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Evaluating Distributed Generation Impacts with a Multiobjective Index

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Abstract—**Evaluating the technical impacts associated with connecting distributed generation to distribution networks is a complex activity requiring a wide range of network operational and security effects to be qualified and quantified. One means of dealing with such complexity is through the use of indices that indicate the benefit or otherwise of connections at a given location and which could be used to shape the nature of the contract between the utility and distributed generator. This paper presents a multiobjective performance index for distribution networks with distributed generation which considers a wide range of technical issues. Distributed generation is extensively located and sized within the IEEE-34 test network, wherein the multiobjective performance index is computed for each configuration. Results are presented and discussed.**

Index Terms-- **Distribution networks, distributed generation, multiobjective analysis.**

I. INTRODUCTION

DISTRIBUTED generation (DG) is expected to play an increasingly important role in the electric power system infrastructure and market. Defined as the development of a set of sources of electric power connected to the distribution network or the customer side of the meter [1], DG technologies include photovoltaic, wind turbines, internal combustion engines, combustion turbines, microturbines and fuel cells, among others. Integration of DG in distribution networks may create technical and safety problems [2]-[8]. Depending on its location, DG may increase fault currents, cause voltage oscillations, interfere in voltage control processes, diminish or increase losses, etc.

Distribution networks with DG are not longer passive, therefore all questions about planning, maintenance and operation become more interesting and demand re-assessment. Thus, main issues include where to locate and how to operate DG to minimize the impact on distribution management. Additionally, it will be necessary to investigate whether DG capability and placement could be used to enhance distribution networks planning and operation [8]-[16]. Consequently, it is critical to assess the technical impacts of DG in power systems, in order to apply generators in a manner that avoids causing degradation of power quality and reliability.

In this work, the technical impacts on medium voltage level reliability and power quality will be assessed based on a steady-state analysis and the application of distribution network impact indices. Then, in order to calculate the multiobjective performance index by relating the different technical issues, relevance (weighting) factors are presented.

Though in practice, distribution engineers present some limitations in determining DG location, the existence of an index based on technical impacts indicates where DG could be more beneficial for the distribution network, i.e. for the electric utility, helping distribution engineers take decisions and even shape the nature of the contract that might be established between the network operator and the distributed generator owner.

This paper is structured as follows: section II presents the distribution network impact indices to be considered in the proposed methodology, section III lays out the multiobjective performance index, in section IV the IEEE-34 test network is described. Finally, in section V results obtained with the multiobjective performance index are analyzed and discussed.

II. DISTRIBUTION NETWORK IMPACT INDICES

There are various technical issues that need to be addressed when considering the presence of generators in distribution networks. Reference [18] presented an approach aimed at quantifying the benefits of DG such as voltage profile, line-loss reduction and environmental impact reduction. However, that proposal disregards technical issues that could measure the negative impacts of DG, thus showing that some potentially beneficial connection points present various drawbacks. In this work, several indices will be computed in order to describe the impacts on the network due to the presence of distributed generation during maximum power generation. Maximum network demand will be used in all indices, including that related to voltage regulation which

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will also use minimum demand to fully capture the voltage variation between both load scenarios. Since distribution networks are inherently unbalanced due to loads characteristics and topology, the indices will consider phases *a*, *b*, *c* and the neutral wire (*n*). This approach is also applicable to balanced systems.

For the *k*-th distribution network configuration considering DG the indices considered are:

A. Real and Reactive Power Losses

In general, losses represent the main concern of electric utilities in technical and economic terms. Consequently, the first and second indices (*ILp* and *ILq*) express real and reactive line power losses, respectively. Thus, a good DG location suggests decreasing the total network losses, which means near unity values of *ILp* and *ILq*.

$$ILp^k = 1 - \frac{\mathrm{Re}\left\{ \sum_{m=1}^{NL} \begin{array}{l} \bar{Z}a_m \left|\bar{J}a_m^k\right|^2 + \bar{Z}b_m \left|\bar{J}b_m^k\right|^2 + \\ \bar{Z}c_m \left|\bar{J}c_m^k\right|^2 + \bar{Z}n_m \left|\bar{J}n_m^k\right|^2 \end{array} \right\}}{\mathrm{Re}\left\{Losses^0\right\}} \qquad (1)$$

$$ILq^k = 1 - \frac{\mathrm{Im}\left\{ \sum_{m=1}^{NL} \begin{array}{l} \bar{Z}a_m \left|\bar{J}a_m^k\right|^2 + \bar{Z}b_m \left|\bar{J}b_m^k\right|^2 + \\ \bar{Z}c_m \left|\bar{J}c_m^k\right|^2 + \bar{Z}n_m \left|\bar{J}n_m^k\right|^2 \end{array} \right\}}{\mathrm{Im}\left\{Losses^0\right\}} \qquad (2)$$

where,

$\bar{Z}a_m$, $\bar{Z}b_m$, $\bar{Z}c_m$, $\bar{Z}n_m$: self impedances of branch *m*.

$\bar{J}a_m^k$, $\bar{J}b_m^k$, $\bar{J}c_m^k$, $\bar{J}b_m^k$: currents through branch *m* for the *k*-th distribution network configuration.

NL : network number of lines.

$Losses^0$: total complex power losses for the distribution network without DG.

B. Voltage

One advantage claimed by well-located-and-sized DG is the enhancement of the voltage profile. Therefore, the third index (*IVD*) is related to the maximum voltage drop. Thus, according to (3), the higher index *IVD* is (close to unity), the better the network performance is.

$$IVD^k = 1 - \max\left(\frac{\left|\bar{V}a_0\right| \text{-} \left|\bar{V}a_i^k\right|}{\left|\bar{V}a_0\right|}, \frac{\left|\bar{V}b_0\right| \text{-} \left|\bar{V}b_i^k\right|}{\left|\bar{V}b_0\right|}, \frac{\left|\bar{V}c_0\right| \text{-} \left|\bar{V}c_i^k\right|}{\left|\bar{V}c_0\right|} \right)_{i=1}^{NN-1} \qquad (3)$$

where,

$\bar{V}a_0$, $\bar{V}b_0$, $\bar{V}c_0$: voltages at root node (equal in magnitude for the three phases)

$\bar{V}a_i^k$, $\bar{V}b_i^k$, $\bar{V}c_i^k$: voltages at node *i* for the *k*-th distribution network configuration.

NN : network number of nodes.

In order to ensure that network voltages will not be adversely affected, scenario of minimum demand during maximum power generation is also considered, since it represents a critical operating case [17]. Thus, the fourth index, related to voltage regulation, shows the difference between nodal voltages during maximum and minimum demand. It is desirable to have this variation as small as possible, i.e. close to unity values for index *IVR*.

$$IVR^k = 1 - \frac{\sum_{i=1}^{NN-1} \max\left(\begin{array}{l} \left\| \frac{\left|\bar{V}a_i^k\right| - \left|\bar{V}a_i^{k\,\min}\right|}{\left|\bar{V}a_i^{k\,\min}\right|} \right\|, \\ \left\| \frac{\left|\bar{V}b_i^k\right| - \left|\bar{V}b_i^{k\,\min}\right|}{\left|\bar{V}b_i^{k\,\min}\right|} \right\|, \left\| \frac{\left|\bar{V}c_i^k\right| - \left|\bar{V}c_i^{k\,\min}\right|}{\left|\bar{V}c_i^{k\,\min}\right|} \right\| \end{array} \right)}{NN - 1} \qquad (4)$$

where,

$\bar{V}a_i^{k\,\min}$, $\bar{V}b_i^{k\,\min}$, $\bar{V}c_i^{k\,\min}$: voltages at node *i* for the *k*-th distribution network configuration considering minimum demand.

C. Current capacity of conductors

As a consequence of supplying power near to loads, current flows may diminish in some sections of the network, thus releasing more capacity, but could also increase to levels beyond distribution line limits. The fifth index (*IC*) gives important information about the level of currents through the network regarding the maximum capacity of conductors. Since re-conductoring is out of the scope of this work, only configurations with *IC* positive values (calculated currents values greater than current capacity) will be analyzed. Within those configurations, close to unity values for this index mean reserve capacity for demand growth.

$$IC^k = 1 - \max\left(\frac{\left|\bar{J}a_m^k\right|}{CCa_m}, \frac{\left|\bar{J}b_m^k\right|}{CCb_m}, \frac{\left|\bar{J}c_m^k\right|}{CCc_m}, \frac{\left|\bar{J}n_m^k\right|}{CCn_m} \right)_{m=1}^{NL} \qquad (5)$$

where,

CCa_m, CCb_m, CCc_m : current capacity of conductors.

D. Reverse power flows

The appearance of reverse power flows indicates that the network voltage profile no longer has a descendant tendency, i.e. some nodes (those with reverse power flow) present voltages magnitudes above their upstream nodes. Therefore, a unity value for this index means that the network voltage profile has a descendant tendency due to its mono-directional power flows.

$$IRPF^k = 1 - \frac{NRPF}{NL} \qquad (6)$$

where,

$NRPF$: number of branches with reverse power flow.

E. Three-phase and Single-phase-to-Ground Short Circuit

The seventh and eighth indices (*ISC*3 and *ISC*1) are related to the protection and selectivity issues since evaluate the maximum short circuit current variation between the scenarios with and without DG. These indices give the power engineer a notion of how the distributed generation is impacting on the protection devices that were planned for a network without such generation units. Hence, a low impact on this concern means close to unity values for *ISC*3 and *ISC*1 indices.

$$ISC3^k = 1 - \frac{\max\left(\dfrac{SCabc_i^k}{SCabc_i^0}\right)}{\dfrac{SCabc_*^k}{SCabc_*^0}} \tag{7}$$

$$ISC1^k = 1 - \frac{\max\left(\dfrac{SCa_i^k}{SCa_i^0}, \dfrac{SCb_i^k}{SCb_i^0}, \dfrac{SCc_i^k}{SCc_i^0}\right)}{\dfrac{SC_*^k}{SC_*^0}} \tag{8}$$

where,

$SCabc_i^k$: Three-phase fault current value in node *i* for the *k*-th distribution network configuration.

$SCabc_i^0$: Three-phase fault current value in node *i* for the distribution network without DG.

$SCabc_*^k$, $SCabc_*^0$: Largest three-phase fault current value in the network for the *k*-th distribution network configuration and its correspondent for the distribution network without DG.

SCa_i^k, SCb_i^k, SCc_i^k : Single-phase fault current value in node *i* for the *k*-th distribution network configuration.

SCa_i^0, SCb_i^0, SCc_i^0 : Single-phase fault current value in node *i* for the distribution network without DG.

SC_*^k, SC_*^0 : Largest single-phase fault current value in the network for the *k*-th distribution network configuration and its correspondent for the distribution network without DG.

The indices described above are signals of the network performance, where close to unity values indicate better network performance. However, these indices not related in such a way that a unique index could inform about how a DG unit is impacting, in a global manner, on a distribution network.

III. MULTIOBJECTIVE INDEX

The multiobjective index for the performance calculation of networks with distributed generation considers all previously mentioned indices by strategically giving a relevance (weighting) factor to each one. This can be performed since all impact indices were normalized, i.e. present non-dimensional values from zero to one.

$$IMO^k = \begin{Bmatrix} w_1 ILp^k + w_2 ILq^k + w_3 IVD^k + w_4 IVR^k + \\ w_5 IC^k + w_6 IRPF + w_7 ISC3^k + w_8 ISC1^k \end{Bmatrix} \tag{8}$$

where,

$$\sum_{i=1}^{8} w_i = 1.0 \wedge w_i \in [0,1]$$

These relevance factors are intended to give the corresponding importance to each technical issue (impact indices) due to the presence of DG and depend on the required analysis (e.g. planning, regular operation, emergency operation).

In general, it is difficult to determine suitable values for the relevance factors. Therefore, the experience of distribution engineers should be harnessed in order to obtain adequate values. Furthermore, the relevance factors should be flexible since electric utilities present different concerns about losses, voltages, protection schemes, etc. This flexibility makes the proposed methodology even more suitable as a tool for finding the most beneficial places where distributed generators may be inserted, regarding the electric utilities' technical perspective, and consequently, regarding the distributed generator owner's economic perspective, since utilities may incentivize (or even disincentivize) connections points that are more beneficial based on the technical impacts.

Table I shows the values for the relevance factors utilized in this work, considering a normal operation stage analysis. Those values may vary according to the network operator concerns. Here, real power losses received a significant relevance (0.30) since it is one of the most important DG benefits. Behavior of the voltage profile (*IVD*, *IVR*, and *IRPF*), as a consequence of total losses reduction and direction of power flows, is also well considered (0.35) due to be a significant power quality issue. Protection and selectivity impacts (*ISC*3 and *ISC*1) received 0.15 since they evaluate important reliability problems that DG presents in distribution networks.

TABLE I
RELEVANCE FACTORS

ILp	*ILq*	*IVD*	*IVR*	*IC*	*IRPF*	*ISC3*	*ISC1*
w_1	w_2	w_3	w_4	w_5	w_6	w_7	w_8
0.30	0.10	0.10	0.15	0.10	0.10	0.05	0.10

The multiobjective index will numerically describe the impact of DG, considering a given location and size, on a distribution network. Close to unity values for the multiobjective performance index means higher DG benefits.

IV. TEST NETWORK

The IEEE 34-bus three-phase medium voltage radial feeder [19] will be used in order to perform the proposed analysis (Fig. 1). Its total demand is 1770 kW, and 72% of the loads are concentrated 56 km far away from the root node (the most distant node is 59 km from the substation). X/R ranges from 0.91 to 2.25. Line-to-line base voltage, V_b, is 24.9 kV. This feeder presents ACSR 1/0, 2 and 4 conductors.

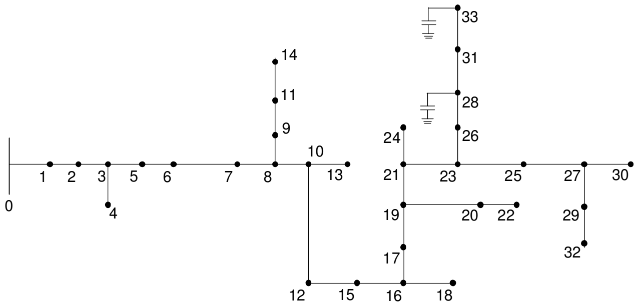


Fig. 1. IEEE-34 test feeder.

The network is simplified by replacing the 24.9 kV /4.16 kV in-line transformer in the original IEEE-34 test feeder with a line and modeling the entire feeder at a single voltage level. The automatic voltage regulator is also not represented.

V. APPLICATIONS

The three-phase four-wire power flow algorithm, based on the current summation backward-forward technique, described in [20], was adopted. Loads were modeled as constant power, and represent the maximum demand.

The impact indices presented in section II were calculated by extensively locating and sizing DG in the above described distribution network in order to illustrate how these indices vary regarding the insertion point and capability of a generation unit.

Fig. 2 and Fig. 3 show the IEEE-34 impact indices for two different generation power outputs: 300 and 1200 kW, respectively (operating at unity power factor). Those values represent 16.9% and 67.8% of the network total demand, respectively. Each figure was obtained by computing the impact indices considering a generator located in each feasible node (three-phase node) of the network.

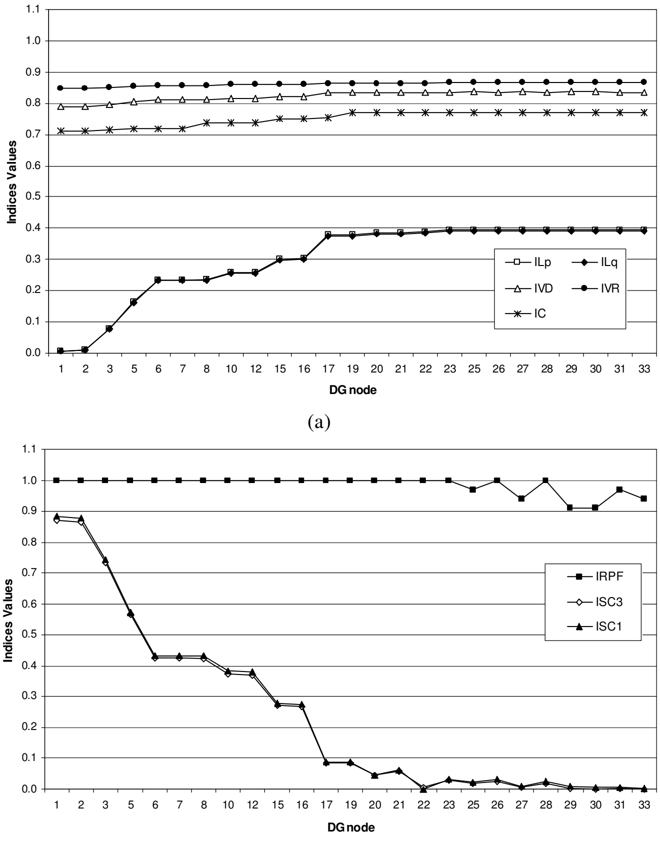
Short circuit analysis was performed based on symmetrical components. The system zero and positive sequence impedances at the HV/MV substation are $Zsys0=j10.7\Omega$ and $Zsys1=2.9+j2.7\Omega$, respectively; the generator's zero, positive and negative sequence impedances are $Zgen0=j1.6758\Omega$, $Zgen1=j6.2972\Omega$ and $Zgen2=j3.7837\Omega$, respectively. The minimum demand level considered was 10% of the maximum and was used for calculating the index *IVR*.

A. Impact Indices and IMO with DG location and size

From Fig. 2a and Fig. 3a it can be observed that indices *ILp*, *ILq*, *IVD*, *IVR* and *IC*, related to the power losses, voltage drop and regulation, and conductor's capacities, achieve higher values when DG is sited near the load concentration, i.e. far from the substation. This fact proves the importance on locating DG near the loads. It can be noted that the values for *ILp* and *ILq* present similar results, however, these indices should be analyzed separately particularly where DG is operating away from unity power factor.

It is also clear that both real and reactive total losses decrease with the power generation output (*ILp* and *ILq* achieved higher values with 1200 kW of power generation). Consequently, the index related with voltage drop (*IVD*) also achieved higher values with higher power generation output. Moreover, since voltage drops were smaller with a higher power generation output, differences between maximum and minimum demand voltages were also smaller. Thus, the index related to voltage regulation (*IVR*) achieved greater values.

The tendency of the maximum usage of the current capacity of conductors index (*IC*) is to increase when the DG unit is near to the load concentration (in this case, far from the substation), i.e. power flow from substation diminished alleviating the capacity of conductors.



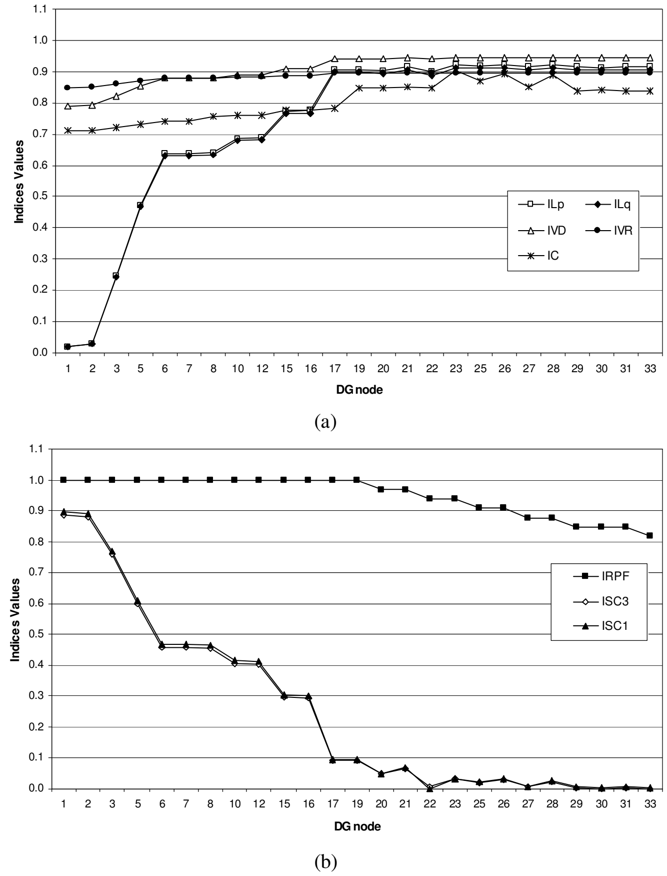
(a)

(b)

Fig. 2. IEEE-34 impact indices for a 300 kW-generator sited at each node of the circuit: (a) Indices *ILp*, *ILq*, *IVD*, *IVR* and *IC*; (b) Indices *IRPF*, *ISC3* and *ISC1*.

The reverse power flow index (*IRPF*) degrades, as expected, mostly when DG is located at end nodes where loads and neighbor loads are smaller than the power generation output. Furthermore, it is clear for Fig. 2b and Fig. 3b that larger generation increases reverse power flow.

As explained in section II, short circuit indices (*ISC3* and *ISC1*), presented in Fig. 2b and Fig. 3b, considered the maximum values of the ratios between short circuit with DG and without DG (original network), with fault in all nodes. The maximum values for those ratios, for the analyzed generator, appeared when a fault occurred at the generation node. Therefore, the greater the distance between the substation and the DG is, the lower the *ISC3* and *ISC1* values are. Also, it is important to remark that indices *ISC3* and *ISC1* present similar tendencies because of the normalization. However, the ratios “fault with DG/fault without DG” are different as indicated in Table II.



(a)

(b)

Fig. 3. IEEE-34 impact indices for a 1200 kW-generator sited at each node of the circuit: (a) Indices *ILp*, *ILq*, *IVD*, *IVR* and *IC*; (b) Indices *IRPF*, *ISC3* and *ISC1*.

Summarizing, the assessment of the impact indices show that each index is capable of indicating how a DG unit is benefiting or harming the distribution network. Nevertheless, while these indices remain as isolated values, it is difficult to use them as a decision making tool. Therefore, the multiobjective performance index (*IMO*) becomes essential for assessing technical impacts in a global manner regarding specific concerns of an electric utility.

Based on the adopted relevance factors (Table I), Fig. 4 shows the *IMOs* obtained by using the impact indices previously calculated on Fig. 2 and Fig. 3, and also considering a case with 600 kW power generation output. It is noticeable that for 300 kW of power generation, most nodes present almost the same *IMOs* values, whereas for 1200 kW, a certain set of nodes (neighborhood of node 19) have the largest *IMOs* values (more benefits to the distribution network). Fig. 4 also shows that the *IMO* values increase with the power generation output, mainly due to the impact on the total power losses.

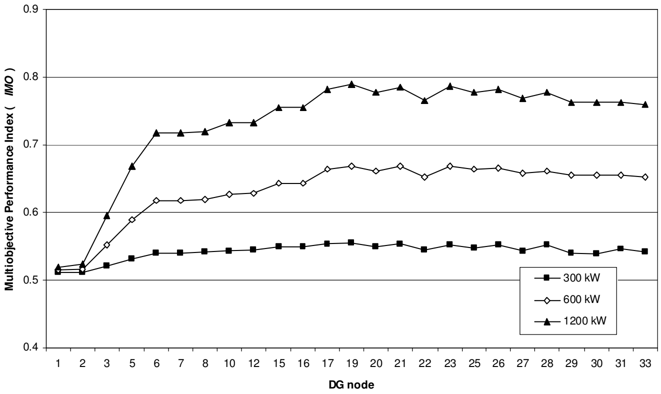


Fig. 4. IEEE-34 multiobjective performance index for three different power generation outputs extensively located in the circuit.

To show how DG insertion can impact on distribution networks, Table II presents the non-normalized impact indices for power generation outputs from Fig. 4, calculated for a DG unit located at node 19 (largest *IMO* for the three power generation output cases). The benefits of DG connection are represented by *ILp*, *ILq*, *IVD*, *IVR*, and *IC*, where losses diminished up to 38%, 64% and 91%, for 300 kW, 600 kW and 1200 kW of output, respectively. Even considering the first case of power generation output (300 kW, feeding 16.9% of the network demand), expressive benefits are achieved when a DG unit is suitably inserted in the feeder: voltage drop and maximum usage of the current capacity of conductors decreased up to 20% compared to the original network (no DG). However, by locating a DG unit at node 19 the maximum three-phase and single-phase short circuit currents are 45 and 57 times the original short circuit currents (no DG), respectively. In the other hand, no reverse power flows were encountered in this case. The values of *ISC3* and *ISC1* means that special attention should be paid to the adjustment and selection of protection devices.

TABLE II
IEEE-34 IMPACT INDICES COMPARISON CONSIDERING DIFFERENT POWER GENERATION OUTPUT (POWER FACTOR 1.0)

Impact Index	no DG	Total Power Generation Output		
		300 kW	600 kW	1200 kW
ILp (kW)	397.32	246.35	143.75	36.93
ILq (kVAr)	366.91	228.97	135.17	37.39
IVD (%)	21.21	16.67	12.70	5.90
IVR (%)	15.15	13.51	12.27	10.46
IC (%)	28.94	23.11	17.94	15.29
IRPF (%)	0.00	0.00	0.00	0.00
ISC3 $\frac{\text{with DG}}{\text{without DG}}$	---	11.47 (2042.9 A/178.0 A)	11.97 (2130.9 A/178.0 A)	12.83 (2284.0 A/178.0 A)
ISC1 $\frac{\text{with DG}}{\text{without DG}}$	---	23.52 (3198.8 A/136.0 A)	24.62 (3348.2 A/136.0 A)	26.50 (3604.6 A/136.0 A)
IMO		0.55460	0.66909	0.78918
Best Performance at bus		19	19	19

B. IMO and Total Line Power Losses

Since most attention is given to the impact on network total losses, Fig. 5 shows *IMO*s and total active power losses for a DG unit located at node 19 with variable power generation output. Dashed squares show the corresponding values for the three cases analyzed above (300, 600 and 1200 kW). It should be noted that the *IMO*s are closely related to the power losses (the smaller the losses are the larger the *IMO* is) due to the high relevance factor assigned to the index *ILp*. Fig. 5 also exhibits that increasing power generation output to values near the network total demand leads the total losses to an increasing tendency. Beyond reaching that point, *IMO*s decrease. Furthermore, the smallest total losses were achieved with 1650 kW of power generation. This compares to a 1575 kW generation that exhibits the maximum *IMO*.

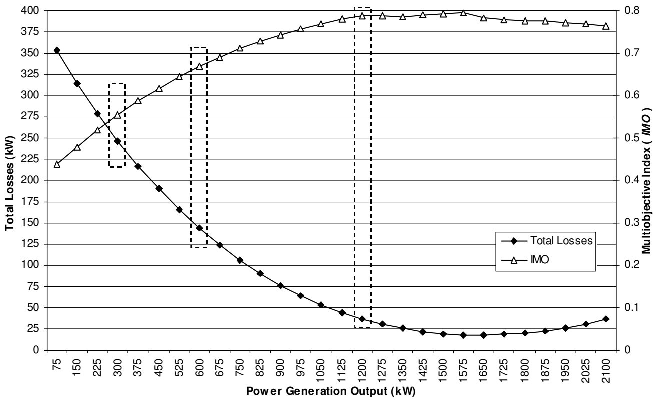


Fig. 5. IEEE-34 multiobjective performance index and total power losses varying the power generation output at node 19.

C. Impact Indices and IMO with different Power Factor

In the same way that technical impacts vary according to the power generation, they vary also according to the operating power factor of generators. Fig. 6 shows the *IMOs* considering 600 kW of power generation and three different operating power factors: 0.95 lagging (producing reactive power), unity and 0.95 leading (absorbing reactive power). Table III shows the non-normalized impact indices for a DG unit located at the most beneficial nodes found for each case.

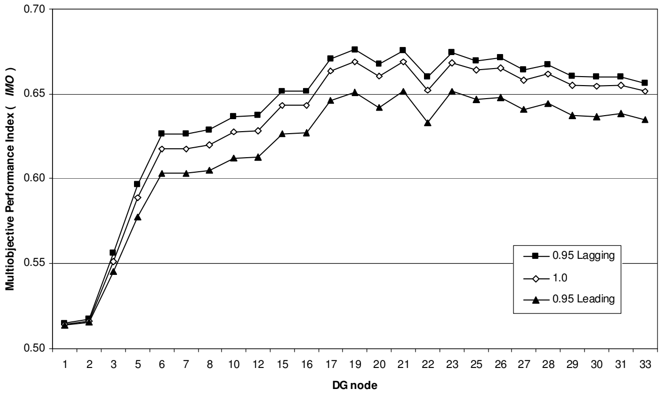


Fig. 6. IEEE-34 multiobjective performance index considering different power factors (power generation 600 kW).

It is evident that the proposed impact indices are sensitive to the reactive power produced or absorbed by distributed generation, and, as such, the *IMOs* of these three cases did not indicate the same node as being optimal. Moreover, results suggest that with 600 kW of power generation, a 0.95 lagging power factor presents more benefits (Fig. 6 and Table III), i.e., producing reactive power improves network performance.

TABLE III
IEEE-34 IMPACT INDICES COMPARISON CONSIDERING DIFFERENT POWER FACTORS (POWER GENERATION 600 KW)

Impact Index	Generation Power Factor		
	0.95 Lagging	unity	0.95 Leading
ILp (kW)	138.87	143.75	155.00
ILq (kVAr)	130.65	135.17	145.49
IVD (%)	11.61	12.70	13.67
IVR (%)	12.04	12.27	12.48
IC (%)	17.49	17.94	18.83
IRPF (%)	0.00	0.00	0.00
ISC3 $\frac{\text{with DG}}{\text{without DG}}$	12.10 (2155.1 A/178.0 A)	11.97 (2130.9 A/178.0 A)	12.16 (2100.5 A/172.8 A)
ISC1 $\frac{\text{with DG}}{\text{without DG}}$	24.92 (3389.2 A/136.0 A)	24.62 (3348.2 A/136.0 A)	24.99 (3296.0 A/131.8 A)
IMO	0.67606	0.66909	0.65150
Best Performance at bus	19	19	21

Since three-phase load data is difficult to obtain, a single-phase analysis is required. Therefore, after adapting the presented impact indices, the analysis described above (varying generation at unity power factor and varying power factor with 600 kW power generation) were carried out considering a single-phase approach. *IMOs* curves presented the same tendencies, and almost the same values, than the three-phase analysis. Nevertheless, high unbalanced loads could make noticeable differences between *IMOs* using single-phase and three-phase approaches.

In general, distribution networks will not present the same impact indices tendencies, regarding power generation output and operating power factor. It is not necessarily surprising that a higher power generation output does not bring more benefits since it will depends mainly on the load distribution and location of the distributed generator.

VI. CONCLUSIONS

Various impact indices were addressed in this work, aimed at characterizing the benefits and negative impacts of DG in distribution networks. Furthermore, a multiobjective performance index that relates impact indices by strategically assigning a relevance factor to each index was proposed.

Though the selection of values of relevance factors will depend on engineering experience, the presented values solved, in a satisfactory and coherent fashion, the DG location problem, considering different power generation outputs, for the IEEE-34 distribution network. Nevertheless, the proposed relevance factors are flexible since electric utilities have different concerns about losses, voltages, protection schemes, etc. This flexibility makes the proposed methodology even more suitable as a tool for finding the most beneficial places where distributed generators may be located, as viewed from an electric utility technical perspective. Consequently, these may have an economic influence, since technical impacts may be used to shape the nature of the contract that might be established between the utility and the distributed generator owner.

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