the EGs in the DN. Lower values of the index IQ^h indicate a smaller need for reactive power generation in the system meaning smaller losses in the capacitors.

4.4. *Critical voltage drop*

The critical voltage drop in the *h*-th configuration is defined by Equation (4):

$$IU^h = \max_{\substack{i=1,NF \\ k=1,NFTi}} \left(\frac{U^h_r - U^h_{ik}}{U^h_r} \right) \tag{4}$$

Equation (4) is defined as the value of the maximal relative voltage drop between the root node and one of the distribution transformers. Lower values of the index IU^h indicate a lower voltage drop, meaning a higher quality voltage profile.

4.5. *Sum of the squared voltage deviation*

The sum of the squared voltage deviation in the *h*-th configuration is defined by Equation (5):

$$IUD^h = \sum_{k=1}^{N} \left(U^h_r - U^h_k \right)^2 \tag{5}$$

Equation (5) is defined as the sum of the squared voltage deviation between the root node and one of the distribution transformers. Lower values of the index IUD^h indicate a higher quality voltage profile.

4.6. *Critical current reserve of the feeders*

The critical current reserve of the feeders in the *h*-th configuration is defined by Equation (6):

$$IJ^h = \frac{1}{\min\limits_{\substack{i=1,NF \\ j=1,NFSi}} \left(\frac{I^r_{ij} - I^h_{ij}}{I^r_{ij}} \right)} \tag{6}$$

Equation (6) is defined as the reciprocal value of the minimal relative values of the margin between the rated and actual current of the feeder. Lower values of the index IJ^h indicate greater current reserve in the feeders, meaning higher security in the operating state.

4.7. Critical current reserve of the supply transformers

The critical current reserve of the supply transformers in the h-th configuration is defined by Equation (7):

$$IS^h = \frac{1}{\min\limits_{i=1,NTS} \left(\frac{I^r_{TSi} - I^h_{TSi}}{I^r_{TSi}} \right)} \tag{7}$$

Equation (7) is defined as the reciprocal value of the minimal relative values of the margin between the nominal and actual current of the supply transformer. Lower values of the index IS^h indicate greater current reserve in the supply transformers, meaning higher security in the operating state.

4.8. Multi-objective indices

Multi-objective indices in the h-th DN configuration are calculated as follows:

$$IM^h = w_q ILP^h + w_2 ILQ^h + w_3 IQ^h + w_4 IU^h + w_3 IUD^h + w_6 IJ^h + w_7 IS^h \tag{8}$$

$$\sum_{i=1}^{7} w_i = 1 \tag{9}$$

where w_i, $i = 1, 7$ are the heuristic weighting factors (the weight of the i-th objective).

The multi-objective, hybrid performance indices IM^h describe the quality of the operating state in each considered DN configuration-variant of placement of the EGs, h. Usually the problem with the weighted sum approach is the difficulty in determining suitable weights. Weighting factors in the performed research are obtained by experienced planning and operation engineers. The values of the heuristic weighting factors w_i are shown in Table I. The objective of the eventual optimization procedure performed by the dispatcher, is to get a minimum value of the multi-objective indice. Lower values of IM^h indicate a better voltage profile, smaller losses, greater current reserve in the supply transformers, greater current reserve in the feeders, meaning better overall performance and higher security in the distribution system with EGs. The proposed multi-objective approach enables the dispatching staff in the distribution companies to adapt the model according to their range list of priorities, simply setting the values of the weighting factors w_i.

Table I. Heuristic weighting factors in the multi-objective indice.

w_i	Operating regimes		Type of network	
	Normal state	Emergency state	Urban network	Rural network
w_1	0.30	0.00	0.15	0.10
w_2	0.20	0.00	0.05	0.10
w_3	0.05	0.10	0.05	0.10
w_4	0.05	0.25	0.05	0.25
w_5	0.20	0.05	0.10	0.25
w_6	0.15	0.30	0.30	0.10
w_7	0.05	0.30	0.30	0.10

5. LOSS ALLOCATION PROCEDURE

In order to observe losses in the DN with EGs, the Z-bus loss allocation method from Reference [12] is applied. The idea of the Z-bus loss allocation method is to obtain the power flow solution and systematically distribute the system losses, P_{loss}, among the N network nodes according to Equation (10):

$$P_{\text{loss}} = \sum_{k=1}^{N} L_k \tag{10}$$

The loss component, L_k, in Equation (10) is the fraction of the system losses allocated to the net real power injection in the node k and can be expressed by Equation (11) [12]:

$$L_k = \text{Re}\left\{ \underline{I}_k^* \left(\sum_{j=1}^{N} R_{kj} \underline{I}_j \right) \right\} \tag{11}$$

The loss component, L_k, in Equation (11) encompasses N terms representing the coupling actions between current injections at all N nodes with the current injection at node k. The dependence of the loss terms on currents rather than power injections is intuitively reasonable. The requirement of the Z-bus loss allocation method that the Y_{bus} matrix of the system be non-singular is met in most of the medium-voltage distribution networks. Namely, medium-voltage distribution lines 20 kV, 24.9 kV, 33 kV, 35 kV and higher rated voltages always have shunt capacitance to the ground. The natural separation of the system losses is based on a power flow solution and the exact network equations. One characteristic of the Z-bus method is the possibility of negative loss allocations. Negative allocation provided monetary incentives to those EGs ‘well’ positioned in the network. On the other hand, EGs and loads ‘poorly’ placed, receive higher loss allocations. If the node has neither load nor generation then the loss allocation is zero. Since in the DN power flow calculations losses are deemed to be supplied from the transmission network that is taken as a slack node, the loss-related charge for this node is zero. In other words, total power losses in the DN are insensitive to changes in active and reactive injections at the slack node [13].

The applied Z-bus loss allocation method is equally efficient in radial and weakly-meshed DN configurations. In this research the compensation-based power flow method from Reference [15] is applied. However, any method that efficiently solves the power flow in the DN with EGs and loops can be applied in the Z-bus loss allocation method.

6. APPLICATIONS

In this part practical aspects of the proposed methodology for observing the performance of distribution systems with EGs are presented. The test network, various case studies, system performance indices and the result of Z-bus loss allocation are presented and discussed.

6.1. Test network

The test network used in the case studies is the IEEE 34 node distribution network (DN) [20] Figure 1. Network data (line resistance r, reactance x, susceptance g, conductance b) are in the file NETWORK

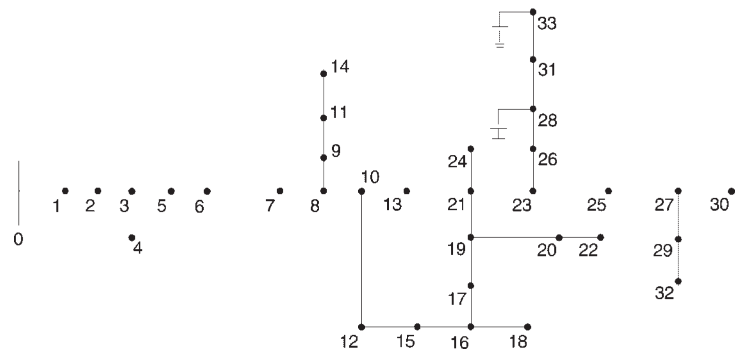

Figure 1. IEEE 34-bus MV test distribution network.

(Table II). The base voltage of the network was $V_b = 24.9\,\text{kV}$, and the reference voltage in the root node in all cases was $V_{ref} = 1.03\,\text{p.u.} = 25.647\,\text{kV}$. The base apparent power was $S_b = 1\,\text{MVA}$. Simplifying the autotransformer 24.9/4.16 kV/kV in the original IEEE 34-bus test feeder is replaced with the line and the network is modelled with the single voltage level. The automatic voltage regulator is also not represented. Active (P) and reactive (Q) load injections per unit (p.u.) are shown in the file INJECT (Table III) In Table IV the specified generator voltage module (V_{gm}), voltage phase angle ($V_{g\ \text{ph-angle}}$), generator real power injection (P_g), as well as the reactive power range (Q_{gmin}, Q_{gmax}) of the EGs in the PV nodes, are presented.

6.2. *Case studies*

Four variants of placement of the EGs in the considered DN are investigated. The proposed methodology is applied on the radial, as well as, meshed network. Loops are created in the nodes 14–15, 22–23 and 30–31 and their impact on the overall system performance is also investigated.

6.3. *System performance indices*

The multi-objective performance indices of the distribution system with already installed EGs is calculated, in the normal, as well as the emergency state, according to the weighting factors from Table I. The objective is to achieve the best distribution system performance. The most important single indices depend on the regime, as well as the type of the DN. For example, in the normal operating condition, the highest priority for the dispatching staff could have active and reactive power losses, as well as the voltage profile in the DN. However, in the emergency state, the highlighted issues are the current balance of the supply transformers, current balance of the feeders, as well as, the voltage profile. Similarly, in the heavy loaded urban DN, the balance between supply transformers and the balance between feeders could be the most important indices. On the other hand, in the rural DN with long medium-voltage distribution lines, serious problems could be the voltage profile in the DN and large voltage drop at the end consumer. Using the proposed methodology, the dispatching staff, actually a DMS decision-maker, has a deep view on the overall system performance of each DN configuration.

The results obtained by applying the proposed methodology on the test DN in the several case studies are shown in Table V. It can be seen that the best feasible variant of the EGs placement in the

Table II. File NETWORK.

i	j	r(p.u.)	x(p.u.)	g(p.u.)	b(p.u.)
0	1	2.030825E-03	8.953083E-04	9.0000E-07	9.0000E-07
1	2	1.361754E-03	6.003423E-04	1.0000E-06	6.0000E-07
2	3	2.536956E-02	1.118441E-02	2.5000E-05	1.1000E-05
3	4	4.596905E-03	2.026589E-03	1.0000E-06	2.0000E-06
3	5	2.951780E-02	1.301320E-02	2.9000E-05	1.3000E-05
5	6	2.340171E-02	1.031687E-02	2.3000E-05	1.0000E-05
6	7	7.871413E-04	3.470187E-04	0.0000E-00	0.0000E-00
7	8	2.440138E-04	1.075758E-04	0.0000E-00	0.0000E-00
8	9	1.346012E-03	5.934020E-04	1.0000E-06	5.0000E-07
8	10	8.036713E-03	3.543061E-03	8.0000E-06	3.0000E-06
9	11	3.790085E-02	1.670895E-02	3.8000E-05	1.6000E-05
10	12	6.611987E-04	2.914957E-04	6.0000E-07	2.0000E-07
10	13	2.385038E-03	1.051467E-03	2.0000E-06	1.0000E-07
11	14	1.081532E-02	4.768037E-03	1.1000E-05	4.7000E-05
12	15	1.608917E-02	7.093062E-03	1.6000E-05	7.1000E-05
15	16	4.093135E-04	1.804497E-04	0.0000E-00	0.0000E-00
16	17	2.899042E-02	1.278070E-02	2.8000E-05	1.2000E-05
16	18	1.836401E-02	8.095946E-03	1.8000E-05	8.0900E-05
17	19	7.871413E-04	3.470187E-04	0.0000E-00	0.0000E-00
19	20	3.064467E-03	6.580539E-03	3.0000E-06	6.0000E-06
19	21	3.856993E-03	1.700392E-03	3.0000E-06	1.0000E-06
20	22	8.312212E-03	3.664518E-03	8.0000E-03	3.0000E-06
21	23	4.589034E-03	2.023119E-03	4.0000E-06	2.0000E-06
21	24	1.275169E-03	5.621703E-04	1.0000E-06	5.0000E-07
23	25	1.590025E-03	7.009778E-04	1.0000E-06	1.0000E-07
23	26	2.203996E-04	9.716525E-05	1.0000E-07	1.0000E-08
25	27	2.109539E-03	9.300102E-04	2.0000E-06	1.0000E-06
26	28	1.062641E-03	4.684753E-04	1.0000E-06	4.0000E-07
27	29	2.203996E-04	9.716525E-05	2.0000E-07	1.0000E-08
27	30	6.769415E-04	2.984361E-04	6.0000E-07	3.0000E-07
28	31	2.865194E-03	1.263148E-03	3.0000E-06	1.0000E-06
29	32	2.558431E-03	1.684948E-03	2.0000E-06	1.0000E-06
31	33	4.171849E-04	1.839199E-04	4.0000E-07	1.0000E-07

considered DN, is the variant 4. In the normal operating condition, the best integral system performance has been achieved in variant 4 in the radial DN as well as in variant 3 in the meshed DN configuration. Similarly, the variant 4 enables the best integral system performances in the emergency conditions. It is obvious that the loops in the DN not only decrease the convergence speed of the distribution power flow, but also have significant impact on the overall performance indices of the system. The impact of the EGs (variant 4) on the integral distribution system performance is shown in Table VI. Three EGs in the considered DN in variant 4 significantly reduced active power losses, improved voltage profile, increased the current reserve of the feeder and supply transformer, but increased reactive power losses. Besides, installing the EGs closer to the end of the feeder significantly improved voltage profile and decreased active power losses in the DN. Total feeder current decreased by about 50% compared to the passive DN.

Table III. File INJECT (non-zero elements).

Node	*P* (p.u.)	*Q* (p.u.)
1	1.910000E-02	9.870000E-03
3	5.290000E-03	2.740000E-03
8	1.300000E-04	7.000000E-05
9	1.130000E-02	5.840000E-03
10	1.490000E-02	7.710000E-03
11	1.184000E-02	2.336000E-02
12	2.060000E-03	1.070000E-03
16	1.240000E-03	6.400000E-04
19	4.370000E-03	2.260000E-03
21	1.000000E-02	5.170000E-03
22	2.700000E-02	2.162000E-02
23	5.000000E-02	0.000000E + 00
25	4.657000E-02	2.972000E-02
26	3.040000E-03	1.570000E-03
27	1.310000E-02	6.770000E-03
28	1.490500E-01	1.490000E-02
29	9.200000E-03	4.760000E-03
30	8.859999E-03	7.090000E-03
31	7.540000E-03	3.900000E-03
33	1.945000E-02	– 1.344300E-01

Table IV. Generators data.

Generators	V_{gm} (p.u.)	V_{gm} (kV)	V_{gph} angle (rad)	P_g (p.u.)	Q_{gmin} (p.u.)	Q_{gmax} (p.u.)
1	1.012048	25.200	0.000	−0.10	−0.06	−0.008
2	1.000000	24.900	0.000	−0.10	−0.06	−0.008
3	0.995984	24.800	0.000	−0.03	−0.03	−0.004

Table V. Multi-objective performance indices *IM* in the test network.

Variant	Generator node	*IM*—Normal state		*IM*—Emergency state	
		Radial DN	Meshed DN	Radial DN	Meshed DN
1	3, 5, 6	11.14	10.30	88.45	76.23
2	3, 8, 16	8.65	8.44	52.05	50.49
3	8, 23, 27	6.22	8.14	14.97	16.74
4	23, 27, 28	6.15	10.73	7.71	8.69

6.4. Loss allocation

The proposed methodology for loss allocation is applied on the radial network, but there are no restrictions on the meshed network configurations. Loss allocation in the considered DN with three PV nodes is determined. The applied power flow algorithm usually achieved the convergence in 3 to 4 iterations in the considered radial DN, and in 15 to 20 iterations in the meshed network configuration.

Table VI. Impact of the EGs on the considered network.

Indice	Radial DN, no EGs	Radial DN with 3 EGs—variant 4
Feeder current I_1(A)	9.82	5.12
P_{loss} (kW)	21.68	4.10
Q_{loss} (kVAr)	0.21	4.44
Maximum voltage drop (%)	5.37	3.30
Sum of the squared voltage deviation	7.21	5.59
Current reserve of the feeder	1.05	1.03
Current reserve of the supply transformer	1.03	1.02
Integral indices IM	3.42	6.16

Table VII. Node voltages and loss allocation coefficients L_k in radial DN with three EGs (variant 4).

Node	V_{mk} (kV)	$V_{ph\text{-}ang\ k}$(rad)	ΔV_k(%)	L_k (kW)
0	25.647	0.000000000	0.000000	0.00000
1	25.641	−0.000416168	0.023069	0.00723
2	25.637	−0.000697185	0.035519	0.00000
3	25.578	−0.005945028	0.265945	0.02507
4	25.578	−0.005945034	0.265945	0.00000
5	25.515	−0.012090890	0.512375	0.00000
6	25.466	−0.016984330	0.705013	0.00000
7	25.464	−0.017149250	0.711454	0.00000
8	25.464	−0.017200380	0.713447	0.00171
9	25.462	−0.017176040	0.718058	0.14895
10	25.454	−0.019030440	0.751345	0.20979
11	25.442	−0.016520630	0.797826	0.15067
12	25.453	−0.019181780	0.753294	0.02930
13	25.454	−0.019030440	0.751345	0.00000
14	25.442	−0.016520910	0.797819	0.00000
15	25.442	−0.022868000	0.796264	0.00000
16	25.442	−0.022961800	0.797343	0.01981
17	25.424	−0.029610100	0.867153	0.00000
18	25.442	−0.022962610	0.797320	0.00000
19	25.424	−0.029790740	0.868990	0.08130
20	25.418	−0.029950340	0.892818	0.00000
21	25.426	−0.030699350	0.859493	0.18812
22	25.409	−0.029887470	0.924998	0.47760
23	25.200	−0.031783450	1.742888	0.00000
24	25.426	−0.030699350	0.859493	0.00000
25	25.201	−0.031786530	1.738553	0.89006
26	25.199	−0.031827390	1.744301	0.05978
27	24.900	−0.031809530	2.912620	0.00000
28	24.800	−0.032039500	3.302531	0.00000
29	24.899	−0.031809380	2.912858	0.18488
30	24.899	−0.031807380	2.913409	0.16372
31	24.802	−0.032450860	3.294008	0.14931
32	24.899	−0.031809380	2.912858	0.00000
33	24.802	−0.032510990	3.292387	1.32008
Total power loss (kW)				4.10562

The power flow solution (voltage magnitude and phase angle, voltage drop), as well as the obtained loss coefficients L_k in the radial DN, are shown in Table VII. The obtained results show that loss allocation in the DN with EGs is a complex function of the loads, network configuration, line parameters, and of the placement and size of the EGs, as well. Moreover, loss allocation coefficients vary in time, as well. In the ideal case, each half hour of the year should be associated to the set of loss allocation coefficients for all the nodes [13].

7. CONCLUSIONS

In this paper the multi-objective approach for observing the performance of the distribution system embedded generators (EGs) in the steady state, is proposed. The developed tool for observing the distribution system performance is based on heuristic and power system analysis. In order to observe the contribution of each consumer and generator node in the DN to the overall losses, the Z-bus loss allocation method [12] is applied. The impact of the integration of EGs on the overall performance of the DN is also investigated. The proposed multi-objective approach enables the dispatching staff in the distribution companies to adapt the model according to their range list of priorities, simply setting the values of the weighting factors w_i in the multi-objective indices. By performing the load estimation in the DN in each half hour, prior to calculation of the multi-objective indices, the proposed methodology can be applied on the open electricity market.

8. LIST OF SYMBOLS

h	configuration—variant of placement of the embedded generators in the DN
N	total number of network nodes (distribution transformers medium voltage/ low voltage)
NG	number of embedded generators in the DN
NTS	number of supply transformers high voltage/medium voltage in the DN
NF	number of the feeders in the DN
NFS_i	number of the sections in the i-th feeder
NFT_i	number of distribution transformers in the i-th feeder
$\underline{Z}_{ij}$	complex impedance of the j-th section of the i-th feeder
R_{kj}	real part of the element k-j of the Z_{bus} network matrix
$\underline{I}_{ij}^h$	actual complex current in the j-th section of the i-th feeder in the h-th variant
I_k	complex current injection in the node k
I_{ij}^r	thermal current in the i-th section of the j-th feeder
I_{TSi}^r	rated current of the i-th supply transformer
I_{TSi}^h	actual current magnitude in the i-th supply transformer in the h-th configuration
U_r^h	voltage magnitude at the root (source) node for the h-th configuration
U_{ik}^h	actual voltage magnitude of the k-th distribution transformer at the i-th feeder in the h-th configuration
U_k^h	actual voltage magnitude of the k-th distribution transformer in the h-th configuration
$P_{\text{g}\ k}$	real power injection of the embedded generator k
$Q_{\text{gen max}\ k}$	maximum reactive power injection of the embedded generator k
$Q_{\text{gen min}\ k}$	minimum reactive power injection of the embedded generator k

$Q^{h}_{\text{gen } k}$	actual reactive power injection of the embedded generator k in the h-th configuration
$V_{\text{gm } k}$	module of the scheduled voltage of the embedded generator k
$V_{\text{g ph-angle } k}$	phase angle of the scheduled voltage of the embedded generator k
w_i	heuristic weighting factor (the weight of the i-th objective in the multi-objective performance indice)
L_k	fraction of the system losses allocated to the net real power injection in the node k (kW)
ΔVk	voltage drop between the supply transformer and the k-th distribution transformer (%)
V_{mk}	module of the voltage at the node k (kV or p.u.)
$V_{\text{ph-ang } k}$	phase angle of the voltage at the node k (rad)
IM	multi-objective performance indice.

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AUTHORS' BIOGRAPHIES

Rade M. Ciric (born in 1962) graduated from the University of Novi Sad, Yugoslavia, in 1987; he received his M.Sc. degree from the University of Belgrade, Yugoslavia in 1992; and gained his Ph.D. from the University of Novi Sad in 2000, all in electrical engineering. He has been with the Electric Power Industry of Serbia—Elektrovojvodina Novi Sad, from 1987 to 2002. Between 1997 and 2001 he was also Associate Researcher in the Group for Distribution Management System at the Faculty of Engineering, University of Novi Sad. Between 2001 and 2002 Dr Ciric was a Post-Doctoral Researcher at UNESP Ilha Solteira, SP, Brazil. Dr Ciric is currently a Visiting Professor at the University of the West of England, Bristol, U.K. His research interests include all aspects of distribution system analysis, DMS, power quality, dispersed generation and utilization of modern techniques and applications in distribution systems (AI).

Antonio Padilha-Feltrin (born in 1956) obtained the B.Sc. degree from EFEI, and the M.Sc. and Ph.D. from UNICAMP, Brazil. He is currently an Associate Professor at UNESP-Ilha Solteira, Brazil. From 1995 to 1997 he was a Visiting Professor at the ECE Department of the University of Wisconsin-Madison. His main interests are in analysis and control of power systems.

Iara Fernanda Ehrenberg Dossi Denis (born in 1973) obtained the B.Sc. degree from EE LINS, and the M.Sc. and Ph.D. from UNESP-Ilha Solteira, Brazil.

