Paper accepted for presentation at 2009 IEEE Bucharest Power Tech Conference, June 28th - July 2nd, Bucharest, Romania

Optimal Investment of Distributed Generation in Restructured Power System

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Abstract-- **The main impacts of DG is to enhance system reliability as it can restore power to the separated part of distribution system in case of a contingency occurs and reduce the overall system operating cost. If the DG operating cost is less than the utility power cost at each hour, DG could be employ to reduce the overall system operating cost. This paper presents a method for optimal investment of distributed generation (DG) in restructured electricity market. Here, the presented method combining optimal power flow and customer interruption cost aims to meet the optimal investment for the DG. By using this method, Distribution Network Operators can find the best sites and capacities which are available to connect an optimal number of DGs among a large number of potential combinations.**

Index Terms-- **Distributed Generation (DG), distribution system, optimal power flow (OPF), customer interruption cost (CIC).**

I. INTRODUCTION

THE RESULTS of the electricity industry restructuring in the power system, generation, transmission and distribution services are being divested into separate businesses and new markets in electricity are evolving. It remains largely uncertain how the newly arising market structures will affect the allocation of the benefits and costs of distributed generation investment.

In the restructured power system, distribution companies (DISCOs) are responsible for distribution system management, delivery of power to the customers and system reliability. It is important to plan and maintain reliable power systems because cost of interruptions and power outages can have severe economic impact on the utility and its customers.

Distributed Generation system involves small amounts of generation (under 50MW) located on the utility's distribution system. With recent advances in technology, using of distributed generation (DG) in the power distribution system is increased. Incorporating DG into the power system poses numerous challenges in terms of interconnection, protection coordination and voltage regulation. Increased reliability and reduced cost are the primary incentives of adding DG to a power network. The installations of DGs on the distribution system provide numerous benefits for Distributed Company (DISCO) and play a major role in this new environment. The penetration and viability of DG at a particular location is influenced by technical and economic factors. The technical merits of DG implementation include voltage support, energy-loss reduction, release of system capacity, and improve utility system reliability. Economical merits, on the other hand, encompasses hedge against high electricity price and deferral of capital investments on a network [1]. In a restructured electricity system, reliability problems and electric supply interruptions are concerned with both utilities and customers. Investment in DG and improving the reliability of the existing networks has always been in a challenge in developing economies. When restructuring happens, the primary focus is usually shifted to revenue and profits at the expense of the reliability [2]. Also reliability indexes used in the past (e.g. SAIFI) ignore the effect of customer type on the interruption costs [3]. Therefore investment in DGs based on such indices fail to maximum benefit of distributed generation expansion planning. The distribution system reliability in the presence of DG may be evaluated using analytical methods for reliability indices calculation in radial networks adapted to handle multiple generation sources at distribution level.

Investment in distributed generation expansion is economical when the operating cost of doing nothing exceeds the present value cost of the proposed investment and the optimal placement and penetration is found to depend on the cost characteristics of DG as well as those of central generations.

This paper presents the application of customer interruption costs (CICs) and optimal power flow (OPF) in optimal DG placement and capacities in uncertainty electricity market. If the distribution company ignores the CIC, the value of the total operating costs may be not the optimal [8],[9]. The proposed method minimized cost of energy and customer interruption cost of the whole distribution network.

The rest of this paper is organized as follows. Section II describes the DG operation and costs. Section III presents the customer interruption cost and reliability. The application of optimal power flow represents in section IV, whereas section V is the proposed method and problem formulation. In section VI the proposed method is applied to a distribution system and finally section VII concludes the paper.

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II. OPERATION OF DISTRIBUTION GENERATION

The cost of utility power depending on the demand and the availability of generation assets, one of the new options for distribution companies are to use DGs for investment plans. The distribution companies may find that investment on the DG systems is cheaper than the purchase from power market for much hours of the year [4]. In order to determine the cost-effectiveness of DG, the estimated cost of electricity from a DG may be compared with the local retail price of electricity from the electric utility.

A. Cost of Distributed Generation

DG planning requires assessment and evaluation of different costs. The cost components relevant to DG analyses are capital and installation cost (total initial investment), operation and maintenance cost and fuel cost. The operation and maintenance (O&M) costs of DG have both fixed and variable components. Fixed O&M consists primarily of plant operating labor and the variable O&M includes periodic inspection, replacement, and repair of system components.

Many deterministic models have also been developed for cost evaluation of DG. In the deterministic case here, with the help of market discount rate life cycle cost that occurs can be expressed as an equivalent annual expense that is constant during each of the N years of the life of system. The complete equation for the life cycle cost of a DG investment 'TC_{life}' is given by:

$$TC_{life} = C_{cap}\{(1-f_l)+f_l\frac{LRF}{CRF}\} + O\&M\left(\frac{1-(1+r_d)^{-N}}{r_d}\right) \quad (1)$$

$$LRF = \frac{r_l}{1-(1+r_l)^{-N_l}} \quad (2)$$

$$CRF = \frac{r_d}{1-(1+r_d)^{-N_l}} \quad (3)$$

life cycle cost of DG TC_{life} :

capital cost (in first year \$) C_{cap} :

fraction of investment paid by loan f_l :

annual cost for maintenance (in first year \$) $O\&M$:

market discount rate r_d :

market loan interest rate r_l :

system life (year) N :

loan period (year) N_l :

Then the levelized annual cost is obtained by multiplying the life cycle cost from (1) by the capital recovery factor for discount rate and system life.

$$A_{life} = \left(\frac{r_d}{1-(1+r_d)^{-N}}\right)TC_{life} \quad (4)$$

A_{life} : levelized annual cost

The total annual cost of DG is summing the levelized annual cost and the annual fuel cost.

B. Uncertainty in DG Planning

The reform of electricity and gas markets has led to major changes in the way decisions are taken on DG investment. Opening the sectors to competition has led to the internalization of risk in investment decision-making. DISCOs now examine power purchase options according to the different financial risks posed by the different solutions.

A number of methods have been used in assessing risks and uncertainties. These include sensitivity analysis, decision analysis, break-even analysis and Monte Carlo simulation [5]. Monte Carlo simulation methods are the numerical methods which allow the solution to mathematical and technical problems by means of system probabilistic models and simulation of random variables. The strength of the Monte Carlo simulation is its ability to handle imprecise variables and to recognize their covariance. This approach can help planners to make appropriate decisions in the restructured environment characterized by many uncertainties [5].

In this paper, values for the electricity price that purchased from electricity market and gas price are selected randomly.

III. RELIABILITY AND CUSTOMER INTERRUPTION COST

DG allocation and sizing is the great importance problem. The installation of DG units at non-optimal places can result in an increase in system losses, decrease in system reliability and, therefore, having an effect opposite to the desired [6]. In this paper we examine and evaluate the effect of DG in distribution system reliability. The benefit of employing DG is illustrated using the reduction in customer interruption cost.

A. Reliability Indices in Distribution Network

Utilities employ a variety of standard indices to measure distribution system reliability. The basic distribution system reliability indices are three load point indices include of the average failure rate λ, the average outage duration r and the annual outage duration U. These three basic indices are important individual load point parameters. The system indices of SAIDI and CAIDI can be calculated from the three basic load point indices. The reliability cost/worth indices of expected energy not supply (EENS), expected interruption cost (EIC) and interrupted energy assessment rate (IEAR) can also be calculated using the three basic load point indices [7].

The reliability indices considered in this paper are:

1. SAIDI: the system average interruption duration

$$SAIDI = \frac{\Sigma(N_{sustained}D_{sustained})}{N_{served}} \quad (5)$$

2. EENS: expected energy not supply

$$EENS = \sum_{i=1}^{N_p} L_i \sum_{j=1}^{N_e} r_{ij} \lambda_{ij} \tag{6}$$

3. EIC: expected interruption cost

$$EIC = \sum_{i=1}^{N_p} L_i \sum_{j=1}^{N_e} C_{ij} \lambda_{ij} \tag{7}$$

4. IEAR: interrupted energy assessment rate

$$IEAR = \frac{EIC}{EENS} \tag{8}$$

Where $N_{sustained}$ is the number of customers impacted by a sustained interruption, N_{served} is the number of customers served on the feeder (or other part of the system), $D_{sustained}$ is the duration of a sustained interruption in minutes, N_p is the total number of load point, N_e is the total number of elements in the distribution system and C is the customer damage function.

A. Application of CICs in DG investment

In a restructured power system DISCOs are responsible for distribution system management, delivery of power to the customers and system reliability. When reliability principles are violated, the impact to the customers and DISCOs can be huge. The interruption cost of each customer depends on type of customer and on the magnitude and the duration of the interruption.

A Standard Industrial Classification (SIC) can be used to divide customer into large user, industrial, commercial, residential, government & institutions and office & building categories [8]. Growing the amount of energy not supplied by DISCO caused increasing the total operation cost. Fig.1 shows that determining and application of the correct CICs caused that planners getting maximum benefit of the DG investments and minimum operation cost.

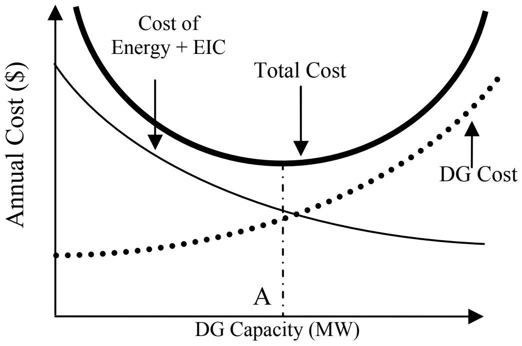

Fig. 1. DG Capacity vs. Cost

DISCO’s investment in DG capacity beyond point A leads to higher total cost than if the investment had not been made at all, This is economically inefficient result on which should be avoided because both the DISCO and the customer are worse off economically if it is made.

IV. OPTIMAL POWER FLOW (OPF)

OPF tool has been used in many pool based restructured electricity markets to calculate the MW generations throughout the system to minimize cost of generation and to manage congestion in the system. In particular we consider the objective function to be the total cost of real power generation. These costs may be defined as polynomials or as piecewise-linear functions of generator output. In a centralized pool based market, the central dispatcher optimally dispatches the generators such that the total cost of energy is minimized while satisfying the operational and security related constraints.

This problem is formulated as follows [10]:

$$\min \sum f_i (P_{gi}) \tag{9}$$

Here f_i is the cost of active power generation for generator i at a given dispatch point and it is assumed to be a polynomial or piecewise-linear function.

A. Constraints

The equality constraints to minimized cost of energy problem are the power flow equations and the inequality constraints are:

- voltage operational tolerance limits at all buses

$$V_i^{\min} \le V_i \le V_i^{\max} \tag{10}$$

- active and reactive power balance equations

$$P_{gi} - P_{Li} - P(V,\theta) = 0 \tag{11}$$

$$Q_{gi} - Q_{Li} - Q(V,\theta) = 0 \tag{12}$$

- active and reactive power generation limit

$$P_{gi}^{\min} \le P_{gi} \le P_{gi}^{\max} \tag{13}$$

$$Q_{gi}^{\min} \le Q_{gi} \le Q_{gi}^{\max} \tag{14}$$

- and line flow limits

$$S_{ij} \le S_{ij}^{\max} \tag{15}$$

B. Locational Marginal Price (LMP)

Besides generation and load power scheduling, market clearing mechanism have to provide prices associated with power production and consumption. Two main approaches have been proposed in competitive markets, namely the spot pricing model which gives Locational Marginal Prices (LMP) and the single-price model based on Market Clearing Price (MCP).

In this paper we use LMP for each MW that DISCO purchase from power market. The LMP is the marginal cost of supplying the next increment of electric energy at a specific bus. LMP is generally composed of three components, a marginal energy component (same for all buses), a marginal loss component and a congestion component. Considering the case of real power spot price at bus i, LMP is given by [10]:

$$LMP_i = \lambda + \lambda \frac{\delta P_L}{\delta P_i} + \sum_{ij=1}^{N_L} \mu L_{ij} \frac{\delta P_{ij}}{\delta P} \qquad (16)$$

$$LMP_i = \lambda + \lambda_{L,i} + \lambda_{C,i} \qquad (17)$$

Where λ is a marginal energy component at the reference bus which is same for all buses, $\lambda_{L,I}$ is the marginal loss component, $\lambda_{C,i}$ is the congestion component. Thus, the spot price at each bus is location specific and differs by the loss component and the congestion component. Theoretically this location-based price equals the economically efficient market value of electricity at that point, factoring into account constraints everywhere in the system.

V. PROBLEM FORMULATION AND SIMULATION PROCEDURE

A. Problem Formulation

The selection of DG locations and capacities are difficult tasks in distribution planning because the problem involved is a combinatorial constrained problem with a non-linear objective function. The main problems studied in the paper are to find the optimal investment of DG and their corresponding sizes and locations in distribution feeders and minimized total cost of distributed network operation.

In a competitive electricity market, the DISCO must purchase power from the main grid. But electricity market prices are not fixed and change by market conditions. Uncertainties in the electricity and gas market price are modeled by using Monte Carlo simulation and the expected cost of energy is calculated. The main objective of this paper is to obtain the optimal investment of DG that minimizes the sum of utility power cost, DG operating cost, and interruption cost. Thus objective function can be expressed as follows:

$$\min \sum_{t=1}^{8760} E(COE) + EIC \qquad (18)$$

Where E(COE) is the expected annual cost of power purchase from the main grid and DG generation cost that is includes capital and operation costs and EIC is the expected interruption cost. The expected interruption cost of energy at each load point depends on the type of customer interrupted and on the magnitude and the duration of interruption.

B. Simulation Procedure

To obtain optimal placement of DG for the minimum total operation cost of distribution network, the simulation procedure consists of the following Steps:

1) Determine the candidate node for installation DG in distribution network.
2) Set the DG in minimum possible size.
3) Specify the CIC for each costumer depends on type of customer and on the magnitude and the duration of the interruption.
4) Generate the failure and restoration history for each component of the distribution system by values of time-to-failure (TTF) and time-to-repair (TTR) of the component. The operating history of each component is in the form of chronological up-down-up operating cycles.
5) Determine the outage durations at the each load point and then obtain the EIC of distribution network for each candidate DG place using the sum of load points expected interruption costs (LPEIC).
6) Values for the main grid electricity and gas price are selected randomly.
7) Determines the LMP in bus that feeds the distribution system by using OPF after install DG.
8) Calculate the annual cost of energy for each wait state of main grid electricity and gas price and candidate places for installing DG by using this formula:

$$COE = \sum_{j=1}^{8760} LMP_{ij} * P_j + C(DG) \qquad (19)$$

$$C(DG) = A_{life} + FC \qquad (20)$$

Where LMP_i is the LMP in the main grid bus at hour j, P is the power that distribution network consumes in hour j, C(DG) is the annualized capital and operation cost of DGs and FC is the annual fuel cost.

9) Calculate the expected annual cost of energy for each DG candidate place.
10) Determine the value of objective function (18).
11) Select the minimum value of the objective function form candidate places for installing DG
12) If objective function is decreased then repeat steps 5)-11) for next DG size and place.

VI. CASE STUDY

A. Test system

The method was applied to a distribution system connected to bus 4 of the IEEE RBTS that is shown in Fig 3. The system and load data were described in [11]. The RBTS defines the customer type and total peak load at each of its busbars. This system is included 38 load points and three types of customers: residential, commercial and small user. For each type of customers, the cost of outage ($/KW) in specific time duration is shown in Table I [4]. In table I, the interruption cost for each customer type depends only on the duration of interruption. The basic reliability parameters for this system are given in [11]. The TTRs of the components were assumed to have log-normal distributions with standard deviations of one third of their average values. The TTFs of the components were assumed to have exponential distributions.

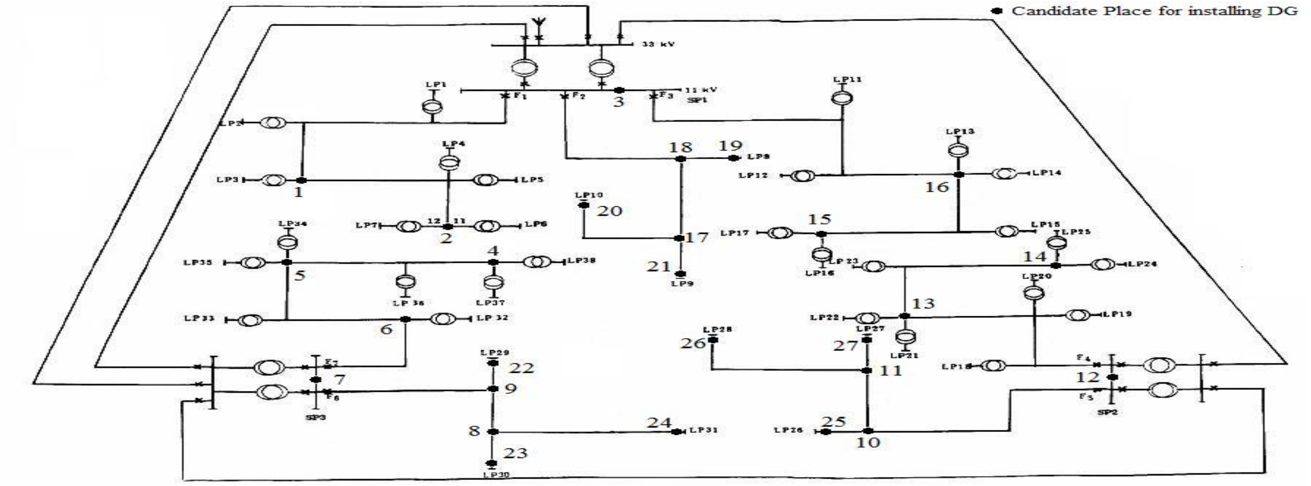

Fig 2. Distribution System for RBTS Bus 4

TABLE I
INTERRUPTION COST PARAMETERS FOR EACH TYPE OF CUSTOMERS

Type of customer	1 min	20 min	60 min	240 min	480 min
Residential	0.001	0.093	0.482	4.914	15.69
Commercial	0.381	2.969	8.552	31.32	83.01
Small user	1.625	3.868	9.085	25.16	55.81

In this distribution network, 27 nodes are candidate for installing DG that is shown in Fig 2. Micro sized gas turbine generators are used in this system.

All DG units were assumed to have fixed 0.8 lagging power factors, the capital cost is 950 $/KW and minimum size of each unit is 500 KW and in table II the necessary parameters for financial analysis is shown.

TABLE II
NECESSARY PARAMETERS FOR FINANCIAL ANALYSIS

fraction of investment paid by loan	0.7
market discount rate	12
market loan interest rate	10
loan period	5
system life	15

B. Results

In this section, different results are presented that were obtained by applying this paper method to evaluate reliability indices and total operation cost when DG is connected to distribution networks.

Fig. 3 shows the EIC and expected cost of energy for install DG in each candidate node in first state of simulation.

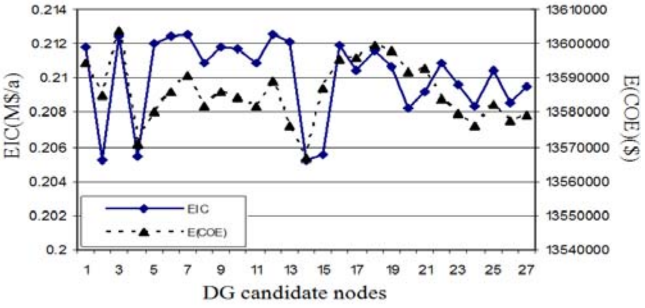

Fig 3. EIC and E(COE)

In the first state of simulation, the distribution company determines that maximum decrease in EIC when the DG is installed in node 4 and the maximum decrease in E(COE) when it is installed in node 14. After calculating objective function, DISCO finds that the best location for installing first DG is in node 14.

The optimal sizes and locations of DGs that must be installing in each node to obtain maximum benefit of DGs are shown in Fig 4.

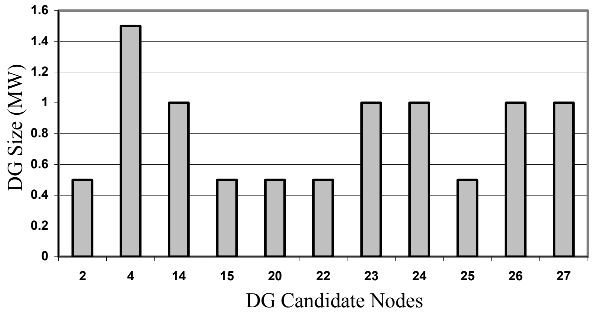

Fig 4. Optimal DG Sizes and Locations

The distribution company determines that the maximum and optimal DG capacity for the minimum annual operation cost of network and the maximum benefit of installing DG is 9 MW. The total benefit of installing DG is shown in Fig 5.

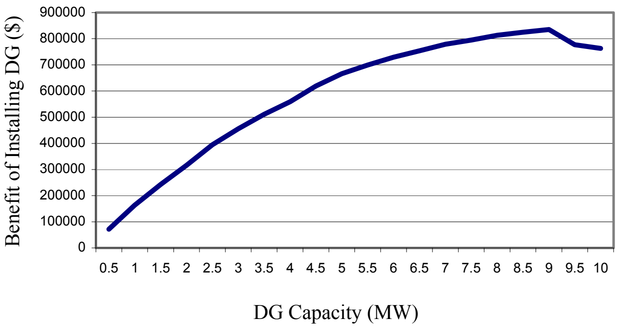

Fig 5. Benefit of Installing DG vs DG Capacity

The installing DG in distribution system impacts on reliability indices. Fig 7, Fig 8 is shown the impact of the DG on the distribution system SAIDI, EENS, and IEAR indices that obtained by using of the (5), (6), and (8).

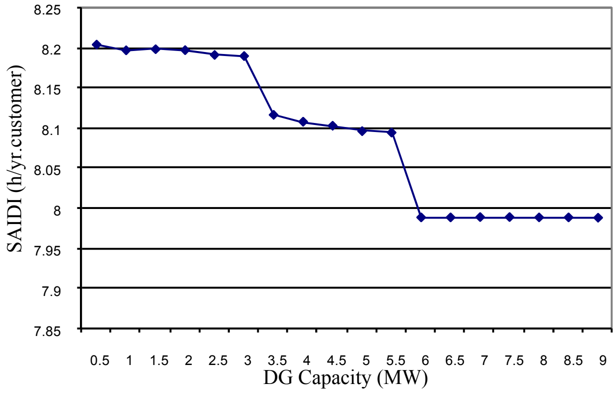

Fig 7. SAIDI Index

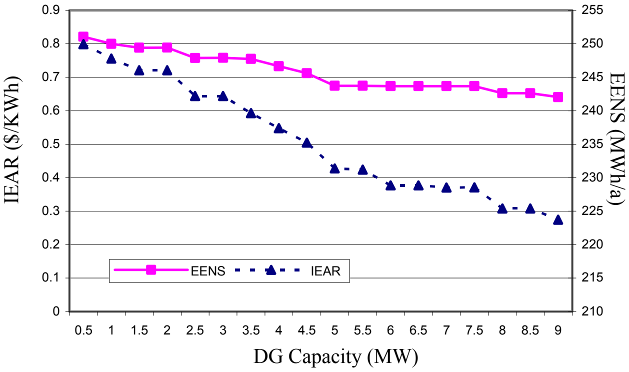

Fig 8. IEAR and EENS

VII. CONCLUSION

Distributed generators have important role in distribution network planning. They could reduce the total distribution system operation costs. But the DGs could have negative effects if their locations or sizes have not been selected in correct form. Also reliability indices used in the past for DG planning ignore the effect of customer type on the interruption costs. If the distribution company ignores the EIC in distribution planning and the type of customers, the total operating cost may be not at the minimum value.

This paper presented a method for determining the optimal investment on the DGs. The proposed method is a combination of technical and economic indices by using the optimal power flow and expected interruption cost of energy in distribution network. At last of paper the impacts of the DGs on the reliability indices are shown.

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