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Optimal Distributed Generation Expansion Planning Based on Techno-Economical Analysis

Mohammad Sadegh Javadi[1] **and Amir Farajifard**[2]
[1]Department of Electrical Engineering, Science and Research Branch, Islamic Azad University, Fars, Iran
[2]Department of Electrical Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran

***Abstract*— Short installation and maintenance period of Distributed Generation (DG) units make them an effective choice for Generation Expansion Planning (GEP) studies in modern power systems. Finding optimal technology and place of DG units should be done in an economical plan that guarantees the investment benefits of investors. In this paper optimal DG expansion decision has been made based on annual load pattern of system and load duration curve. Also an economical evaluation has been presented on expansion choices using sensitivity analysis and value of investment. Presented approach considers both concerns of Independent System Operator (ISO) and Generation Companies (GenCos). A short-term Security Constraint Unit Commitment (SCUC) for each scenario has been considered from ISO's point of view and in the other hand, a long-term economical study in returning the investment capital has been evaluated by each GenCo as a decision makers. The proposed algorithm is applied to IEEE-24 Bus test system. The simulation results show that the presented method is both satisfactory and consistent with expectation.**

***Keywords*—** Distributed Generation, Load Duration Curve, Sensitivity Analysis and Decision Making

I. INTRODUCTION

Distributed generation is not a new subject in power system studies. On first years of electric industry foundation, power transmission was done by Direct Current (DC) systems and power systems were not so expanded. Power plants were just able to supply demands around themselves because of low capacity of generation and disabilities on electricity transmission. In this situation power plants supply demands locally and this is like what DG units is doing now. In recent decades power system restructuring changes aims of scheduling and planning by changes in economical lows on generation, transmission and distribution. Also developments in new generation technologies make DG alternatives attractive for owners and planners of power systems [1].

With increasing DG penetration on generation side, parameters like number and capacity of DG units, their place and their effects in system operation indices like loss, voltage profile, reliability and stability of power system should be considered on scheduling [2]. In recent decades with deregulation in electric industry, determining the best technical and economical place for DG is in more attention and different methods are used for finding the best decision.

A method based on Lagrangian relaxation has been developed by [3] to consider the stability and economical limits on optimal placement. Ref. [4] uses Genetic Algorithm to reduce loss of distribution network with finding optimal capacity and place of DG units. Ref. [5] finds optimal parameters of DG expansion using Optimal Power Flow (OPF) and social welfare index. Ref. [2] solves the DG expansion problem in distribution network of a restructured power system by using heuristic search algorithm.

In this paper an algorithm based on Normalized Locational Marginal Price (NLMP) in one year period and Load Duration Curve (LDC) of system has been used to solve DG expansion problem in order to reduce the deviation of price on all buses of power system which lead to maximum social welfare, from ISO's point of view. Same LMP on all buses (with allowing a little deviation) means that operation of power system is near to perfect competition status. Also it should be noticed that increasing DG units in system will proportionally reduce the benefits of each GenCo's profit. So the minimum acceptable rate of return for investment should be considered in decision making from GenCo's point of view and it should be approved by long-term power market transactions.

From the viewpoint of generation and transmission planning, it is always crucial to simulate or forecast LMPs, which may be obtained using the traditional production (generation) cost optimization model, given the data on generation, transmission, and load [6], [7]. Typically, dc optimal power flow (DCOPF) is utilized for LMP simulation or forecasting based on production cost model via linear programming (LP) owing to LP's robustness and speed. The popularity of DCOPF lies in its natural fit into the LP model. Moreover, various third-party LP solvers are readily available to plug into DCOPF model to reduce the development effort for the vendors of LMP simulators [8]. In this paper, we consider DC-OPF model which is utilized by GAMS and a second order MATLAB code is implemented to the

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M. S. Javadi is with the Department of Electrical Engineering, Islamic Azad University, Science and Research Branch, Fars, Iran; e-mail: msjavadi@gmail.com

A. Farajifard is with the Department of Electrical Engineering, Islamic Azad University, Science and Research Branch, Tehran, Iran; e-mail: a_farajifard@yahoo.com

economical analysis of DG projection.

This paper is organized as follows. In section II, available DG technologies have been presented. Locational Marginal Price theatrical consideration and problem formulation are addressed in section III and IV, respectively. In the section IV, ISO's and GenCo's profit maximization is also addressed. Simulation results are presented in section V and conclusion of this paper is conducted in last section.

II. DG TECHNOLOGIES

Distributed Generation (DG) is generation in demand place, but in some cases it is common to use it for units which use renewable sources for electricity generation. This type of generators, beside their technology, has almost low capacities; most of them have less than 300 kW.

Distributed generation technologies can be divided to three main groups:

- Gas technologies
- Renewable resources technologies
- Energy storing technologies

DG is expected to play key role in future competitive markets because of their economic viability and based on the study of Electric Power Research Institute (EPRI) and Natural Gas Foundation, 30% of power generation share will be of DG [9-10]. Many definitions of DG have appeared in the literature based on their size, technologies, location, power delivery area and operational constraints with their economical and operational benefits [2, 11-12]. The DG technologies may comprise small gas turbines, micro-turbines, fuel cells, wind and solar energy. DG can be connected in an isolated or an integrated way in the power system network and issues relating to policy of integrating DGs into power system planning and their impacts on steady-state power system operation, contingency analysis, protection coordination as well as dynamic behavior were discussed in [12], [13].

III. LOCATIONAL MARGINAL PRICING

Locational Marginal price of network's each node is Lagrange multiplier of corresponding power balance equation. LMP at each bus includes marginal cost of energy generation in that node, marginal cost of power transmission loss and a part that shows congestion on lines that have been ended to aforementioned bus, called marginal congestion costs. LMP formulation is as below:

$$LMP_i = \lambda + \lambda \frac{\partial P_L}{\partial P_i} + \sum_{ij}^{NL} \mu L_{ij} \frac{\partial P_{ij}}{\partial P_i} \qquad (1)$$

Where

λ: is marginal energy cost,

$\lambda \frac{\partial P_L}{\partial Pi}$: is marginal loss and

$\sum_{ij}^{NL} \mu L_{ij} \frac{\partial P_{ij}}{\partial P_i}$: is marginal congestion cost.

As shown in above formula, LMP is consisted of loss and congestion costs beside generation cost. So increase LMP in a bus shows higher level of energy consumption than energy generated or transmitted to that bus. If LMP of buses in a network get equal means than total social welfare in that network is in maximum.

In this paper it is assumed that payment mechanism for generation units is based on nodal price. On the other hand the LMP of each bus is base of price of that node in that time horizon. For calculating LMP, different load situations should be simulated, because it is common that the LMP in peak-load increases - which has small duration – and on the other side, in mid-load or low-load duration, prices in network decrease and get stable and same. So we used LDC to calculate LMP in different daytimes. For this calculation, after gathering data, the LDC curve has been divided to different levels to make the calculation more real.

IV. DG EXPANSION PLANNING FORMULATION

The aim of Generation Expansion Planning (GEP) in power system from viewpoint of ISO is supply the demand with lowest cost and highest system reliability. From the viewpoint of investors and generation companies, the main goal is achieving maximum benefit from generation and covering costs of generation and investment. In this way finding the best strategy and its economical evaluation is very important. From the viewpoint of investors the investment return should be guaranteed at first. So each investor in generation side simulates its presence in generation market and the decision variable of each investor is the unit type, generation technology and suitable place for unit installation with considering the infrastructures which is necessary for generation development. In this step some constraints like budget limits and minimum expected rate of return exists. Sensitivity analysis should be used for evaluating the technology type. For this purpose the investor organization must know the existent technologies and their buy and installation costs (as fix costs) and operation costs (as variable costs). The buy and installation costs are known from the first.

Generation costs of a unit commonly are introduced by a mathematical function. For gas burning and gas micro-turbine units a quadratic cost function have been considered. But investor has no information about hourly generation properties of his unit in market. So he should simulate probable decisions on market model before decision making and evaluate the market characteristic and make a sensitivity analysis on his profit and cost. In a competitive power market, none of generation or retail companies are able to propose a fix and known bid to ISO. On the other hand investment organizations don't like to invest on projects that have not a brief mechanism for returning investments. In an untraditional market only ISO can give these guarantees to investors.

This problem is one of many challenges which decision and policy makers are faced on energy supply side. These factors attract policies to starting free markets and allow the ISOs to make Power Purchasing Agreements (PPA) for guarantee the return of investments. Without these agreements, investments on creating new generation units will face with unsolvable problems which lead to main problems on reliability of supply side.

Independent Power Producers (IPP), choose projects that maximize their benefits. These companies predict the corresponding profits of their expansion suggestions with simulating different load distribution scenarios and study the generation condition of their choices by predict the cost of fuel and selling energy in market in a time planning horizon which has relation with life time of generating unit.

In this simulations the amount of investment, size of unit, profit, fuel cost, the requirements corresponding to different fuels and amount of generated energy will be determined. This set of information and others like costs of system-maintenance, crew and finance costs- make all of data needed for decision making. Then IPPs do the studies about investment present value. The discounting currency flow of study is considered by yearly discount rate in the time of investment.

The predicted revenue of investor in this situation is a function of fuel costs and predicted energy requirements in simulation. Cost prediction for each one of energy carriers which are an input for generation unit is doing by an especial method. In this paper we assume that the predicted results are ready and have been reported to ISO as a quadratic cost function.

A. *ISO's Problem Formulation Point of View*

The objectives function from ISO's point of view is as follows:

$$Min \sum_{i=1}^{N_B}\sum_{j=1}^{N_G}\sum_{t=1}^{N_T} aP_{i,j,t}^2 + bP_{i,j,t} + c \qquad (2)$$

In which the object is the minimization of demand supplementation costs. a, b and c are generation cost coefficients of j-th unit which is placed in i-th node at t-th operation time period. N_B is the number of nodes, N_G is the maximum number of installed units on corresponding node and N_T is the study's total time duration.

Operation constraints are:

$$PG_{i,t} = \sum_{j=1}^{N_G} P_{i,j,t} \qquad (3)$$

$$P_{i,j}^{\min} * I_{i,j,t} \le P_{i,j,t} \le P_{i,j}^{\max} * I_{i,j,t} \qquad (4)$$

$$PG_t - PD_t = B\,\delta_t \qquad (5)$$

$$\delta_{1,t} = 0 \qquad (6)$$

$$P_{km,t} = \frac{\delta_{k,t} - \delta_{m,t}}{X_{km}} = B_{km}(\delta_{k,t} - \delta_{m,t}) \qquad (7)$$

$$P_{km}^{\min} \le P_{km,t} \le P_{km}^{\max} \qquad (8)$$

Where:

$PG_{i,t}$: Total generation in i-th bus at time t.

$P_{i,j}^{\min}$ and $P_{i,j}^{\max}$: the down and up limits of generation units.

$I_{i,j,t}$: Status of j-th generation unit on i-th bus at time t which can be "0" or "1".

PG_t : Units generation matrix at time t.

PD_t : Loads demand matrix at time t.

B : Suceptance matrix of studied network.

δ : Angles matrix of network bus.

$P_{km,t}$: Transmitted power from bus k to bus m at time t.

$P_{km}^{\min}$ and $P_{km}^{\max}$: down and up limits of transmitted power from bus k to bus m.

X_{km} : Reactance of line km.

Eq. (3) states that generation at each node is sum of all installed units at that bus considering the available units and new DG units. Equation (4) considers the technological limits of units and implies that generation of each unit should be limited to its margins. Eq. (5) and (6) are the dc load flow equations and Eq. (7) and (8) are the limits of power transmission at studied network.

B. *GenCo's Objective Function*

From the standpoint of investor in generation side, the return of investment in expected time period must be at maximum guaranteed at nominal life time of DG unit. In fact, in econometric analysis from the investor side, the DG unit replacement and size and technology determination is doing by sensitivity analysis based on Minimum Acceptable Rate of Return (MARR). The calculation in this section has been done by econometrics methods.

$$P = A\left[\frac{(1+i)^n - 1}{i(1+i)^n}\right] \qquad (9)$$

$$P = A\left(\frac{P}{A}, i\%, n\right) \qquad (10)$$

In which:

P: the present (current) investment value

A: the determined revenue at yearly time period

n: the number of years at study period

$i\%$: minimum accepted rate of return for investor.

So the investor chooses the unit type, place and size by sensitivity analysis. In this paper, against others, the decision making has not been considered only peak load condition because the price at peak condition is so high in unreal manner and the units with lower efficiency determine the final prices. But in compare with other load levels like mid-load condition which has more load duration participant than peak-load, these units are off and prices are smoother and power market condition is nearer to competitive markets. So the decision making should not be done just based on peak-load condition.

V. SIMULATION STUDIES

In order to explain the generation expansion planning and

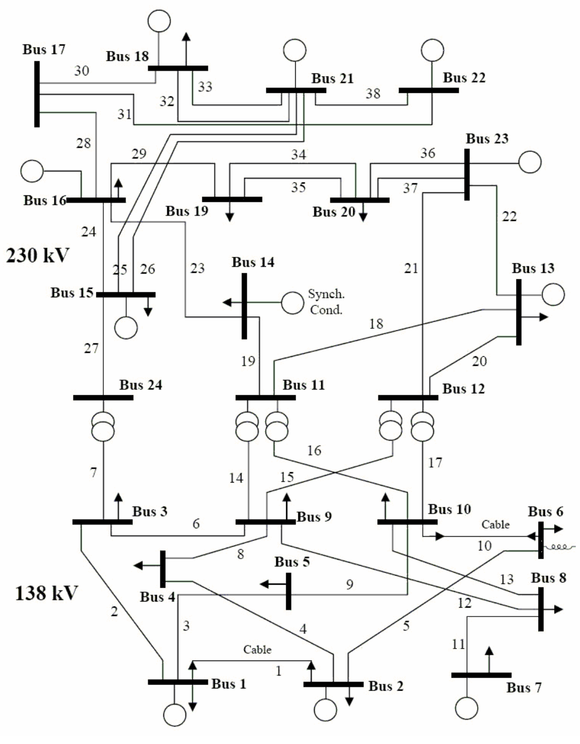

Fig. 1. IEEE 24-Bus test system

optimal DG units' placement from proposed units to the market, the IEEE 24-Bus Reliability Test System (RTS) has been considered. Single-line diagram of this system is presented in Fig. 1. The modification in available generation units has been shown in table I. It is assumed that installed units on each node are owned by a company and the suggested costs of IPPs are same for all units. For better evaluation of result, the lower generation limits of all units are settled at "0". In this situation the optimization problem omits from mixed-integer nature and results achieve faster. Load duration curves of entire and peak hours are illustrated in Fig. 2 and Fig. 3, respectively.

For evaluating the condition of considered DG units, three technologies have been chosen. The information of these units is available at table II. This table contains the price data of DG units, size, maximum number of owned units and MARR which has been calculated by econometric equations 9 and 10. Results of simulation show that the best choice for investment on DG units is node 8. This node has the 6% of network load (peak load of 171 MW) and has been connected to the network by three lines. From three nodes connected to this node by lines, node 7 is a generation node with three 100MW units which has 4.4 % (125MW at peak-load) of network load. The capacity of line 7-8 is 175 MW and it is in full load condition for load higher than 1995 MW (almost 30% of year).

The generation at this node is 300MW and the demand is 125 MW at peak-load. Based on power flow equations on network, for consuming the demand at node 8 and load distribution between generation units, it is necessary to transmit 13.48 MW from node 9 to 8 and 17.48 MW from node 8 to 10. So this node is a good candidate for expansion planning by DG units because the load at this node is higher than mean load of network and its reliability is lower because it is connected to network by just one line.

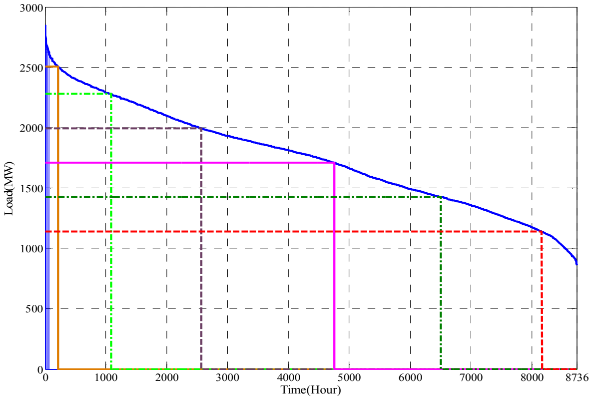

Fig. 2. Entire Load Duration Curve (LDC)

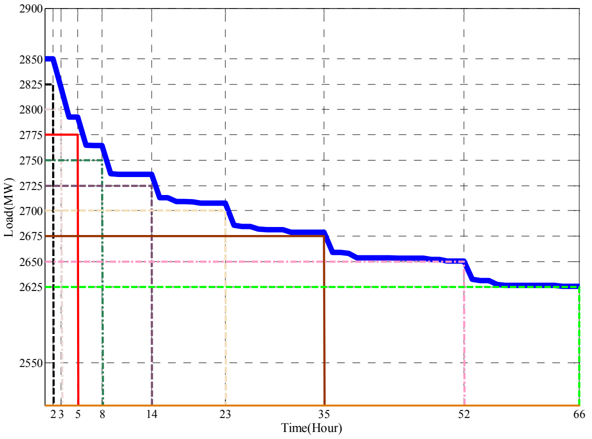

Fig. 3. Load Duration Curve (LDC) at peak hours

Four units is assumed as maximum number of DGs and also assumed that if the DG is bought, only one type of technology will be used because of reliability of unit and operation and maintenance problems.

The results show that increasing in number of DG units will lead to decreasing the total operation costs of system and also profits of Investor Company.

In this situation because of investment rate of return calculated by investor, if technology 1 is chosen, maximum installation of 2 units will be economically acceptable. If technology 2 is chosen, 3 units will be optimal and if the expensive technology is chosen, all 4-units have the economical benefits. But because of decreased costs of system, units 1 and 2 will achieve more incentive policies from the viewpoint of ISO which has not been studied in this paper. Fig. 4 shows the amount of DG's benefit versus number of DG additions. The simulation results show that the profit of all technologies decreases when the number of units increase. This issue is because of the impacts of high efficiency technologies units and their shares of the power market. When the market share of each GenCo would be decreased, the amounts of revenue decrease. It also can be seen from the Fig. 5 whish illustrates the total operational cost corresponding with the number of available technologies.

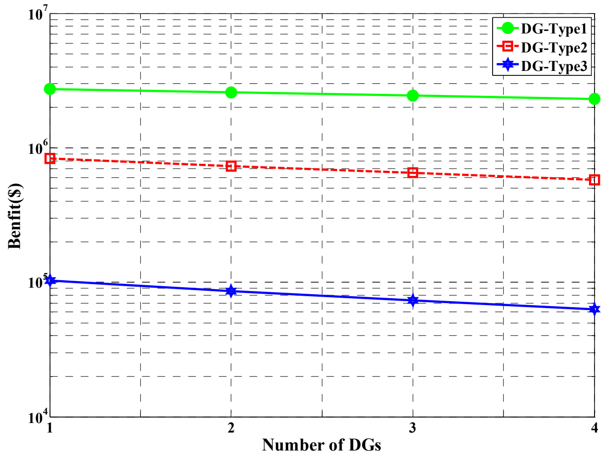

Fig. 4. DG's benefit versus number of units

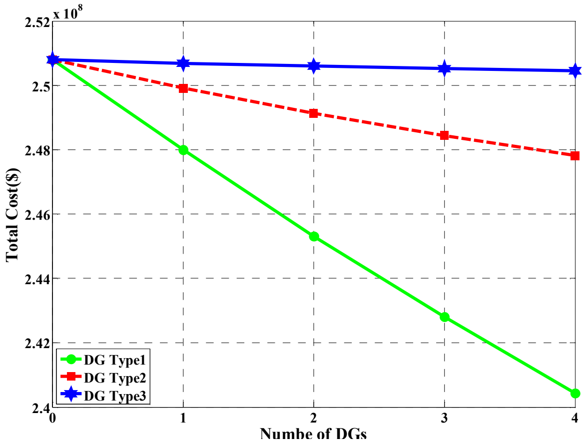

Fig. 5. Impact of DG's on total operational cost of entire system

VI. CONCLUSION

This paper present a two stage DG expansion planning from points of view of both ISO and GenCos. In this model, a bargaining process is also designed to manage the market economical and technical issues. Based on the aforementioned approach, we consider three types of DGs from point of view of GenCos. For evaluating the submitted proposals in DGEP, a SCUC program is implemented by ISO. In this program, total available and candid generation units which is distributed entire of power system is considered in order to determination of hourly operation cost and LMP. Based on this methodology, both GenCos and ISO would have a sense of future condition of the power market. Simulation results also show that the presented method is both satisfactory and consistent with expectation.

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Appendix:

Table A.1 IEEE 24-Bus Test System Unit Data (Operational Data)

Bus	a	b	c	Pmax
1	0.2917	35.07	3591.39	192
2	0.0000	64.96	306.70	192
7	0.0322	19.18	1940.98	300
13	0.0322	19.18	649.99	591
15	0.0628	27.22	1829.71	215
16	0.0191	14.86	552.80	155
18	0.0191	14.86	1105.60	400
21	0.0086	30.00	1992.36	400
22	0.0112	14.17	927.15	300
23	0.0017	17.55	1160.23	660

Table A.2 IEEE 24-Bus Test System Unit Data (Investment Data)

Type DG	a	b	c	Cap. (MW)	MAR ($)	Max. Inv. (Unit)
1	0.02	15	0.0	50	2500000	4
2	0.03	20	0.0	50	650000	4
3	0.04	25	0.0	50	60000	4