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Distributed Generation Planning for Losses, Voltage Profile, Line Congestion and Total System Cost Improvement

S. Porkar [1,2], P. Poure[3], A. Abbaspour-Tehrani-fard [1], S. Saadate[2]

Abstract – *The main goal of this paper is to obtain the optimal Distributed Generation (DG) investments as well as purchase additional power from Transmission Companies (TRANSCOs). To do this, a new mathematical modeling and a new software package interfacing between the two powerful softwares MATLAB and GAMS are used. The proposed model optimizes total system planning costs and consequently costumers' bills, reduces total system losses, guaranties system voltage profiles and prevents feeders' congestion. This new model and software package have been executed in two different cases depending if system voltage profiles are in their permissible margin or not; in each case, three different scenarios are studied, depending on planning problem constraints. The simulation results show the economical and electrical benefits of DG installation by solving the distribution system planning problem and by improving power quality of the distribution system. It is illustrated that DG installation also can increase the main feeders' lifetime by reducing their loading and adds the benefit of using the existing distribution system for further load growth without the need for feeders upgrading.* ***Copyright © 2009 Praise Worthy Prize S.r.l. - All rights reserved.***

Keywords: *Distributed Generation (DG), Distribution System Planning, Distribution Company (DISCO), Transmission Company (TRANSCO), GAMS-MATLAB interface*

Nomenclature

A_{Depr}	Annualized factor
B	total number of system buses possible to connect DG
BCL	DISCO Budget Capacity Limit ($)
C_{Invi}	DG investment cost ($/MVA) = 0.5 M$/MW
$C_{P\,i}$	Active electricity price of TRANSCO number *i* ($/MWh) = 70 $/MWh
$C_{Q\,i}$	Reactive electricity price of TRANSCO number *i* ($/MVar.h)
$C_{O\&M\,i}$	DG operating (power generation and O&M) cost at bus *i* ($/MWh) = 50 $/MWh
d	Discount rate = 10%
G	Total number of TRANSCOs connected to distribution system
Obj	Objective function
$P_{DG\,i}$	DG's generated power at bus *i* (MW)
$P_{DG\,i}^{\max}$	Total DG units capacity limit at bus *i* (MVA)
$P_{G\,i}$	Active power dispatched from TRANSCO number *i* (MW)
$P_{G\,i}^{\max}$	Maximum active power dispatched from TRANSCO number *i* (MW)
P_i^d	Total active power demand at bus *i* (MW)
P_{ij}	Power flow in feeder connecting bus *i* to bus *j* (MW)
$Q_{G\,i}$	Reactive power dispatched from TRANSCO number *i* (MVar)
$Q_{G\,i}^{\max}$	Maximum reactive power dispatched from TRANSCO number *i* (MVar)
$Q_{G\,i}^{\min}$	Minimum reactive power dispatched from TRANSCO number *i* (MVar)
Q_i^d	Total reactive power demand at bus *i* (MVar)
Q_{ij}	Reactive power flow in feeder connecting bus *i* to bus *j* (MVar)
$S_{ij}^{f}(\theta,V)$	Apparent power flow through line connected between *i*,*j* (MVA)
$S_{ij}^{\max}$	Maximum permissible line power flow capacity
T	Horizon planning period (year) = 5 years
V_i	Bus voltage at bus *i*
$V_i^{\max}$	Maximum permissible voltage at bus *i* (V)
$V_i^{\min}$	Minimum permissible voltage at bus *i* (V)

I. Introduction

Deregulation or liberalization of the electricity market will change traditional distribution system planning [1-3]. In these conditions, Distribution Companies (DISCOs) focus on making profit. Thus, DISCOs are mostly tending to maximize the utilization of existing assets and avoid redundant investments [1, 3]. On the other hand, a particular attention is paid on minimization of investment, operation and maintenance costs. Also, system optimization and planning

methodologies are serving as decision-making function, which help to quickly find the best solutions [1].

Taking into account the processes of deregulation and the development of new technologies such as Distributed Generation (DG) as local generation, the traditional approach to the planning of electricity distribution networks must be reconsidered or extended [4-7].

DGs are one of the new attractive capacity options for distribution system planning, which have been predicted to be used extensively in the distribution systems, because of their economical and operational benefits [6-9]. Clearly, DG influences power losses in the distribution systems. Decrease or increase of losses mainly depends on the local power plant size, on its location and on the system power flows. Because of the nonlinearity properties of network equation, there is not a global law to determine the effects of DG sizing and sitting [3, 8-11].

More, DG can improve system voltage profile [9-14]. It is also a potentially cost-effective way to defer Transmission and Distribution (T&D) investment that would otherwise be required to serve growing electrical demand [15-16]. Even though fuel cost may be higher, DG is placed closer to the load and does not require nearly as much transmission and distribution infrastructure to serve loads. Further, DG can be installed in small modular increments rather than the large capacities characteristic of most high voltage lines [17-20].

However, the introduction of DG into distribution systems will significantly complicate distribution planning and operating practices and requires substantially greater data collection and analysis efforts [16, 17]. Consequently, a suited DG sizing and sitting is mandatory. Improper placement or mistaken size of DGs can dramatically reduce their benefits: It can even increase system losses or total system cost [1].

In this paper, a new distribution system planning model implementing DG is proposed. This model optimizes total system cost including investment, operation and DGs' maintenance; cost of purchasing power from the Transmission Companies (TRANSCOs) connected to DISCO's distribution system territory and cost of electrical system power losses. The optimization results determine the optimum size and location of DG as well as optimum required additional power which should be purchased from TRANSCOs.

Three different cases depending on the distribution system conditions and different scenarios depending on planning constraints have been considered to study their effects on choosing the optimum solution. Also, we have studied the effects of DG on guaranteeing acceptable voltage profile and keeping system lines capacity in their safety margins. To solve this optimization problem, a new software package, which consists in a specific interface between GAMS and MATLAB has been developed. To evaluate and validate the proposed model and software package, the IEEE 30-bus system has been used as a study case and results have been discussed.

II. New Mathematical Modelling

In this section, we discuss the mathematical formulation for the new proposed model. The DISCO is considered to be the investor, the owner and the operator of the new installed DGs in the distribution system. The DISCO has the following alternatives to serve its load demand growth:

1) Purchasing the required extra power from the TRANSCOs connected to DISCO's distribution system territory and pumping it to its distribution system through its junction substations without the need for feeders and substations upgrading.
2) Investing in DG as an alternative candidate option to serve load locally.

The objective function proposed in this paper is total electricity market price ($/MWh). By this way, this model proposes a new estimation for billing DISCO's customers. This model is used for total system costs optimization and includes investment, operation and maintenance costs of DGs, cost of purchasing additional power from the TRANSCOs and cost of electrical system power losses. A list if the symbols we used is resumed in Appendix A. The new mathematical problem formulation is the following:

$$Minimize \quad obj = \frac{\left(C_{In\,DG} + C_{O\&M\,DG}\right) + C_E}{\sum_{i=1}^{B} P_{DG\,i} + \sum_{i=1}^{G} P_{G\,i}} \tag{1}$$

Where:

- $C_{In\,DG}$ is the investment of candidate DG, described in Eq. 2 and 3:

$$C_{In\,DG} = \frac{\sum_{i=1}^{B} C_{Inv\,i}.P_{DG\,i}^{\max}}{A_{Depr} * 8760} \tag{2}$$

with series of annualized costs [1, 2] computed from:

$$A_{Depr} = \left[\frac{(1+d)^T - 1}{d(1+d)^T}\right] \tag{3}$$

- $C_{O\&M\,DG}$ is the operating cost of DG, defined by the Eq.4:

$$C_{O\&M\,DG} = \sum_{i=1}^{B} C_{O\&M\,i}.P_{DG\,i} \tag{4}$$

- C_E is the cost of purchasing additional power from TRANSCOs and defined by the Eq. 5:

$$C_E = \sum_{i=1}^{G} C_{p\,i}.P_{G\,i} \tag{5}$$

It is to be noted that the cost of system power losses is included in the total power ($C_{O\&M\ DG} + C_E$) produced by the DGs and purchased from the TRANSCOs. More, there are some security, financial, configuration and operation constraints, which must be satisfied during the whole planning period. These constraints are discussed in the following [20]:

a. Equality constraints

- Active power balance equations:

$$\left(P_{DG\,i} + P_{G\,i}\right) - P_i^d - \sum_{j=1} P_{ij} = 0 \quad (6)$$

- Reactive power balance equations:

$$Q_{G\,i} - Q_i^d - \sum_{j=1} Q_{ij} = 0 \quad (7)$$

b. Inequality constraints

- TRANSCOs generation limits:

$$0 \le P_{G\,i} \le P_{G\,i}^{\max} \quad (8)$$

- Distribution substation's capacity constraints:

$$Q_{G\,i}^{\min} \le Q_{G\,i} \le Q_{G\,i}^{\max} \quad (9)$$

- Apparent power flow limit of lines:

$$\left|S_{ij}\right| \le S_{ij}^{\max} \quad (10)$$

- Bus voltage limits:

$$V_i^{\min} \le V_i \le V_i^{\max} \quad (11)$$

- DGs generation limits:

$$0 \le P_{DGi} \le P_{DGi}^{\max} \qquad \forall i = 1,..., B \quad (12)$$

- Financial limits:

$$\sum_{i=1}^{B} C_{INVi} . P_{DGi}^{\max} \le BCL \quad (13)$$

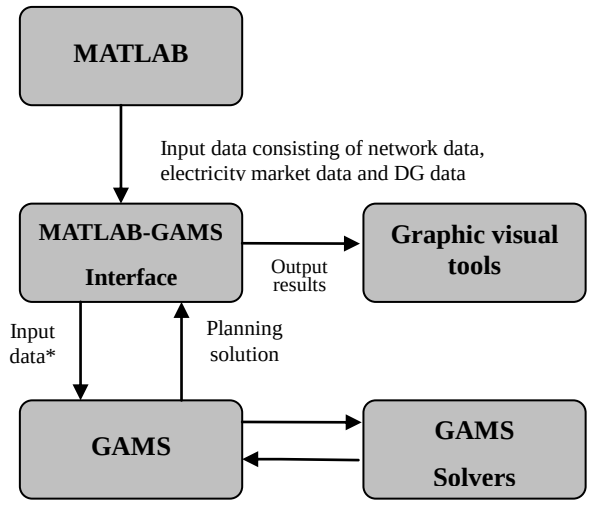
This financial constraint imposes a limit on the value of investment or on the DG capacity that the DISCO can invest in.

III. New Simulation Method

In the one hand, the optimization tools proposed in MATLAB* environment are useful for small-scale nonlinear models; the lack of ability to perform automatic derivatives makes it impractical for large scale nonlinear optimization such as system planning problems considered in this paper.

In the other hand, modeling languages such as General Algebraic Modeling System (GAMS)** have such a capability and have been used in many large scale nonlinear applications. GAMS is a powerful software for solving general mathematical optimization problems. It has been specifically designed for large and complex problems [21] and uses a proprietary language. A large number of solvers for mathematical programming models are proposed in GAMS [21]. GAMS model types include linear programming (LP), mixed-integer programming (MIP), mixed-integer nonlinear programming (MINLP), and different forms of nonlinear programming (NLP) such as Dynamic Non-Linear Programming (DNLP). However, while modeling languages have some capabilities for data manipulation and visualization, to a large extent specialized software tools like MATLAB are much better at these tasks.

As GAMS is not dedicated to the optimization of power applications, it is not user-friendly and entering data and output analysis is not easy at all. So, we developed a specific link between MATLAB and GAMS to solve distribution system planning problem implementing DGs. This link gives to the MATLAB users the ability to use all the optimization capabilities of GAMS, and allows visualization of GAMS models directly by means of a user-friendly Graphic User Interface (GUI) of MATLAB. Complex optimization models can be formulated in GAMS, data (parameter, matrix, sets) can be passed from MATLAB, and solutions can be returned to MATLAB. Fig. 1 shows the structure of this new software package.



* In format of adjustable with GAMS

Fig. 1: MATLAB-GAMS interface

IV. STUDY CASE

In this section, we used the standard IEEE 30-Bus system as study case. It consists of two TRANSCOs connected at buses-1 and 2. The voltage of the buses-1 and 2 is equal to 132KV and the voltage of the other ones is equal to 33KV. The total load of the IEEE 30-Bus system at the horizon year (5 years) is assumed to be increased by 28 % from 242.2 MVA to 310 MVA (283.4MW + 126.2 MVar).

In the proposed model, it is possible to model and

* MATLAB 7.4.0.365 (R14) license GREEN Lab.
** GAMS 22.6 Demo free version.

test different DG technologies (such as Wind turbine, Photovoltaic, Fuel Cell, Microturbine and Combustion Gas Turbine) by only changing the values of DG investment and operating cost ($C_{Inv}, C_{O\&M}$). The technology used in this paper is Combustion Gas Turbine, because sitting of this kind of DG has less environmental restrictions. This kind of technology is also known to be environmentally friendly and produces the least pollution compared to other fossil fuel DGs [17, 22]. The investment cost and the maintenance and operation (M&O) cost of this kind of DG are assumed to be 0.5 M$/MVA and 50 $/MWh respectively [20]. The price of purchasing additional power by the DISCO from the TRANSCOs is equal to 70 $/MWh [1, 11].

The individual DG capacity is equal to 1MVA for a maximum number of 4 DG units installed. According to financial resource limit, the maximum DG groups' capacities are 20 MVA. The discount rate is equal to 10%. It is assumed that the investment of the DG investors return to them after five years ($T = 5yr$) and from the 6th year this amount is their avenue [20].

V. System conditions and problem constraints

The proposed model has been implemented using the proposed software package on two different system conditions and three different system constraints. In the following, two different system conditions are discussed, so called "case I" and "case II".

CASE I: This case study is the standard IEEE 30-Bus system, depicted in the previous section. In this case, system voltage has not any problem even by load growth. In other words, the system voltage profiles are not violated and their permissible limits satisfied.

CASE II: In this case, system voltage profile is out of its permissible margin. To provide this condition, it is assumed that a compensator; for example the compensator at bus number 8 is out of service.

In each case, we have considered three different scenarios (A, B and C) according to different constraints as discussed below.

SCENARIO A:

In this scenario, no financial source has been invested in DG. Therefore, DISCO has only one option to serve load growth in its territory: purchasing additional power from TRANSCOs. This scenario is the reference to compare the effect of DG installation on system losses, cost, voltage profiles and line congestion.

SCENARIO B:

In this scenario, it is assumed that the budget is enough to install 20 MW of DG. The effect of DG installation on total system losses reduction, costs and system voltage profiles' improvement has been studied. The effect on line congestion has been ignored: it is assumed that distribution system feeders' capacity is not violated even by load growth. Therefore, the Eq. 10 is assumed to be satisfied. The maximum and minimum permissible voltages (in per unit) at each bus are equal to 1.05 and 0.96 respectively.

SCENARIO C:

In this scenario, the effect of DG installation on voltage profile, line congestion, total system losses and costs improvement has been considered. So the problem constraints are the same as for the scenario B with additional power flow limit (Eq. 10). To provide this condition, the permissible margins values of lines capacity have been reduced ($S_{ij}^{\max}$).

It is assumed that the distribution feeders have an upper design capacity limit as presented in Table 1 for the total power that can be carried by each feeder during peak loads.

Table 1: Distribution feeders' design capacity limit constraints

Feeder (from-to)	Capacity limit (MW)
1-2 (two lines), 1-3, 3-4, 2-5	80
4-6	70
2-6	55
2-4, 6-7, 4-12, 6-8	40
6-9, 9-10, 5-7	25
6-10, 12-15, 10-21, 27-28, 6-28, 12-16, 10-17, 10-22	20
The others	5

VI. Analysis and results

In this section, the simulation results for each of the two cases I and II (depending on system conditions) and for the three scenarios (depending on problem constraints) are discussed. It is to be noted that without DG installation and with the constraints on system voltage profiles and system feeders' security margin, the studied planning problem has not any solution.

VI.1. CASE I

The results of the three proposed scenarios in the case I are summarized in Table 2. The results of the scenarios B and C are compared with the scenario A (supplying load growth by purchasing additional power from TRANSCOs, without DG installation).

The simulation shows that the combination of purchasing power from TRANSCOs and DG installation presents better solutions. Locations, sizes, and purchased additional power are defined in Table 2. The second row of this table shows the required additional active power (MW) which should be purchased to serve load growth in the three scenarios.

Table 2: Optimum solutions for the three scenarios in the Case I.

		Scenario A	Scenario B	Scenario C
Additional substation purchased (MW)		70,1 @ Bus# 1	47 @ Bus# 1	47,2 @ Bus# 1
Losses	Total loss (MW)	18.031	14.936	15.086
	Loss reduction %	-	17,16	16,33
	Losses Cost ($/h)	1262,17	1045,52	1056,02
DG Capacity (MW) & Location		-	4 @ Bus# 5, 19, 30 3 @ Bus# 24 2 @ Bus# 7, 26 1 @ Bus# 29	4 @ Bus# 19, 30 3 @ Bus# 18, 23 2 @ Bus# 14, 15 1 @ Bus# 24, 26
Electricity Market Price ($/MWh)		70	69,669	69,669
DG installation benefit ($/h)		-	315,860	301,860
Benefit over 5 years compared without DG installation (M$)		-	13,835	13,221

In this optimal solution the additional purchased power in scenarios B and C is reduced by 23.1 MW and 22.9 MW, respectively and instead of it, seven and eight groups of DGs (totally 20 MW for both scenarios) are installed, respectively. The next row of this table summarizes the total system losses. It is shown that DG installation in scenarios B and C has allowed reduction of the power flow in the feeders, reduction of the total system losses by 17.16% and 16.33%, respectively and therefore increased feeders' lifetime. It adds the opportunity to use the existing distribution system for future load growth without the need of feeders upgrading.

The two last rows in Table 2 show the total customer saved money per hour and over five years respectively. These amounts of budget (13.835 M$ or 13.221 M$) are enough to install 27 or 26 MW of above mentioned DG (See Section 4).

Fig. 2 presents the optimum sitting and sizing of DG in the scenarios B and C. As it is shown in this figure, the results may be different according planning problem constraints.

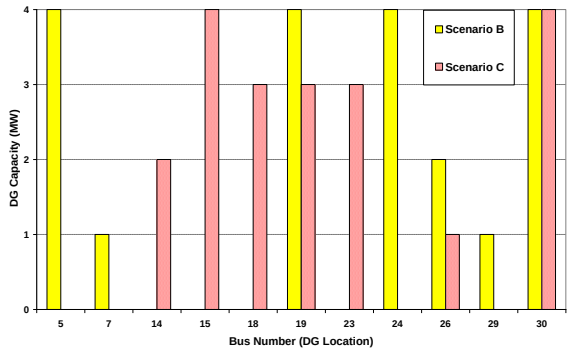


Fig. 2: Optimum location and sizing of DG (case I).

Fig. 3 shows system voltage profiles in the three scenarios. As shown in this figure, without DG installation, system voltage profiles are in their permissible margins. More, with DG installation, system voltage profiles are improved.

System line power flows in the three scenarios are shown in Fig. 4; in this figure, the lines with power flow lower than 10 MW are not shown. The effect of DG size and location on the lines' power flow is especially declared in line between buses number 4 and 12.

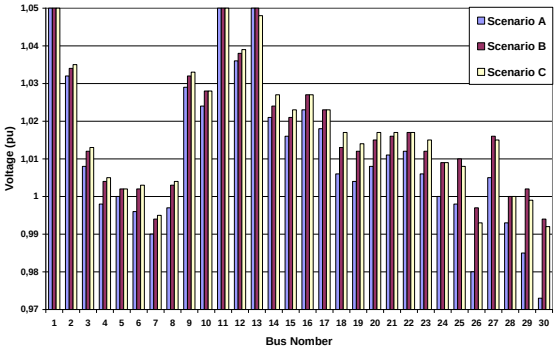


Fig. 3: System voltage profiles (Case I).

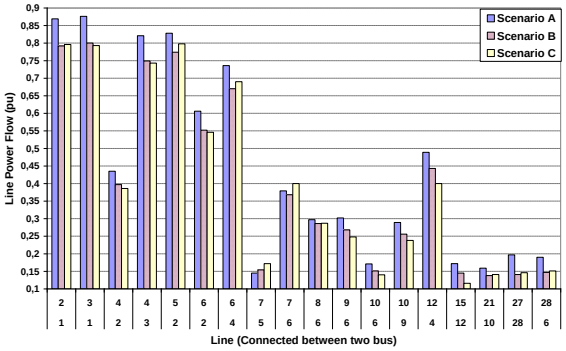


Fig. 4: Lines' power flow for the three scenarios. (Case I)

VI.2. Case II

As discussed before, we study in this case II the effect of DGs on system voltage profile improvement. Therefore, the compensator at bus 8; for example, is supposed to be out of service. Here, DGs should prevent voltage violations as well as reduce the total system losses and costs. The major simulation results are summarized in the Table 3. The optimal sizing and sitting of DG, the system voltage profiles and the system line power flow are shown in Fig. 5, 6 and 7, respectively.

Table 3: Optimum solutions for the three scenarios in the Case II.

		Scenario A	Scenario B	Scenario C
Additional substation purchased (MW)		70.9 @ Bus# 1	47.7 @ Bus# 1	47.9 @ Bus# 1
Losses	Total loss (MW)	18.831	15.564	15.779
	Loss reduction %	-	17,35	16,21
	Losses Cost ($/h)	1318,17	1089,48	1104,53
DG Capacity (MW) & Location		-	4 @ Bus# 5, 19, 24, 30 2 @ Bus# 26 1 @ Bus# 7, 29	4 @ Bus# 15, 30 3 @ Bus# 18, 19, 23 2 @ Bus# 14 1 @ Bus# 26
Electricity Market Price ($/MWh)		70	69,669	69,670
DG installation benefit ($/h)		-	322,860	308,860
Benefit over 5 years compared without DG installation (M$)		-	14,141	13,528

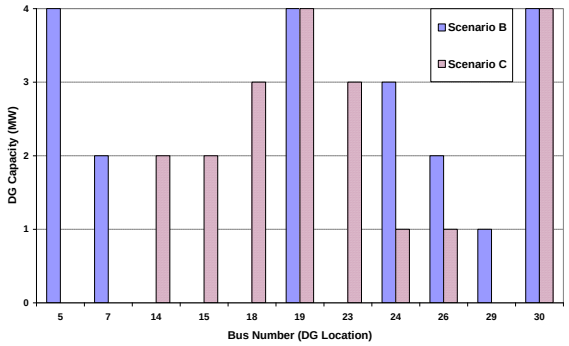


Fig. 5: Optimum location and sizing of DG (Case II).

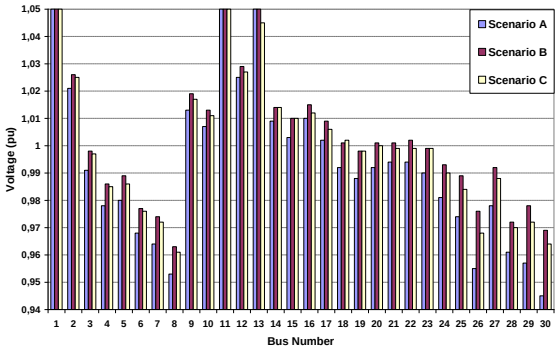


Fig. 6: System voltage profiles (Case II).

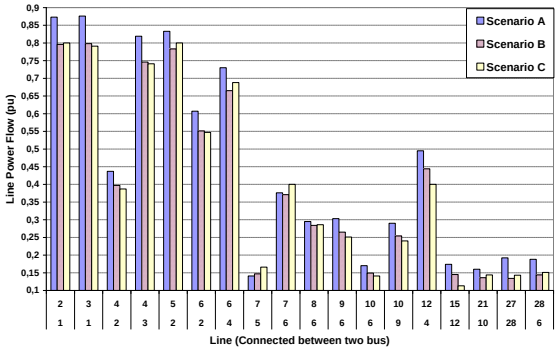


Fig. 7: Line power flow in the three scenarios. (Case II)

As it is shown in Fig. 6, before DG installation (scenario A), voltages are violated at buses numbers 8, 26, 29 and 30 (voltages below 0.96 pu). After DG installation, in scenarios B and C, the system voltage profiles are in their permissible margins. In these cases, DGs have an additional object: they guaranty the system voltage profiles.

VII. Conclusion

This paper has discussed a novel mathematical model for implementing DG as an attractive option in distribution system planning problem. The main object of this framework is to minimize the total costumers' bill. In other words, total system costs must be minimized with simultaneously guarantying system voltage profiles and preventing feeder congestion. More, we have developed a new software package by interfacing the two powerful softwares, MATLAB and GAMS. The resulting framework was implemented successfully to estimate the optimal DG capacity investment (sizing and sitting) to serve peak demands optimally, integrated with purchasing power from TRANSCOs. The IEEE 30-Bus system has been chosen as study case.

In this paper, to provide a condition to study effect of DG on voltage profiles guarantying, we have changed a part of the standard IEEE system by considering that the compensator at bus number 8 is out of service. The results also show that this new system condition changes the optimum solution. Three different scenarios according planning constraints have been studied. The proposed model is presented, simulated and discussed for the two studied system conditions and the three different planning problem constraints, portrayed in the paper. The results vary over the system conditions and the type of scenario under study.

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