An Approach to Quantify the Technical Benefits of Distributed Generation

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***Abstract*—Recent changes in the electric utility infrastructure have created opportunities for many technological innovations, including the employment of distributed generation (DG) to achieve a variety of benefits. After a brief discussion of the benefits, this paper proposes a general approach and a set of indices to assess some of the technical benefits in a quantitative manner. The indices proposed are: 1) voltage profile improvement index; 2) line-loss reduction index; 3) environmental impact reduction index; and 4) DG benefit index. Simulation results obtained using a simple 12-bus test system and a radial system are presented and discussed to illustrate the value and usefulness of the proposed approach.**

***Index Terms*—Benefits of distributed generation, distributed generation, emission reduction, line-loss reduction, voltage profile improvement.**

NOMENCLATURE

AE_{ij}	Amount of emission of ith pollutant for jth conventional plant per megawatt hour (MWh) of energy generated.
AE_{ik}	Amount of emission of ith pollutant for kth DG plant per MWh of energy generated.
B	Total number of conventional generators in the system.
BI	Distributed generation benefit index.
BW_{EIR}	Benefit weighting factor for environmental impact reduction
BW_{LLR}	Benefit weighting factor for line-loss reduction.
BW_{VPI}	Benefit weighting factor for voltage profile improvement.
D_i	Line length for distribution line i, km.
DG	Distributed generation.
EDG_k	Amount of energy generated by the kth DG plant, MWh.
EIRI	Environmental impact reduction index.
EG_j	Amount of electrical energy generated by the jth conventional power plant, MWh.
EG_{Aj}	Amount of electrical energy generated by the jth conventional power plant with the employment of DG, MWh.
EI_i	Weighting factor for ith pollutant.
EIRI	Environmental impact reduction index.
$EIRI_i$	Environmental impact reduction index for the ith pollutant.
H	Total number of DG plants in the system.
$I_{A,i}$	Line current in distribution line i with employment of DG, pu.
$I_{L,i}$	Line current in distribution line i without DG, pu.
II_i	Improvement index for ith attribute.
k_i	Weighting factor for load bus i.
L_i	Load at bus i, pu.
$LL_{w/DG}$	Total line losses in the system with employment of DG, pu.
$LL_{wo/DG}$	Total line losses in the system without DG, pu.
LLRI	Line-loss reduction index.
M	Total number of lines in the distribution system.
N	Total number of load busses.
NP	Total number of pollutants under consideration.
$PE_{iw/DG}$	Amount of emissions for the ith pollutant with DG, kg.
$PE_{iwo/DG}$	Amount of emissions for the ith pollutant without DG, kg.
PV	Photovoltaic systems.
R_i	Line resistance for line i, pu/km.
RI_j	Reduction index for jth attribute.
V_i	Voltage magnitude at bus i, pu.
$VP_{w/DG}$	Voltage profile index of the system with DG, pu.
$VP_{wo/DG}$	Voltage profile index of the system without DG, pu.
VPII	Voltage profile improvement index.
WECS	Wind electric conversion systems.

I. INTRODUCTION

WITH THE impending deregulated environment faced by the electric utility industry and recent advances in technology, several DG options are fast becoming economically viable [1]–[9]. A multitude of recent events have created a new environment for the electric power infrastructure. They are listed below.

- Deregulation of the electric utility industry and the ensuing break up of the vertically integrated utility structure.
- Public opposition to building new transmission lines on environmental grounds.
- Keen public awareness of the environmental impacts of electric power generation.
- Rapid increases in electric power demand in certain regions of the country.
- Significant advances in several generation technologies that are much more environmentally benign (wind-electric

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generation, microturbines, fuel cells, and photovoltaics) than conventional coal, oil, and gas-fired plants.
- Increasing public desire to promote "green" technologies based on renewable energy sources.
- Awareness of the potential of DG to enhance the security of electric power supply, especially to critical loads, by creating mini- and micro-grids in the case of emergencies and/or terrorist acts, and/or embargoes of energy supplies.

All the factors listed above have led to an upsurge in interest in the development and utilization of DG. The key element of this new environment is to build and operate several DG units near load centers instead of expanding the central-station power plants located far away from customers to meet increasing load demand [10].

DG can be powered by both conventional and renewable energy resources [11]–[14]. Technologies that utilize conventional energy resources include IC engines, gas turbines, fuel cells, and microturbines. There are many new technologies that utilize renewable energy resources. However, at the present time, the ones that show promise for DG applications are: biomass systems, PVs, solar-thermal-electric systems, WECS, and geothermal systems. The rating of DG can range from a few kilowatts up to 100 MW. While smaller units (a few kilowatts to a few megawatts) are typically installed in distribution networks, larger units (tens of megawatts to 100 MW) are likely to be installed in locations where subtransmission lines intersect with gas pipelines. Some DG technologies produce electrical energy almost as efficiently as large central-station power plants and at a cost competitive with centralized generation for certain applications with less environmental impacts and flexibility in siting. DG can be used to match increased customer demand where the upgrade or installation of new transmission/distribution lines are not available for one reason or another. However, employment of DG in existing systems can cause several potential operating conflicts such as voltage flicker, misoperation of protection, and reverse power flow [15]–[17]. Therefore, such issues must be taken into consideration to assure an acceptable level of safety and reliability.

Several benefits accrue by integrating DG with utility networks. These benefits should be clearly understood, analyzed, and quantified in order to increase the potential and value of DG penetration. The benefits of DG have been evaluated and quantified in terms of capacity credit, energy value, and energy cost saving [18], [19]. In addition, quantification of voltage profile improvement, line-loss reduction, and environmental impact reduction have attracted the attention of researchers [20], [21].

The purposes of this paper are to briefly discuss the benefits of employing DG and propose a general approach and a set of indices to assess and quantify some of the technical benefits of DG in terms of voltage profile improvement, line-loss reduction, and environmental impact reduction.

II. Benefits of Employing DG

Most of the benefits of employing DG in existing distribution networks have both economic and technical implications and they are interrelated. While all the benefits can be ultimately valuated in terms of money, some of them have a strong technical flavor than others. As such, it is proposed to classify the benefits into two groups—technical and economic [22], [23].

The major technical benefits are:
- reduced line losses;
- voltage profile improvement;
- reduced emissions of pollutants;
- increased overall energy efficiency;
- enhanced system reliability and security;
- improved power quality;
- relieved T&D congestion.

The major economic benefits are:
- deferred investments for upgrades of facilities;
- reduced O&M costs of some DG technologies;
- enhanced productivity;
- reduced health care costs due to improved environment;
- reduced fuel costs due to increased overall efficiency;
- reduced reserve requirements and the associated costs;
- lower operating costs due to peak shaving;
- increased security for critical loads.

In this paper, a general approach is presented to quantify the technical benefits of DG. It is then applied to assess three major technical benefits, namely voltage profile improvement, line-loss reduction, and environmental impact reduction.

III. Approach

Technical benefits of introducing DG can accrue in one of two broad categories.

i) Improvement of a certain attribute such as voltage profile, reliability, power quality, etc.
ii) Reduction of an attribute such as line losses, emissions, congestion, etc.

By comparing and taking the ratio of a measure of an attribute with and without DG (with the loads served being the same), an index can be derived for each of the attributes. If the introduction of DG is beneficial, indices corresponding to the attributes in Category i) will be greater than unity and indices corresponding to the attributes in Category ii) will be less than unity.

Designating the indices as $\mathrm{II_i}$ and $\mathrm{RI_j}$ for the different attributes in categories i) and ii), respectively, an overall composite BI can be formulated as

$$\mathrm{BI} = \sum_i \mathrm{BW}_i II_i + \sum_j \mathrm{BW}_j \frac{1}{\mathrm{RI}_j} \tag{1}$$

in which $\mathrm{BW_i}$ and $\mathrm{BW_j}$ are the benefit weighting factors and

$$\sum_i \mathrm{BW}_i + \sum_j \mathrm{BW}_j = 1. \tag{2}$$

The use of weighting factors will enable the emphasis of certain critical attributes depending on the location of the DG units, types of loads served by the distribution system and the region involved. With this formulation, the planner can select the locations and ratings of DG that will result in the highest value for BI to maximize the benefits.

IV. Quantification of Benefits

A set of indices is proposed to quantify some of the technical benefits of DG. They are VPII, LLRI, EIRI, and BI.

A. VPII

One of the justifications for introducing DG is to improve the voltage profile of the system and maintain the voltage at customer terminals to within an acceptable range. By introducing DG in the system, voltage profile can be improved because DG can provide a portion of the real and reactive power to the load, thus helping to decrease current along a section of the distribution line, which, in turn, will result in a boost in the voltage magnitude at the customer site [24].

The proposed VPII quantifies the improvement in the VP in a simple manner with the inclusion of DG. It is defined as the ratio of the voltage profile index of the system with DG to the voltage profile index of the system without DG (base case system) and is expressed as

$$\mathrm{VPII} = \frac{\mathrm{VP}_{w/\mathrm{DG}}}{\mathrm{VP}_{wo/\mathrm{DG}}} \tag{3}$$

where $\mathrm{VP}_{\mathrm{w/DG}}$ and $\mathrm{VP}_{\mathrm{wo/DG}}$ are measures of the voltage profile of the system with DG and without DG, respectively, with the same loads at the different load buses. The general expression for VP is given as

$$\mathrm{VP} = \sum_{i=1}^{N} V_i L_i k_i \tag{4}$$

with

$$\sum_{i=1}^{N} k_i = 1 \tag{5}$$

where $\mathrm{V_i}$ is the voltage magnitude at bus i in per-unit, $\mathrm{L_i}$ is the load at bus i in per-unit, $\mathrm{k_i}$ is the weighting factor for load bus i, and N is the total number of load buses in the distribution system. As defined, the expression for VP provides an opportunity to quantify and aggregate the importance, amounts, and the voltage levels at which loads are being supplied at the various load busses in the system. This expression should be used only after making sure that the voltages at all the load busses are within allowable minimum and maximum limits, typically between 0.95 and 1.05 pu. The weighting factors are chosen based on the importance and criticality of the different loads. No overarching rules can be formulated at the present time. Starting with a set of equal weighting factors, modifications can be made and, based on an analysis of the results, the set that will lead to the most acceptable voltage profile on a system-wide basis can be selected. It should be noted that if all the load busses are equally weighted, the value of $\mathrm{k_i}$ is given as

$$k_1 = k_2 = k_3 = \cdots = k_N = \frac{1}{N}. \tag{6}$$

The voltage profile expression in (4) recognizes the influences of the amount and importance of load at each bus. It allows the possibility of a low-load bus with important load to have a strong impact. In general, weighting factors are assigned based on the importance/criticality of load at each bus.

An alternate approach is to focus on how close the voltage profile is to nominal voltage levels (typically 1 pu). An index based on the difference between nominal and actual voltage levels should then be minimized or, alternately, the reciprocal of that index should be maximized. Such a procedure could easily run into the problem of extremely large values for the index. Since a check is made first to ensure that all voltages are within acceptable limits and since by far the largest benefit appears to be line-loss reduction, the VPII formulation as given above is deemed acceptable. However, if it is necessary to exclude VPII in the formulation of BI, that can be easily accomplished by setting the corresponding benefit weighting factor to zero.

B. LLRI

Another major potential benefit offered by DG is the reduction in electrical line losses. The loss can be significant under heavy load conditions. The utility is forced to pass the cost of electrical line losses to all customers in terms of higher energy cost. With the inclusion of DG, line loss in the distribution system can be reduced.

Obviously, line-loss reductions are due to reductions in power flows resulting from the introduction of DG. However, depending on the ratings and locations of DG units, it is possible to have an increase in loss at very high (and unrealistic) penetration levels.

The proposed LLRI is defined as the ratio of total line losses in the system with DG to the total line losses in the system without DG and is expressed as

$$\mathrm{LLRI} = \frac{\mathrm{LL}_{w/\mathrm{DG}}}{\mathrm{LL}_{wo/\mathrm{DG}}} \tag{7}$$

where $\mathrm{LL}_{\mathrm{w/DG}}$ is the total line losses in the system with the employment of DG and is given as

$$\mathrm{LL}_{w/\mathrm{DG}} = \sum_{i=1}^{M} I_{A,i}^2 R_i D_i \tag{8}$$

where $\mathrm{I_{A,i}}$ is the per-unit line current in distribution line i with the employment of DG, $\mathrm{R_i}$ is the line resistance for line i (pu/km), $\mathrm{D_i}$ is the ith distribution line length (km), and M is the number of lines in the distribution system.

Similarly, $\mathrm{LL}_{\mathrm{wo/DG}}$ is given as

$$\mathrm{LL}_{wo/\mathrm{DG}} = \sum_{i=1}^{M} I_{L,i}^2 R_i D_i \tag{9}$$

where $\mathrm{I_{L,i}}$ is the per-unit line current in distribution line i without DG. As before, the loads at the different load buses are assumed to be the same both with and without DG.

C. EIRI

Another great potential benefit of DG is the production of energy with minimal greenhouse gas emissions and other pollutants as compared to conventional technologies. Concerns about greenhouse effect are growing rapidly in the public's view. Greenhouse effect is a result of rising carbon dioxide and other greenhouse gas emissions. It is believed that greenhouse effect will lead to global warming and world-wide climate change.

Introduction of DG will result in a reduction of capacity needs of conventional plants due to two reasons: 1) the real power generated by DG units will directly reduce the output requirements and 2) the resulting line-loss reductions will further decrease the output needs from conventional plants.

The basic idea behind the proposed EIRI is to compare the emission of a particular pollutant with and without the employment of DG; it can be expressed as

$$\mathrm{EIRI}_i = \frac{\mathrm{PE}_{iw/\mathrm{DG}}}{\mathrm{PE}_{iwo/\mathrm{DG}}} \tag{10}$$

for the ith pollutant (CO_2, SO_2, NO_x, etc.)
where $\mathrm{PE}_{\mathrm{i\,w/DG}}$ and $\mathrm{PE}_{\mathrm{i\,wo/DG}}$ are the amount of emissions with and without DG, respectively, for the ith pollutant and they are expressed as

$$\mathrm{PE}_{iw/\mathrm{DG}} = \sum_{j=1}^{B} (\mathrm{EG})_{Aj}(\mathrm{AE})_{ij} + \sum_{k=1}^{H} (\mathrm{EDG})_k(\mathrm{AE})_{ik} \tag{11}$$

$$\mathrm{PE}_{iwo/\mathrm{DG}} = \sum_{j=1}^{B} (\mathrm{EG})_{j}(\mathrm{AE})_{ij} \tag{12}$$

where $(\mathrm{EG})_{\mathrm{Aj}}$ and $(\mathrm{EG})_{\mathrm{j}}$ are the amount of electrical energy generated by the jth conventional power plant with and without the employment of DG, respectively (MWh), $(\mathrm{AE})_{\mathrm{ij}}$ is the amount of emission of ith pollutant for jth conventional plant per MWh of energy generated, $(\mathrm{AE})_{\mathrm{ik}}$ is the amount of emission of ith pollutant for the kth DG power plant per MWh of energy generated, $(\mathrm{EDG})_{\mathrm{k}}$ is the amount of energy generated by the kth DG plant (MWh), B is the total number of conventional generators in the system, and H is the total number of DG plants in the system. Once again, the loads supplied at different buses are assumed to be the same both with and without DG.

In reality, power plants emit many pollutants into the atmosphere. Thus, it is useful to define a composite index to include all the major pollutants. This index can be formulated as

$$\mathrm{EIRI} = \sum_{i=1}^{\mathrm{NP}} (\mathrm{EI})_i(\mathrm{EIRI})_i \tag{13}$$

with

$$0 \le (\mathrm{EI})_i \le 1 \tag{14}$$

and

$$\sum_{i=1}^{\mathrm{NP}} (\mathrm{EI})_i = 1 \tag{15}$$

where $(\mathrm{EI})_{\mathrm{i}}$ is the weighting factor for the ith pollutant and NP is total number of pollutants of interest.

D. BI

The BI is a composite index proposed to quantify the overall benefits of DG. Among the several benefits offered by DG, only three major ones are considered in this paper: voltage profile improvement, line-loss reduction, and environmental impact reduction. Therefore, BI in (1) can be formulated as

$$\mathrm{BI} = (\mathrm{BW}_{\mathrm{VPI}})(\mathrm{VPII}) + \left(\frac{\mathrm{BW}_{\mathrm{LLR}}}{\mathrm{LLRI}}\right) + \left(\frac{\mathrm{BW}_{\mathrm{EIR}}}{\mathrm{EIRI}}\right) \tag{16}$$

with

$$\begin{aligned} 0 &\le \mathrm{BW}_{\mathrm{VPI}} \le 1 \\ 0 &\le \mathrm{BW}_{\mathrm{LLR}} \le 1 \\ 0 &\le \mathrm{BW}_{\mathrm{EIR}} \le 1 \end{aligned} \tag{17}$$

and

$$\mathrm{BW}_{\mathrm{VPI}} + \mathrm{BW}_{\mathrm{LLR}} + \mathrm{BW}_{\mathrm{EIR}} = 1 \tag{18}$$

where $\mathrm{BW}_{\mathrm{VPI}}, \mathrm{BW}_{\mathrm{LLR}}$, and $\mathrm{BW}_{\mathrm{EIR}}$ are the benefit weighting factors for voltage profile improvement, line-loss reduction, and environmental impact reduction, respectively.

Once again, the choice of weighting factors comes into question. The simplest approach is to give equal weights to the three indices considered in this study. If more indices are included, they can all be given equal weights. However, if DG is introduced to mitigate a certain specific problem (such as voltage profile improvement or lowering emissions), then the corresponding index can be assigned a greater weight as compared to others.

Generally, the highest value of VPII implies the maximum benefit in terms of voltage profile improvement while the lowest values of LLRI and EIRI imply the highest benefits in terms of line-loss reduction and environmental impact reduction, respectively. Therefore, the highest value of BI corresponds to the maximum composite benefit of DG. This index can be used to select the best locations and ratings for DG installations for maximum benefit.

Reliability: Enhancing distribution system reliability is one of the major benefits of employing DG. The well-known indices such as SAIFI, SAIDI, CAIFI, and CAIDI are used to quantify reliability. By calculating the values of such important and relevant indices with and without DG, attribute ratios can be developed for incorporation into (1). However, this will require outage information on DG units which is not readily available since most of them are still in the developmental stages.

V. Test System

Radial distribution systems serving loads far away from transmission and subtransmission (medium-voltage) lines are widely used. Any DG units introduced in such lines will typically have low ratings (a few kilowatts up to a few megawatts), most likely installed by customers in their premises. However, DG units in the tens of megawatts (up to 100 MW) will most likely find their place in medium-voltage subtransmission systems. The test system used in this paper belongs to this category and is similar to the one illustrated in [15, Fig. 8]. The main purposes of the test system are to show how the procedure presented in

TABLE I
LOAD DATA FOR SYSTEM UNDER STUDY

Load Point	Load (pu)	Power Factor (lag)
L1	0.425	0.96
L2	0.125	0.98
L3	0.250	0.96
L4	0.200	0.95
L5	0.175	0.96
L6	0.050	0.97
L7	0.175	0.94
L8	0.050	0.97
L9	0.113	0.97
L10	0.150	0.97
L11	0.075	0.95
L12	0.225	0.93

TABLE II
DISTRIBUTION LINE LENGTH DATA

From Bus	To Bus	Length (km)
1	2	30
1	3	50
2	3	40
2	6	10
3	4	20
3	5	30
4	5	40
4	8	30
5	7	30
6	8	20
6	9	10
7	11	20
8	10	10
8	11	30
11	12	20

TABLE III
IMPORTANT POLLUTANT EMISSIONS OF CONVENTIONAL GENERATORS UNDER STUDY

Generator	CO_2 in kg/MWh	SO_2 in kg/MWh	NO_x in kg/MWh
1	850	1.0	1.2
2	750	0.8	1.0
3	900	1.1	1.3

this paper can be used and how different indices depend on the key operating parameters.

A 12-bus test system is used to evaluate the benefits of DG by employing the proposed indices and approach. All per-unit quantities used in this study are on a 400-MVA base. This system consists of three conventional generators located at buses 1, 5, and 12 with ratings of 1.0, 0.75, and 0.625 pu, respectively. A total load of 2.013 pu located unevenly on every bus is assumed as listed in Table I. Resistance and reactance of all the distribution lines are assumed to be 0.000 625 and 0.003 75 pu/km, respectively. The lengths of the distribution lines are listed in Table II. The significant emissions of each of the generators are listed in Table III. Emissions from DG units

TABLE IV
ASSUMED BUS WEIGHTING FACTOR SETS

Bus	Set#1	Set#2	Set#3	Set#4	Set#5
1	0.083	0.211	0.115	0.300	0.200
2	0.083	0.062	0.034	0.036	0.050
3	0.083	0.124	0.068	0.200	0.120
4	0.083	0.099	0.054	0.058	0.070
5	0.083	0.087	0.048	0.050	0.080
6	0.083	0.025	0.150	0.014	0.020
7	0.083	0.087	0.048	0.050	0.070
8	0.083	0.025	0.150	0.014	0.100
9	0.083	0.056	0.031	0.033	0.060
10	0.083	0.075	0.041	0.043	0.070
11	0.083	0.037	0.200	0.022	0.030
12	0.083	0.112	0.061	0.180	0.130

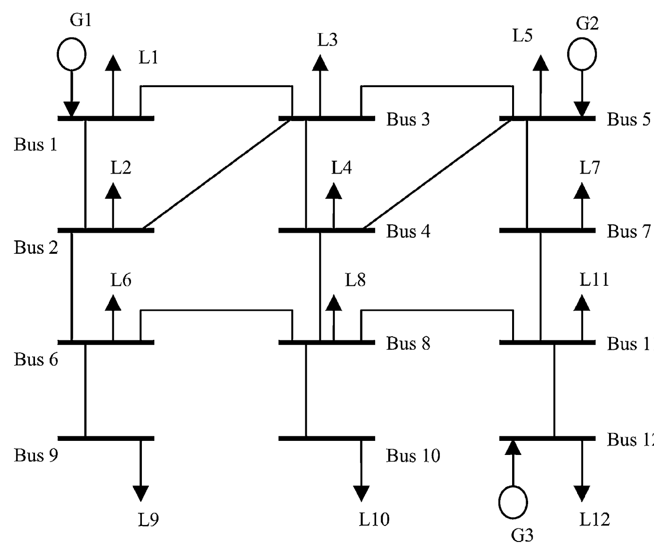

Fig. 1. Single-line diagram of the system under study.

are assumed to be negligibly small in this study. The sets of weighting factors assumed for each bus are listed in Table IV. Fig. 1 shows a one-line diagram of the system under study.

A typical radial system example is considered in Appendix A. The general nature of the results obtained is similar to the ones documented below for the system shown in Fig. 1.

VI. SIMULATION CASE STUDIES AND RESULTS

Four cases are simulated and studied for assessing the benefits of DG as proposed in this paper. For each case, the influence of varying ratings and power factors of DG are investigated. Emissions from distributed generators are considered to be negligibly small in this study. The cases considered are listed as follows.

Case 1) DG located at bus 9.
Case 2) DG located at bus 10.
Case 3) 50% of DG is located at bus 9 and the remaining 50% is located at bus 4.
Case 4) 50% of DG is located at bus 9 and the remaining 50% is located at bus 10.

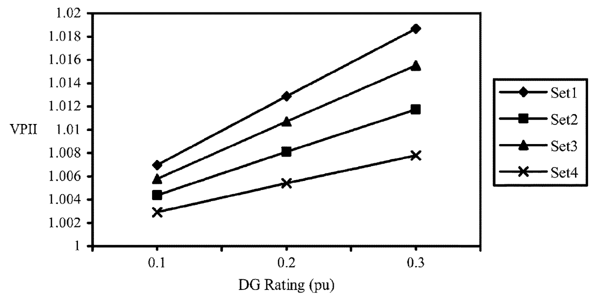

Fig. 2. Variation of voltage profile improvement index with DG rating for different sets of bus weighting factors (case 3 with DG operating at 0.9-pf lag).

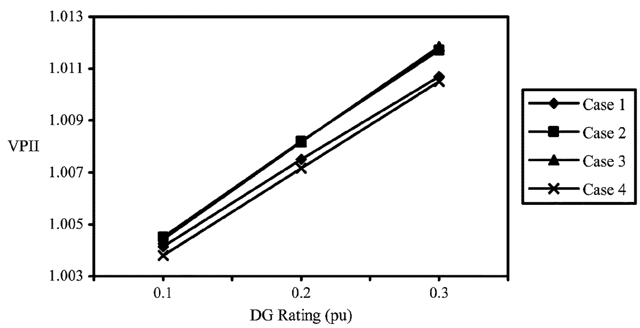

Fig. 3. Voltage profile improvement results with different DG ratings (DG operating at 0.9-pf lag and weighting factor set 5 used).

VII. Discussion of Results

A. Voltage Profile Improvement Results

Bus weighting factors are significant in determining VPII. They should be selected with care. To study their impact, four sets of bus weighting factors (sets 1 through 4) as listed in Table IV are used to quantify the voltage profile improvement and the results are shown in Fig. 2. It can be seen that VPII exhibits the highest value under weighting factor set 1 (equal weights). With weighting factor set 4 (importance given to high load buses), the VPII has the lowest value. This is due to the fact that voltages at high load buses before employing DG (base case) are relatively high as compared to low load buses. Therefore, the voltage profile improvement at high load buses with the employment of DG is not as significant as the improvement at low load buses. As a result, the VPII with bus weighting factor set 3 (importance given to low load bus) is higher than for the case with weighting factor set 4.

DG rating plays a significant role in determining VPII as shown in Fig. 3. As the DG rating increases, so does VPII. The location and operating power factor of DG are also important factors in improving the voltage profile. Generally, DG can supply reactive power to the system under lagging power factor operating conditions thus helping to support the system voltage profile. With leading power-factor operation, DG draws reactive power from the system, thus causing higher voltage drops in the system. It can be seen from Fig. 4 that DG has not been beneficial to the system $(\mathrm{VPII} < 1)$ under leading power factor conditions. It should be noted that voltages at every bus before employing DG (base case) were maintained within 5% of the reference voltage (1 pu). Therefore, an improvement of about

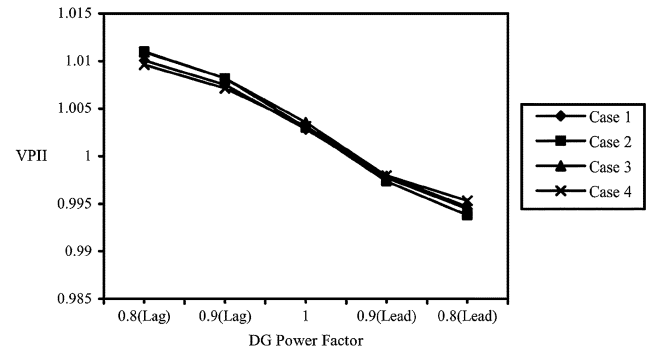

Fig. 4. Impact of DG operating power factor on voltage profile improvement (DG rating is 0.2 pu and weighting factor set 5 used).

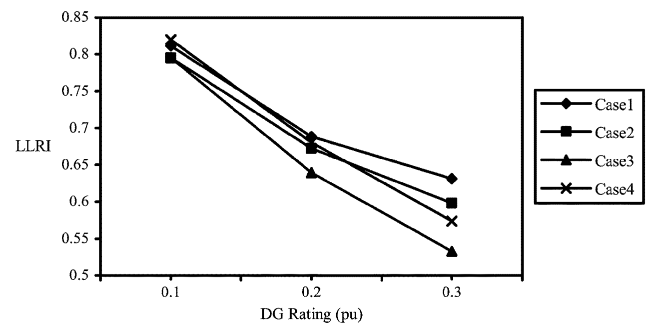

Fig. 5. Variation of line-loss reduction index with DG rating (DG operating at 0.9-pf lag).

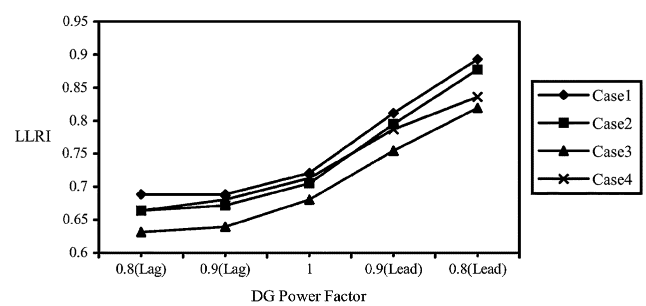

Fig. 6. Impact of DG operating power factor on line-loss reduction (DG rating is 0.2 pu).

0.4%–1.5% indicates a reasonably good and significant impact on voltage profile.

B. Line-Loss Reduction Results

Simulation results show that DG significantly reduces electrical line losses in the system. For the cases considered, up to 46% reduction $((1-\mathrm{LLRI})\times 100)$ is achieved with the employment of DG. The rating, location, and operating power factor of DG are all very important contributing factors in determining the amount of line-loss reduction. However, higher DG penetration cannot always guarantee lower line losses. For example, as DG rating increases from 0.2 to 0.3 pu in cases 1 and 2, the rate of decrease actually declines as shown in Fig. 5. This fact should be taken into account before determining the rating of DG. The results also indicate that DG operating power factor plays a vital role in line-loss reduction. It can be seen from Fig. 6 that LLRI exhibits the lowest value under lagging power factor condition and sharply increases under leading power factor conditions.

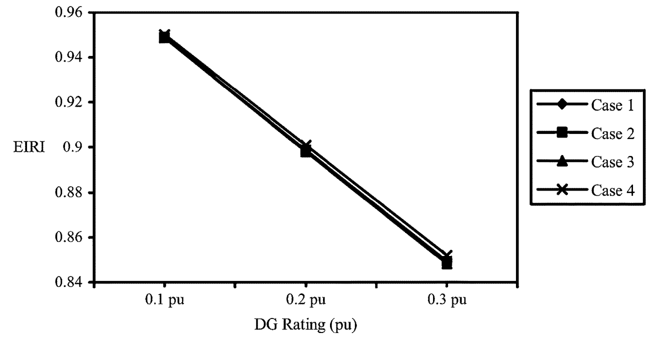

Fig. 7. Environmental impact reduction results for different DG ratings (DG operating at 0.9-pf lag).

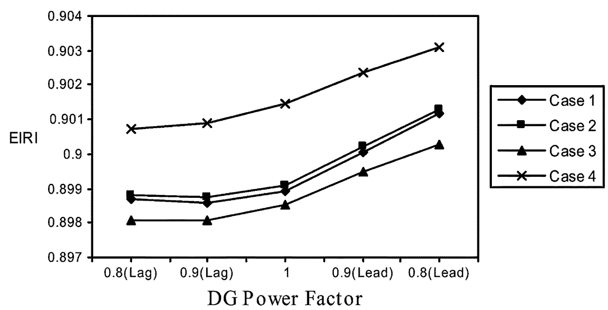

Fig. 8. Impact of DG operating power factor on environmental impact reduction (DG rating is 0.2 pu).

C. Environmental Impact Reduction Results

Among several pollutant emissions, only three major ones are considered in this paper: CO_2, SO_2, and NO_x. It is assumed that all the pollutants are equally weighted. The results clearly indicate that DG significantly reduces pollutant emissions. As with other benefits, the amount of pollutant emissions reduction depends on the ratings and locations of DG. As DG rating goes up, the EIRI significantly decreases as shown in Fig. 7. Since each conventional generator emits different amounts of pollutant emissions, the locations and operating power factors of DG can affect the amount of emission reductions. However, the impacts of locations and operating power factors of DG are relatively small as compared to the impact of the ratings of DG as shown in Fig. 8. This is because the amount of real power generated by DG is the same at all DG power factors. As a result, the amount of real power generated by conventional generators with the employment of DG does not change much except for changes in line losses, resulting only in small changes in emissions.

D. DG Benefit Results

The overall combined benefits of DG should be considered to arrive at conclusions regarding the best locations and ratings for DG installations. To calculate the DG BI, benefit weighting factors for voltage profile improvement, line-loss reduction, and environmental impact reduction are required. To study the influence of these weighting factors on BI, a three-dimensional plot is developed as shown in Figs. 9 and 10. It can be seen that BI increases as $\mathrm{BW_{LLR}}$ increases and BI decreases as $\mathrm{BW_{VPI}}$ increases. This is because line-loss reduction dominates among all

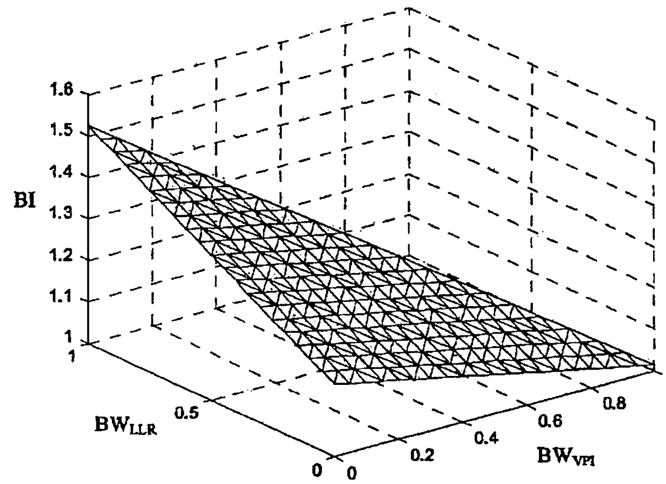

Fig. 9. Variation of DG BI with weighting factors (case 1 with 0.3 pu rating and 0.8-pf lag).

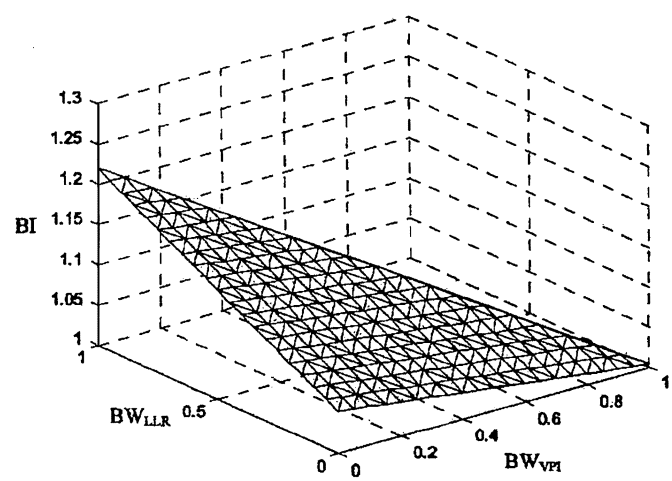

Fig. 10. Variation of DG BI with weighting factors (case 4 with 0.1 pu rating and 0.9-pf lag).

the benefits. For example, in case 1 with a DG rating of 0.3 pu and operating at 0.8-pf lag, DG reduces line losses by as much as 34% while the system voltage profile is improved by only 1.5% and emissions are reduced by nearly 15%. The results from the two study cases confirm that BI attains its maximum value when $\mathrm{BW_{LLR}}$ is set at its maximum value of unity, and $\mathrm{BW_{VPI}}$ and $\mathrm{BW_{EIR}}$ are both set at zero.

VIII. Concluding Remarks

The introduction of DG in a distribution system offers several benefits to utilities, customers, and society, such as reduced line and transformer losses, reduced central generating station reserve requirements, improved system voltage profile, increased system reliability and enhanced power quality, peak shaving, reduced environmental impacts, and relieved transmission and distribution congestion.

This paper has proposed an approach to quantify the technical benefits of introducing DG. It is then applied to a subset of benefits and a set of indices are derived. They are VPII, LLRI, EIRI, and BI.

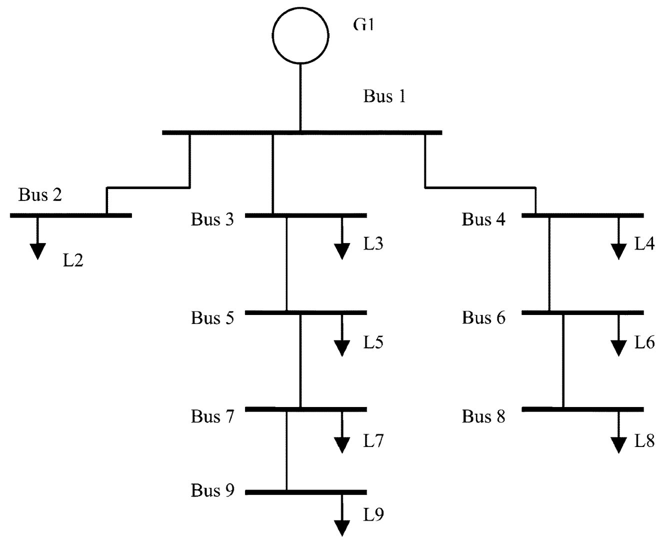

Fig. A-1. Single-line diagram of radial system.

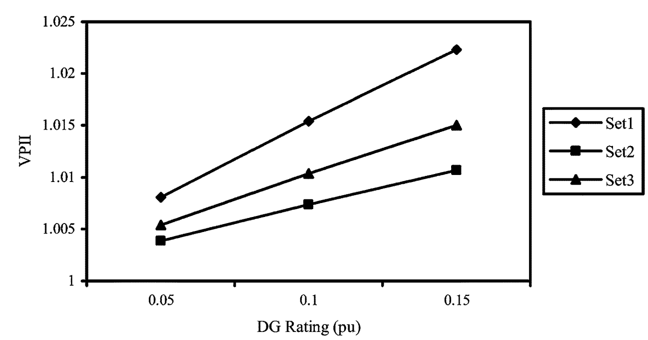

Fig. A-2. Variation of voltage profile improvement index with DG rating for different sets of bus weighting factors (case 3 with DG operating at 0.9-pf lag).

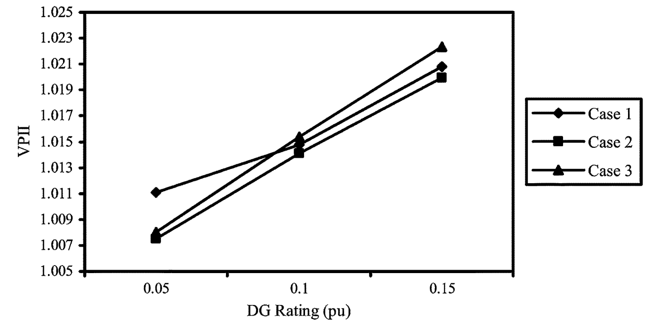

Fig. A-3. Voltage profile improvement results with different DG ratings (DG operating at 0.9-pf lag and equal bus weighing factor used).

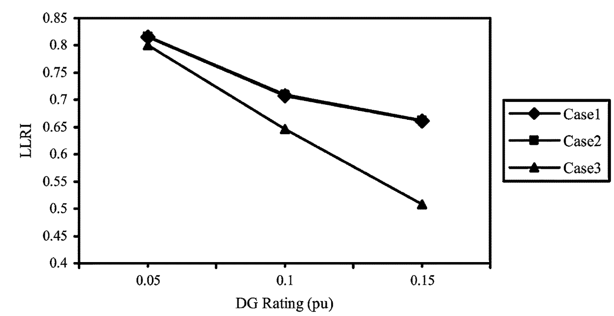

Fig. A-4. Variation of line-loss reduction index with DG rating (DG operating at 0.9-pf lag).

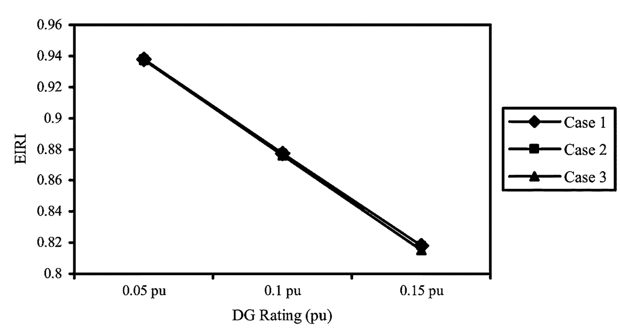

Fig. A-5. Environmental impact reduction results for different DG rating (DG operating at 0.9-pf lag).

Simulation results obtained using two test systems clearly show that DG can improve system voltage profile, reduce electrical line losses, and reduce pollutant emissions. As expected, DG rating plays a vital role in determining the amount of voltage profile improvement and environmental impact reduction. Typically, VPII goes up and EIRI goes down as DG rating increases. However, this trend may not always be applicable to line-loss reduction because the amount of line-loss reduction may actually decrease in some cases. The operating power factor of DG is also important in determining the benefits. The results clearly indicate that introduction of DG is not beneficial to the voltage profile if operated under leading power factor conditions. The location of DG is also significant to both voltage profile improvement and line-loss reduction. However, it should be noted that location and operating power factor of DG have only a minor impact on environmental impact reduction as compared to DG rating.

Line-loss reduction benefit dominates all the rest. Therefore, the choice of unity weighting factor $(\mathrm{BW}_{\mathrm{LLR}} = 1)$ for line-loss reduction yields the highest composite BI.

The results show that case 2 (DG rating maintained at 0.2 pu with 0.8-pf lag) is the best for maximizing the overall benefits of DG when $\mathrm{BW}_{\mathrm{VPI}}, \mathrm{BW}_{\mathrm{LLR}}$, and $\mathrm{BW}_{\mathrm{EIR}}$ are set at 0.6, 0.06, and 0.34, respectively. However, if line-loss reduction is given the maximum importance $(\mathrm{BW}_{\mathrm{VPI}} = 0, \mathrm{BW}_{\mathrm{LLR}} = 1$, and $\mathrm{BW}_{\mathrm{EIR}} = 0)$, the simulation results indicate that case 3 is the best scenario for employing DG. Along the same lines, for the radial system example considered in Appendix A, the proposed approach can be used to identify the best location(s) for DG units depending on the specific requirements.

Clearly, numerous other aspects of DG require analyses and studies. Some of these are: DG modeling, reactive power support, impacts on T&D congestion, economic analysis, detailed reliability analysis, impact of DG on voltage regulation and the interaction of DG with voltage regulation devices such as ULTC, LDC, and capacitors, optimizing the operating schedules of DG, incorporation of the temporal and other characteristics of loads, and potential impacts on system stability. All these offer rich and fertile grounds for many future studies.

TABLE A-1
LOAD DATA FOR RADIAL SYSTEM UNDER STUDY

Load Point	Load (pu)	Power Factor (lag)
L2	0.3000	0.91
L3	0.1000	0.93
L4	0.1250	0.94
L5	0.0750	0.94
L6	0.0750	0.94
L7	0.0625	0.95
L8	0.0500	0.94
L9	0.0500	0.95

TABLE A-2
DISTRIBUTION LINE LENGTH DATA

From Bus	To Bus	Length (km)
1	2	10
1	3	20
1	4	30
3	5	15
4	6	15
5	7	10
6	8	10
7	9	15

TABLE A-3
ASSUMED LOAD BUS WEIGHTING FACTOR SETS

Bus	Set#1	Set#2	Set#3
2	0.125	0.358	0.250
3	0.125	0.119	0.100
4	0.125	0.149	0.050
5	0.125	0.090	0.100
6	0.125	0.090	0.050
7	0.125	0.075	0.150
8	0.125	0.060	0.100
9	0.125	0.060	0.200

APPENDIX A

A nine-bus radial distribution test system is shown in Fig. A-1. A total load of 0.8375 pu (on a 400 MVA base) is located unevenly at various buses as listed in Table A-1. Lengths of different segments of the distribution system are listed in Table A-2. Line and generator parameters are assumed to be the same as discussed in the main paper for the test system shown in Fig. 1. Three sets of load bus weighting factors are considered as listed in Table A-3.

Three cases are simulated and studied. The cases considered are listed below:

Case 1) DG located at bus 9;
Case 2) DG located at bus 8;
Case 3) 50% of DG is located at bus 9 and the remaining 50% is located at bus 8 (Fig. A-2).

The DG unit(s) is assumed to operate at a power factor of 0.9 lag in all cases.

It can be seen from the results listed in Table A-4 that the best location for a DG rated 0.05 pu is at Bus 9 (corresponding to Case 1), no matter which set of weighting factors is used. With a total installed DG capacity of 0.1 pu, the best VPII is obtained with Case 3 for weighting factor set 1, Case 2 for set 2 and Case 1 for set 3. When the total installed DG capacity is 0.15 pu, the best cases in terms of VPII are Case 3 for sets 1 and 2 and Case 1 for set 3 (Fig. A-3). The load bus weighting factors selected on the basis of the significance of different loads do influence the best place to locate DG based on overall voltage profile improvement.

TABLE A-4
TABULATION OF SELECTED CASES OF VOLTAGE PROFILE IMPROVEMENT INDEX WITH DIFFERENT SET OF LOAD BUS WEIGHTING FACTOR

Case	Set#1	Set#2	Set#3
Case 1 with 0.05 pu rating	1.011077	1.005767	1.008285
Case 1 with 0.1 pu rating	1.014785	1.006281	1.013569
Case 1 with 0.15 pu rating	1.020807	1.008831	1.019118
Case 2 with 0.05 pu rating	1.007491	1.004008	1.003097
Case 2 with 0.1 pu rating	1.014092	1.007531	1.005831
Case 2 with 0.15 pu rating	1.019928	1.010637	1.008254
Case 3 with 0.05 pu rating	1.008026	1.003845	1.005391
Case 3 with 0.1 pu rating	1.015401	1.007373	1.010348
Case 3 with 0.15 pu rating	1.022333	1.010690	1.014998

The general nature of variation of LLRI (Fig. A-4) and EIRI (Fig. A-5) in the case of the radial system example is similar to the one observed for the test system example of Fig. 1.

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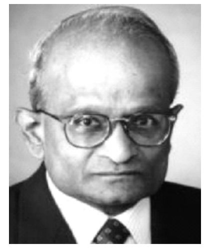

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