A Dual-index Based Analytical Approach for DG Planning Considering Power Losses

Duong Quoc Hung, *Student Member, IEEE*, N. Mithulananthan, *Senior Member, IEEE, and* A. Lomi, *Member, IEEE*

***Abstract*— This paper presents a new multiobjective index-based analytical methodology to calculate the optimal size and power factor of distributed generation (DG) unit at various locations. This multiobjective index (*IMO*) is related to real and reactive power losses. A computational procedure is also developed to specify the best location where the *IMO* value is the lowest. The results obtained on a 38-bus test system demonstrate the effectiveness of the proposed methodology and computational procedure as validated by an exhaustive load flow solution (ELF). The optimal power factor and indices weights can minimize the *IMO* value while maximizing DG penetration and achieving the best voltage profile.**

***Index Terms*— Distributed generation, optimal power factor, optimal size, reactive power loss index, real power loss index.**

I. Introduction

Power industry deregulation, fossil fuel resource depletion, fuel cost uncertainties and environmental concerns have encouraged integration of renewable DG resources (e.g., biomass, wind and solar) in distribution systems. These sources have offered several positive impacts on distribution networks such as loss reduction, voltage and reliability enhancement, network reinforcement deferral, and green house gas emission reduction [1]-[3]. However, accommodating high DG penetration with improper planning and operations in some circumstances may reduce benefits and even jeopardize the performance of the existing systems with high losses and excessive voltage rise [1]-[3].

Real power loss minimization plays a significant role in distribution system performance enhancement [1]-[15]. Similarly, reactive power loss reduction could also play an important role in reducing voltage drops, releasing system capacity and enhancing loadability, voltage stability and security [2]-[5]. Depending on the nature of the distribution system, the former or the latter may be dominant. In some systems, both can play an equal role in improving the system performance. In addition, in competitive electricity market, reactive power provision has been recognized as an ancillary service and hence could have an economic impact on the market [16]. However, most existing studies [1], [6]-[13] have focused on placing DG units to minimize real power or energy loss by neglecting benefits of reactive power loss reduction. Depending on the system characteristics, this would potentially limit DG penetration and subsequently not achieve the best voltage profile. Moreover, some recent researches [2]-[5], [14] have shown the importance of the reactive power loss in DG planning. Consequently, it is critical to assess the mutual impact of real and reactive power losses on optimal DG location and size selection. On the other hand, most analytical approaches presented so far [6]-[13] can address DG placement for real loss reduction as a single-objective. Additionally, a few studies [8]-[11] have indicated the significance of optimal DG power factor operation in minimizing power losses.

This paper proposes a new *IMO*-based analytical methodology and computational procedure to accommodate DG unit for minimizing real and reactive power losses simultaneously. Here, the impact of the optimal power factor and indices weights on the optimal location and size of DG unit are highlighted. The results of the proposed approaches are validated by the ELF solution.

The rest of the paper is structured as follows: Section II describes power losses. Section III presents impact indices related to real and reactive power losses and a combination of both known as *IMO*. Section IV introduces the analytical methodology and computational procedure to accommodate DG unit. Section V portrays the 38-bus test distribution system along with numerical results and discussions. Finally, Section VI summaries the contributions of the work.

II. Power Losses

A. Power Losses without DG Unit

The total real and reactive power losses (i.e., P_L and Q_L) in a distribution system with N buses can be calculated by (1) and (2) respectively, popularly known as "exact loss formula" [17].

$$P_L = \sum_{i=1}^{N}\sum_{j=1}^{N}\left[\alpha_{ij}\left(P_iP_j + Q_iQ_j\right) + \beta_{ij}\left(Q_iP_j - P_iQ_j\right)\right] \qquad (1)$$

$$Q_L = \sum_{i=1}^{N}\sum_{j=1}^{N}\left[\gamma_{ij}\left(P_iP_j + Q_iQ_j\right) + \xi_{ij}\left(Q_iP_j - P_iQ_j\right)\right] \qquad (2)$$

where $\alpha_{ij} = \frac{r_{ij}}{V_iV_j}\cos(\delta_i - \delta_j)$; $\beta_{ij} = \frac{r_{ij}}{V_iV_j}\sin(\delta_i - \delta_j)$;

$\gamma_{ij} = \frac{x_{ij}}{V_iV_j}\cos(\delta_i - \delta_j)$; $\xi_{ij} = \frac{x_{ij}}{V_iV_j}\sin(\delta_i - \delta_j)$;

$V_i\angle\delta_i$ is complex voltage at the bus i^{th}; $r_{ij} + jx_{ij} = Z_{ij}$ is the

D. Q. Hung and N. Mithulananthan are with the School of Information Technology and Electrical Engineering, the University of Queensland, Brisbane, Qld. 4072, Australia (e-mail: hung.duong@uq.edu.au; mithulan@itee.uq.edu.au).

A. Lomi is with the Department of Electrical Engineering, National Institute of Technology, Malang, Indonesia (e-mail: abraham@itn.ac.id).

ij^{th} element of impedance matrix $[Z_{bus}]$; r_{ij} and x_{ij} are the resistance and reactance of a line between bus *i* and *j*; P_i and P_j are respectively active power injections at the i^{th} and j^{th} buses; Q_i and Q_j are respectively reactive power injections at the i^{th} and j^{th} buses.

B. Power Losses with DG Unit

The active and reactive power injection at bus *i* where DG unit is installed is respectively given as follows [8]

$$P_i = P_{DGi} - P_{Di} \tag{3}$$

$$Q_i = Q_{DGi} - Q_{Di} = a_i P_{DGi} - Q_{Di} \tag{4}$$

where $Q_{DGi} = a_i P_{DGi}$, $a_i = (sign)\tan(\cos^{-1}(pf_{DGi}))$, $sign = +1$: DG unit injecting reactive power, $sign = -1$: DG unit consuming reactive power; P_{DGi} and Q_{DGi} are respectively the real and reactive power injections from DG unit at bus *i*; P_{Di} and Q_{Di} are respectively the real and reactive power of load at bus *i*; pf_{DGi} is the operating power factor of DG unit at bus *i*.

Substituting (3) and (4) into (1) and (2), we can obtain the total real and reactive power losses with DG unit (i.e., P_{LDG} and Q_{LDG}) as follows

$$P_{LDG} = \sum_{i=1}^{N}\sum_{j=1}^{N}\begin{bmatrix} \alpha_{ij}\left((P_{DGi}-P_{Di})P_j + (a_i P_{DGi}-Q_{Di})Q_j\right) \\ +\beta_{ij}\left((a_i P_{DGi}-Q_{Di})P_j - (P_{DGi}-P_{Di})Q_j\right)\end{bmatrix} \tag{5}$$

$$Q_{LDG} = \sum_{i=1}^{N}\sum_{j=1}^{N}\begin{bmatrix} \gamma_{ij}\left((P_{DGi}-P_{Di})P_j + (a_i P_{DGi}-Q_{Di})Q_j\right) \\ +\xi_{ij}\left((a_i P_{DGi}-Q_{Di})P_j - (P_{DGi}-P_{Di})Q_j\right)\end{bmatrix}. \tag{6}$$

It is revealed from (5) and (6) that the system real and reactive power loss is as a function of: both P_{DGi} and Q_{DGi} or both P_{DGi} and a_i (or pf_{DGi}). Such variables have a significant impact on the system power loss.

III. Impact Indices and Multiobjective Index

A. Impact Indices

System losses are a key consideration particularly given to economic and environmental efficiency [2]. A beneficial DG placement would reduce losses. In this paper, two real and reactive power loss indices are calculated to evaluate the impact of DG inclusion in a distribution system. These indices play a critical role in DG planning and operation due to their significant impacts on utility revenue and system power quality [3], [5]. They can be defined as follows [2]-[5], [14]:

1) Real Power Loss Index (ILP): is defined as the ratio of the total real power loss of the distribution system after and before DG inclusion (P_{LDG} and P_L).

$$ILP = \frac{P_{LDG}}{P_L}. \tag{7}$$

2) Reactive Power Loss Index (ILQ): is defined as the ratio of the total reactive power loss of the distribution system with and without DG unit (Q_{LDG} *and* Q_L).

$$ILQ = \frac{Q_{LDG}}{Q_L}. \tag{8}$$

B. Multiobjective Index

The multiobjective index (*IMO*) for the performance evaluation of the distribution network with DG unit considers the real and reactive power indices by strategically giving a weight to each one. This can be performed as all impact indices were normalized (values between 0 and 1). *IMO* can be expressed as

$$Minimize\ \ IMO = \sigma_1 ILP + \sigma_2 ILQ \tag{9}$$

where $\sum_{i}^{2}\sigma_i = 1.0 \wedge \sigma_i \in [0,1]$.

These weights are intended to give the corresponding importance to each impact index due to DG inclusion and depend on the required analysis (e.g., planning, operation and cost) [2]-[5], [14]. In this study, the active power loss receives a significant weight of 0.6, leaving the reactive power loss weight of 0.4. These weights are reflecting a real power loss cost higher than a reactive power loss cost. However, investigation of the impact of weight variations on optimal location, size and power factor of DG unit is also explained in section V.D.

IV. Proposed Methodology

A. Optimal Size and Power Factor at Various Locations

Substituting (7) and (8) into (9), we obtain

$$IMO = \frac{\sigma_1}{P_L}P_{LDG} + \frac{\sigma_2}{Q_L}Q_{LDG}. \tag{10}$$

It is obvious that equation (10) has two components, real and reactive power losses. When DG unit is connected at any bus in a distribution system, the variation of each component as a function of the DG penetration level related to active power DG size and its value *a* show a U-shaped trajectory. Consequently, *IMO* also follows a U-shaped curve. It can reach a minimum value if the partial derivative of (10) with respect to the active power injection from DG unit and value *a* at bus *i* (P_{DGi} and a_i) become zero.

$$\frac{\partial IMO}{\partial P_{DGi}} = \frac{\sigma_1}{P_L}\frac{\partial P_{LDG}}{\partial P_{DGi}} + \frac{\sigma_2}{Q_L}\frac{\partial Q_{LDG}}{\partial P_{DGi}} = 0 \tag{11}$$

$$\frac{\partial IMO}{\partial a_i} = \frac{\sigma_1}{P_L}\frac{\partial P_{LDG}}{\partial a_i} + \frac{\sigma_2}{Q_L}\frac{\partial Q_{LDG}}{\partial a_i} = 0. \tag{12}$$

The derivative of (11) and (12) with respect to P_{DGi} and a_i can be expressed as

$$\frac{\partial P_{LDG}}{\partial P_{DGi}} = 2\sum_{j=1}^{N}\left[\alpha_{ij}\left(P_j + a_i Q_j\right) + \beta_{ij}\left(a_i P_j - Q_j\right)\right] \tag{13}$$

$$\frac{\partial Q_{LDG}}{\partial P_{DGi}} = 2\sum_{j=1}^{N}\left[\gamma_{ij}\left(P_j + a_i Q_j\right) + \xi_{ij}\left(a_i P_j - Q_j\right)\right] \tag{14}$$

$$\frac{\partial P_{LDG}}{\partial a_i} = 2\sum_{j=1}^{N}\left[\alpha_{ij} Q_j + \beta_{ij} P_j\right] \tag{15}$$

$$\frac{\partial Q_{LDG}}{\partial a_i} = 2\sum_{j=1}^{N}\left[\gamma_{ij} Q_j + \xi_{ij} P_j\right]. \tag{16}$$

Substituting equations (13) and (14) into (11), we get

$$\begin{aligned}&\frac{2\sigma_1}{P_L}\sum_{j=1}^{N}\left[\alpha_{ij}\left(P_j + a_i Q_j\right) + \beta_{ij}\left(a_i P_j - Q_j\right)\right] \\ &+ \frac{2\sigma_2}{Q_L}\sum_{j=1}^{N}\left[\gamma_{ij}\left(P_j + a_i Q_j\right) + \xi_{ij}\left(a_i P_j - Q_j\right)\right] = 0\end{aligned}. \tag{17}$$

Equation (17) can be rearranged as follows

$$\begin{aligned}&\frac{\sigma_1}{P_L}\left[\alpha_{ii}\left(P_i + a_i Q_i\right) + A_i + a_i B_i\right] \\ &+ \frac{\sigma_2}{Q_L}\left[\gamma_{ii}\left(P_i + a_i Q_i\right) + C_i + a_i D_i\right] = 0\end{aligned} \tag{18}$$

where $A_i = \sum_{\substack{j=1\\ j\neq i}}^{n}\left(\alpha_{ij} P_j - \beta_{ij} Q_j\right)$; $B_i = \sum_{\substack{j=1\\ j\neq 1}}^{n}\left(\alpha_{ij} Q_j + \beta_{ij} P_j\right)$;

$C_i = \sum_{\substack{j=1\\ j\neq i}}^{n}\left(\gamma_{ij} P_j - \xi_{ij} Q_j\right)$; $D_i = \sum_{\substack{j=1\\ j\neq 1}}^{n}\left(\gamma_{ij} Q_j + \xi_{ij} P_j\right)$.

Substituting (3) and (4) into (18), we obtain

$$P_{DGi} = \frac{\left[\begin{array}{l}\left(\frac{\sigma_1}{P_L}\alpha_{ii} + \frac{\sigma_2}{Q_L}\gamma_{ii}\right)\left(P_{Di} + a_i Q_{Di}\right) \\ -\frac{\sigma_1}{P_L}\left(A_i + a_i B_i\right) - \frac{\sigma_2}{Q_L}\left(C_i + a_i D_i\right)\end{array}\right]}{\left(a_i^2 + 1\right)\left(\frac{\sigma_1}{P_L}\alpha_{ii} + \frac{\sigma_2}{Q_L}\gamma_{ii}\right)}. \tag{19}$$

Similarly, substituting (15) and (16) into (12), we get

$$\frac{2\sigma_1}{P_L}\sum_{j=1}^{N}\left(\alpha_{ij} Q_j + \beta_{ij} P_j\right) + \frac{2\sigma_2}{Q_L}\sum_{j=1}^{N}\left(\gamma_{ij} Q_j + \xi_{ij} P_j\right) = 0. \tag{20}$$

Equation (20) can be rearranged as follows

$$\frac{\sigma_1}{P_L}\left(\alpha_{ii} Q_i + B_i\right) + \frac{\sigma_2}{P_L}\left(\gamma_{ii} Q_i + D_i\right) = 0. \tag{21}$$

Substituting (3) and (4) into (21), we get

$$a_i = \frac{Q_{Di}}{P_{DGi}} - \frac{\frac{\sigma_1}{P_L}B_i + \frac{\sigma_2}{Q_L}D_i}{P_{DGi}\left(\frac{\sigma_1}{P_L}\alpha_{ii} + \frac{\sigma_2}{Q_L}\gamma_{ii}\right)}. \tag{22}$$

Finally, the P_{DGi} and a_i, where the value of *IMO* can reach a minimum level, can be obtained from (19) and (22) as

$$P_{DGi} = P_{Di} - \frac{\frac{\sigma_1}{P_L}A_i + \frac{\sigma_2}{Q_L}C_i}{\frac{\sigma_1}{P_L}\alpha_{ii} + \frac{\sigma_2}{Q_L}\gamma_{ii}} \tag{23}$$

$$a_i = \frac{\left(\frac{\sigma_1}{P_L}\alpha_{ii} + \frac{\sigma_2}{Q_L}\gamma_{ii}\right)Q_{Di} - \left(\frac{\sigma_1}{P_L}B_i + \frac{\sigma_2}{Q_L}D_i\right)}{\left(\frac{\sigma_1}{P_L}\alpha_{ii} + \frac{\sigma_2}{Q_L}\gamma_{ii}\right)P_{Di} - \left(\frac{\sigma_1}{P_L}A_i + \frac{\sigma_2}{Q_L}C_i\right)}. \tag{24}$$

The optimal power factor of DG unit at each bus *i* (opf_{DGi}) can be obtained from (24) as follows

$$opf_{DGi} = \cos\left(\tan^{-1}\left(a_i\right)\right). \tag{25}$$

B. Computational Procedure

In this study, the approximate *IMO* approach to specify the optimal location that is similar to the approximate loss method reported in [7] is adopted. This procedure requires load flow to be carried out only twice, one for the system without DG unit and another for the system with added DG unit to obtain the final solution. Hence, the proposed computational procedure is less computationally demanding.

Step 1: Set real and reactive power loss weights (σ_1 and σ_2).
Step 2: Run base case load flow and find P_L and Q_L using (1) and (2) respectively.
Step 3: Find the optimal size and power factor for each bus using (23) and (25), respectively.
Step 4: Place DG unit obtained earlier at each bus. Calculate approximate values: P_{LDG}, Q_{LDG} and *IMO* for each case using (5), (6) and (10), respectively.
Step 5: Locate the optimal bus where *IMO* is the lowest with the corresponding optimal size at that bus.
Step 6: Run load flow with the DG unit obtained in *step 5* and calculate exact values: $P_{LDG,}$ Q_{LDG} and *IMO* using (5), (6) and (10), respectively.

When the power factor of DG unit is pre-specified, the computational procedure is similar to the above with the exception that the optimal DG size for each bus is calculated using (19) rather than (23).

V. Case Study

A. Test Systems

The proposed methodology has been applied to a 12.66 kV 38-bus radial distribution system. The complete system data are given in [14]. This system is supplied from one substation with a total load of 3.715 MW and 2.300 MVar. DG unit considered is a renewable energy source with predicable output (e.g., biomass) that is normally employed for combined heat and power (CHP) applications, and can be placed at any bus. It is modeled as a synchronous machine that can operate at any desired power factor. It is further assumed that DG unit is owned and operated by distribution network operators.

The proposed methodology has been developed and simulated in MATLAB environment. To validate the effectiveness of the proposed method, the exhaustive load flow (ELF) approach as an exact solution has also been developed in Matlab environment. DG unit is placed at each bus. Its size is changed from 0% to 100% of the total system load demand plus loss in each step of 0.25%. The power factor of DG unit is also varied for each case from 0 to unity (leading/lagging) in each step of 0.001. The *IMO* value is calculated for each case by load flow analyses. The optimal location, size, and power factor are obtained in the case where the *IMO* value is the lowest without any voltage violations.

B. Optimal Sizes and Power Factors at Various Locations

After base case load flow analysis, the optimum sizes and power factors of DG unit at various buses with the corresponding indices: real power loss (*ILP),* reactive power loss *(ILQ)* and multiobjective (*IMO)* are obtained in Fig. 1. This indicates the importance of the DG location close to load for minimizing indices. The optimum sizes at buses are significantly different in the range from 0.33 to 4.60 MVA. The largest size is found at bus 2, closest to the substation bus, where the *IMO* value is the highest. The power factors at various buses are in the broad range from 0.76 to 0.89 lagging as the load power factors at buses are substantially different in the large range from 0.31 to 0.99 lagging. As far as one bus is concerned, the respective figure would provide the optimum size and corresponding optimal power factor to which the *IMO* value is the lowest. As shown in Fig. 1, the optimum location is bus 6 where the approximate *IMO* value is 0.3554 with the corresponding optimal size of 2.983 MVA and lagging power factor of 0.8221. After running load flow again with DG unit obtained at bus 6 only, the accurate *IMO* value is 0.3252 with a difference of nearly 8.85%. However, this difference has no impact on the final solution of the optimum location, size and power factor. It is also observed that the *IMO*, *ILP* and *ILQ* values follow an almost similar pattern. At each bus, the *ILP* value is lower than the *ILQ* value, indicating that the real loss reduction due to DG placement has a more positive impact on the *IMO* value than reactive loss reduction in this system. However, this depends on system load characteristics. The system loss reaches a significant reduction level of 61.38 kW and 48.22 kVAr from the base case loss of 202.21 kW and 134.85 kVAr.

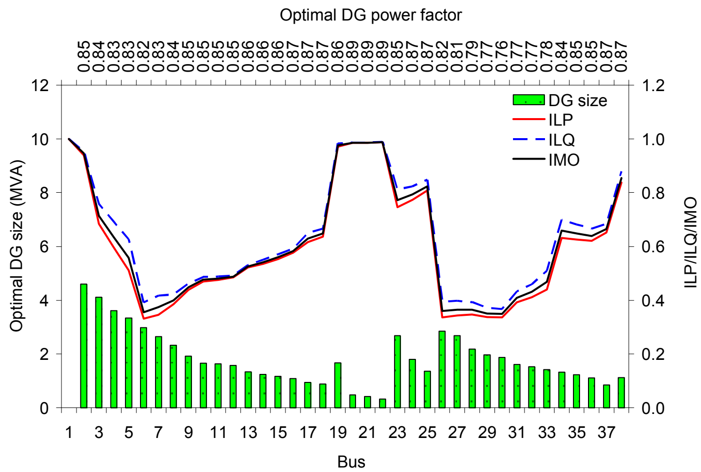

Fig. 1. Optimal DG sizes and power factors at various locations.

Table I summarizes the optimum location, size and power factor of DG unit and its corresponding *IMO, ILP* and *ILQ* values and power losses. The results of the proposed method are in close agreement with the ELF solution. The optimal location, power factor and *ILQ* value and reactive power loss of both approaches are the same. The difference in the size, *IMO* and *ILP* values and real power loss between both approaches is negligible. In addition, the computational time of the proposed approach is insignificantly shorter than that of the ELF solution.

TABLE I
COMPARISON OF DG PLACEMENT RESULTS AT OPTIMAL LOCATION

Method	Bus	S_{DG} (MVA)	opf_{DG} (lag)	*ILP*	*ILQ*	*IMO*	P_{LDG} (kW)	Q_{LDG} (kVAr)	CPU (s)
ELF	6	3.043	0.8221	0.3030	0.3576	0.3248	61.26	48.22	> 134.78
Proposed	6	2.983	0.8221	0.3036	0.3576	0.3252	61.38	48.22	0.06

TABLE II
COMPARISON OF DG PLACEMENT RESULTS WITH DIFFERENT POWER FACTORS

Power factor	Bus	S_{DG} (MVA)	*ILP*	*ILQ*	*IMO*	P_{LDG} (kW)	Q_{LDG} (kVAr)
0.85 leading	8	0.989	0.8789	0.8896	0.8805	177.72	119.96
Zero (Q_{DG} only)	30	1.208	0.7089	0.7126	0.7104	143.35	96.09
Unity (P_{DG} only)	6	2.452	0.5141	0.5534	0.5298	103.94	74.61
0.85 lagging	6	2.979	0.3050	0.3592	0.3267	61.67	48.43

C. Power Factor Impact

Table II shows the results of DG placement with different power factors using the proposed approach. The power factors are pre-specified at 0.85 leading, zero, unity and 0.85 lagging. The operating power factor has a significant impact on the location, size, *IMO, ILP* and *ILQ* values and power losses. For instance, when DG unit operates at 0.85 leading power factor, the optimal location is bus 8 and the optimal size is 0.989 MVA. The *IMO, ILP and ILQ* values are respectively 0.8805, 0.8789 and 0.8896. The corresponding real and reactive power losses are 177.72 kW and 119.96 kVAr respectively. These results are remarkably different from the optimal solution when DG unit operates at the optimal power factor of 0.8221 lagging as described earlier in Table I.

Fig. 2 shows the voltage profiles of the system without DG unit and with DG unit considering different power factors. In the absence of DG unit, the voltages at several buses are under the lower limit of 0.94 p.u. [18]. On the other hand, when DG unit with unity or lagging power factors is connected to the system, the bus voltages improve significantly within acceptable limits of 0.94 and 1.06 p.u [18]. It is worth mentioning that DG unit operating at the optimal power factor can produce better voltage profile enhancement than other DG unit running at non-optimal power factors (e.g., 0.85 leading).

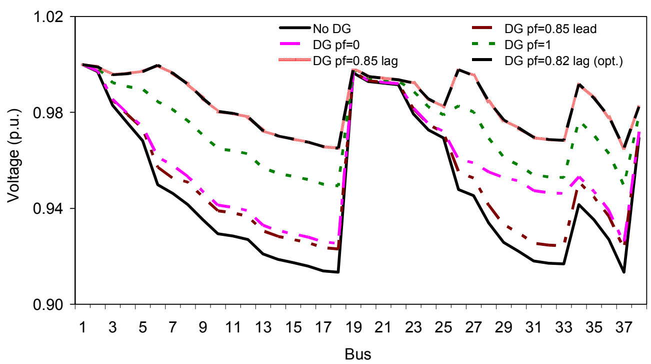

Fig. 2. Voltage profiles with different DG power factors.

Overall, it is revealed from the results that the DG unit operating at optimal power factor can minimize the *IMO* value, while maximizing penetration (optimal DG size) and achieving the best voltage profile enhancement compared to DG unit with other power factors. However, when the real and reactive power loss weights are optimally chosen, a better result can be obtained as explained in the next section.

D. *Weight Impact Considering Optimal Power Factor*

It is assumed that the real and reactive power loss costs are neglected in weight selection. Consequently, technical and environment benefits are considered. Table III shows the results of DG placement at the optimal power factor for the system with various weights. The real power loss weight (σ_1) is varied in the range from 0 to 1 in a small step of 0.1. The reactive power loss weight (σ_2) is subsequently equal to be 1 minus σ_1.

It is observed that the weights have a significant impact on the location, size and power factor of DG unit and its corresponding *IMO, ILP* and *ILQ* values and power losses. When weight σ_1 is in the range from 0 to 0.4, the optimal location is bus 30 and the optimal power factor is approximately 0.76 (lagging). On the other hand, when weight σ_1 is in between 0.5 and 1, the optimal bus is bus 6, and the optimal power factor is roughly 0.82 (lagging). The *IMO* value and its corresponding *ILP* value reduce and the optimal DG size raises when weight σ_1 increases. The lowest *ILP* value is obtained when weight σ_1 is unity. In contrast, the minimum *ILQ* value is achieved when weight σ_1 is 0.4. However, the optimal solution is obtained when weight σ_1 reaches unity at which the *IMO* value is 0.3032. In this case, the *ILP* value is 0.3032 that is lower than the *ILQ* value of 0.3576. This indicates that the *ILP* value due to DG insertion has a more positive impact on the *IMO* value than the *ILQ* value.

TABLE III
COMPARISON OF DG PLACEMENT RESULTS AT OPTIMAL POWER FACTOR WITH DIFFERENT WEIGHTS

σ_1	σ_2	Bus	S_{DG} (MVA)	opf_{DG} *(lag)*	*ILP*	*ILQ*	*IMO*	P_{LDG} (kW)	Q_{LDG} (kVAr)
0	1	30	1.818	0.7591	0.3214	0.3471	0.3471	65.00	46.80
0.1	0.9	30	1.827	0.7599	0.3210	0.3469	0.3443	64.91	46.78
0.2	0.8	30	1.836	0.7608	0.3205	0.3468	0.3415	64.82	46.76
0.3	0.7	30	1.845	0.7616	0.3201	0.3466	0.3387	64.73	46.74
0.4	0.6	30	1.854	0.7624	0.3197	0.3465	0.3358	64.65	46.73
0.5	0.5	6	2.974	0.8219	0.3037	0.3577	0.3307	61.41	48.23
0.6	0.4	6	2.983	0.8221	0.3036	0.3576	0.3252	61.38	48.22
0.7	0.3	6	2.991	0.8224	0.3034	0.3576	0.3197	61.36	48.22
0.8	0.2	6	3.000	0.8226	0.3033	0.3576	0.3142	61.34	48.22
0.9	0.1	6	3.008	0.8228	0.3032	0.3576	0.3087	61.32	48.22
1	***0***	***6***	***3.017***	***0.8230***	***0.3032***	***0.3576***	***0.3032***	***61.30***	***48.22***

In addition, it is seen from Table III that the optimal size for weight σ_1 of unity is 3.017 MVA with an optimal power factor of 0.8230 (lagging). This value is considerably larger than 1.818 MVA with 0.7591 (lagging) for weight σ_1 of zero. However, the difference in real and reactive power losses between both cases is insignificant, at 5.69 % and 2.94 % respectively. This indicates the importance of optimal power factor selection with the corresponding weight.

Fig. 3 illustrates the voltage profiles with different weights for the system, considering the optimal power factor for each case. The best voltage profile is obtained when DG unit is placed with weight σ_1 of unity. However, the voltage profiles with weights zero and 0.6 are insignificantly different from that with weight σ_1 of unity. This is due to the fact that the power factor is optimally selected with the corresponding weights as previously mentioned.

Overall, it is found from the results that when DG unit operating at the optimal power factor and indices weights simultaneously can lead to the lowest *IMO* value while maximizing DG penetration and achieving the best voltage profile enhancement. Subsequently, environmental benefits can be obtained as a result of increasing renewable DG penetration and reducing usage of fossil fuel energy resources.

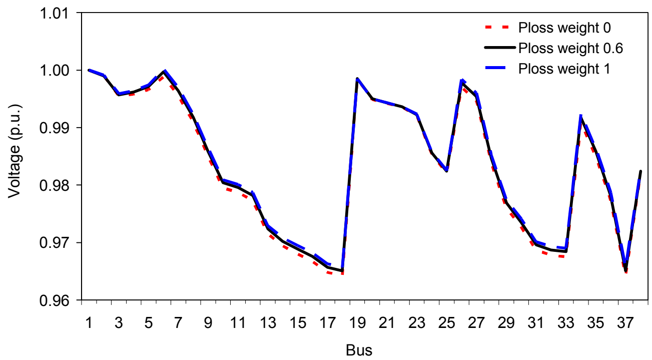

Fig. 3. Voltage profiles with different weights considering optimal power factor.

VI. Conclusions

This paper has proposed a new multiobjective index-based analytical methodology for sizing DG unit for each location where the significance of the optimal DG power factor is highlighted. The multiobjective index (*IMO*) based on *ILP* and *ILQ* indices related to real and reactive power losses is utilized. A computational procedure has been developed to identify the best placement where the *IMO* value is the lowest, corresponding to the optimal size and power factor at that location. This approach can also be utilized as a useful tool for assessing the mutual impact of real and reactive power losses on optimal location, size and power factor of DG unit. The numerical results show the effectiveness of the proposed approach as verified by the exhaustive load flow solution in terms of optimal power factor, loss reduction and computational time. The significant impact of indices weights on the optimal location, size, power factor, *IMO* value and power losses has been observed. It is worth mentioning that optimizing power factor and indices weights simultaneously can minimize the *IMO* value, while maximizing DG penetration and achieving the best voltage profile enhancement.

References

[1] D. Gautam and N. Mithulananthan, "Optimal DG placement in deregulated electricity market," *Elect. Power Systs. Res.*, vol. 77, no. 12, pp. 1627-1636, Oct. 2007.
[2] L. F. Ochoa, A. Padilha-Feltrin, and G. P. Harrison, "Evaluating distributed generation impacts with a multiobjective index," *IEEE Trans. Power Del.*, vol. 21, no. 3, pp. 1452-1458, July 2006.
[3] L. F. Ochoa, A. Padilha-Feltrin, and G. P. Harrison, "Evaluating distributed time-varying generation through a multiobjective index," *IEEE Trans. Power Del.*, vol. 23, no. 2, pp. 1132-1138, Apr. 2008.
[4] A. M. El-Zonkoly, "Optimal placement of multi-distributed generation units including different load models using particle swarm optimisation," *IET Gener. Transm. Distrib.*, vol. 5, no. 7, pp. 760-771, July 2011.
[5] D. Singh and K. S. Verma, "Multiobjective optimization for DG planning with load models," *IEEE Trans. Power Syst.*, vol. 24, no. 1, pp. 427-436, Jan. 2009.
[6] C. Wang and M. H. Nehrir, "Analytical approaches for optimal placement of distributed generation sources in power systems," *IEEE Trans. Power Syst.*, vol. 19, no. 4, pp. 2068-2076, Nov. 2004.
[7] N. Acharya, P. Mahat, and N. Mithulananthan, "An analytical approach for DG allocation in primary distribution network," *Int. J. Elect. Power Energy Syst.*, vol. 28, no. 10, pp. 669-678, Dec. 2006.
[8] D. Q. Hung, N. Mithulananthan, and R. C. Bansal, "Analytical expressions for DG allocation in primary distribution networks," *IEEE Trans. Energy Convers.*, vol. 25, no. 3, pp. 814-820, Sep. 2010.
[9] D. Q. Hung and N. Mithulananthan, "Multiple distributed generator placement in primary distribution networks for loss reduction," *IEEE Trans. Ind. Electron.*, to be published.
[10] D. Q. Hung and N. Mithulananthan, "Alternative analytical approaches for renewable DG allocation for energy loss minimization," accepted for presenting at IEEE/PES General Meeting, USA, 22-26 July, 2012.
[11] D. Q. Hung and N. Mithulananthan, "An optimal operating strategy of DG unit for power loss reduction in distribution systems," accepted for presenting at ICIIS-2012, Chennai, India, 06-09 Aug., 2012.
[12] D. Q. Hung and N. Mithulananthan, "A simple approach for distributed generation integration considering benefits for DNO," accepted for presenting at PowerCon 2012, Auckland, New Zealand, 30 Oct.-02 Nov., 2012.
[13] T. Gözel and M. H. Hocaoglu, "An analytical method for the sizing and siting of distributed generators in radial systems," *Elect. Power Syst. Res.*, vol. 79, no. 7, pp. 912-918, Jun. 2009.
[14] D. Singh and R. K. Misra, "Effect of load models in distributed generation planning," *IEEE Trans. Power Syst.*, vol. 22, no. 4, pp. 2204-2212, Nov. 2007.
[15] D. Q. Hung and N. Mithulananthan, "Community energy storage and capacitor allocation in distribution systems," in *Proc. 21st AUPEC, Brisbane, Australia*, 25-28 Sept. 2011.
[16] C. A. Canizares, K. Bhattacharya, I. El-Samahy, H. Haghighat, J. Pan, and C. Tang, "Re-defining the reactive power dispatch problem in the context of competitive electricity markets," *IET Gener. Transm. Distrib.*, vol. 4, no. 2, pp. 162-177, Feb. 2010.
[17] I. O. Elgerd, *Electric energy system theory: an introduction*. New York: McGraw-Hill Inc., 1971.
[18] G. P. Harrison, A. Piccolo, P. Siano, and A. R. Wallace, "Hybrid GA and OPF evaluation of network capacity for distributed generation connections," *Elect. Power Systs. Res.*, vol. 78, no. 3, pp. 392-398, Mar. 2008.

Duong Quoc Hung (S'11) received the M.Eng. degree in electric power system management from Asian Institute of Technology, Bangkok, Thailand in May 2008. He is currently working toward the Ph.D. degree at the School of Information Technology and Electrical Engineering, the University of Queensland, Australia.

He has had 10-year working experience as an electrical engineer with Southern Power Corporation, Electricity of Vietnam. His research interests are distribution system analysis and distributed generation.

Nadarajah Mithulananthan (SM'10) received the Ph.D. degree in electrical and computer engineering from the University of Waterloo, Ontario, Canada, in 2002, the B.Sc. (Eng.) degree from the University of Peradeniya, Sri Lanka, in May 1993, and the M.Eng degree from the Asian Institute of Technology, Bangkok, Thailand, in August 1997.

He was an electrical engineer with the Generation Planning Branch of the Ceylon electricity Board, and as a project leader with Chulalongkorn University, Bangkok, Thailand. He is currently a senior lecture with the University of Queensland (UQ), Brisbane, Australia. Prior to joining UQ, he was an associate Professor with the Asian Institute of Technology, Bangkok, Thailand. His research interests are the integration of renewable energy in power systems and power system stability and dynamics.

Abraham Lomi (M'2000) received his B. Eng. in Electrical Engineering from National Institute of Technology, Malang, Indonesia, his M. Eng in Electrical Power Engineering from Bandung Institute of Technology, Bandung, Indonesia and his Doctor of Engineering in Electric Power Systems Management from the Asian Institute of Technology, Thailand in 1987, 1992 and 2000, respectively.

He is currently a full Professor at Department of Electrical Engineering, National Institute Technology, Malang, Indonesia. He was assigned as a Visiting Professor at the School of Information Technology and Electrical Engineering, The University of Queensland, Brisbane, UQ, Australia during September to December 2011. Professor Lomi is a member of Indonesian Institute of Engineers and Indonesia Association of Audit Technology. His research interests include power system stability, power electronics, power quality and renewable energy.