Optimal DG placement under Standard Market Design using GA

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Abstract**—This paper presents a novel methodology for optimal placement of Distributed Generation (DG) in an Optimal Power Flow (OPF) based wholesale electricity market. DG is placed in real time wholesale electricity market. The problem of optimal placement including size is formulated for two different objectives, namely, fuel cost reduction and to provide voltage stability at distribution level. DG reduces the cost of electricity to the costumer, relieve network congestion and provide environmental friendly energy close to load centers. The candidate locations for DG placement are identified on the basis of locational marginal price (LMP). OPF is widely used for both the operation and planning of a power system. The key feature of standardization of restructured power market like Standard Market Design (SMD) is the LMP scheme. OPF problem by placing DG in Deregulated Environment is solved using Genetic Algorithm (GA). The proposed methodology is tested with IEEE 30 bus test system.**

Keywords: **Distributed Generation, Locational Marginal Pricing, Standard Market Design, Optimal Power Flow and Genetic Algorithm.**

TABLE 1: INDEX FOR ABBREVIATIONS

Nomenclature	
OPF	Optimal Power Flow
DG	Distributed Generation
LMP	Locational Marginal Price
SMD	Standard Market Design
GA	Genetic Algorithm
LMP^{energy}	Marginal cost of providing Energy
LMP_i^{cong}	i^{th} Node that accounts for the costs of congestion
LMP_i^{loss}	i^{th} Node that accounts for the marginal real power losses
P_{gi} ,Q_{gi}	calculated real , reactive power generations for PQ bus i
P_{Li} ,Q_{Li}	calculated real and reactive power loads for PQ bus i
$P(V,\square)$, $Q(V,\square)$	Injected real and reactive powers
a_i	basic cost coefficient of the i^{th} generator
b_i	linear cost coefficient of the i^{th} generator
c_i	Quadratic cost coefficient of the i^{th} generator
N_g	number of generators including the slack bus generator
P_G	vector of real power outputs of all generator units
P_{gi}^{max} ,Q_{gi}^{max}	upper real and reactive power generation limits of generator at bus *i*
P_{gi}^{min} ,Q_{gi}^{min}	lower real and reactive power generation limits of generator at bus *i*
V_i^{max} ,V_i^{min}	upper and lower limits of voltage at bus *i*
S_{ij}^{max} ,S_{ji}^{max}	complex power flow limit for line *ij* and line *ji*
S_{ij} ,S_{ji}	complex power transfer from bus *i* to bus *j*, and bus *j* to bus *i*
pop _size	population size
pop_vn	population counter
gen_max	Maximum generations

I. INTRODUCTION

The electricity market has experienced enormous setbacks in delivering on the promise of deregulation. In theory, deregulating the electricity market would increase the efficiency of the industry by producing electricity at lower costs and passing those cost savings on to customers. For the electric industry, deregulation means the generation portion of electricity service will be open to competition. However, the transmission and distribution of the electricity will remain regulated and our local utility company will continue to distribute electricity to us and provide customer services to us. The generation of electricity is being deregulated, which means we will have the opportunity to shop around for the electricity power generation supplier of choice [1].The restructured power markets have evolved around scale of economy making the smaller generating units viable and feasible.

DGs are considered as small power generators (typically 1 kW – 50 MW) that complement central power stations by providing incremental capacity to power system. Penetration and viability of DG at a particular location is influenced by technical as well as economic factors. The technical merits of DG implementation include voltage support, energy loss reduction, and release of system capacity and improve utility system reliability [2]. Economical merit encompasses hedge against high electricity price. This incentive is enhanced with vertical unbundling of utilities and market mechanisms such as real time pricing. By supplying loads during peak load periods, where the cost of electricity is high, DG can best serve as a price hedging mechanism. DG can have a great

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value in a highly congested area where LMPs are higher. In such situation, it can serve the local load and effectively reduce the load. The placement of DG should be carried out with due consideration to its size and location. The placement should be optimal in order for the maximum benefit of DG implemented in the network. Improper placement in some situations can reduce benefits and even jeopardize the system operation. Numerous techniques are proposed so far to address the viability of DGs in power system. Capacity investment planning of distributed generation under competitive electricity market from the perspective of a distribution company is proposed [3]. An approach for optimal design of grid connected DG systems in relation to its size and type to satisfy onsite reliability and environmental requirements is presented in Ref. Besides, several optimization tools, including artificial intelligence techniques, such as GA, tabu search, etc., are also proposed for achieving the optimal placement of DG. An optimization approach GA has been used to obtain penetration level of DG for minimizing the total cost of operation including fixed and variable cost and losses for a defined planning horizon are presented [4].

Distributed generators include synchronous generators, induction generators, reciprocating engines, micro turbines, combustion gas turbines, fuel cells, solar photovoltaic, and wind turbines. The planning studies include penetration level and placement evaluation, which are influenced by the type of DG.

The cost of the electricity available from the grid is given by the nodal LMP while the cost of electricity of the DG depends upon its type, capacity, etc. The first objective is to locate DG at economically viable locations (siting problem) [5]. The penetration level of the DG has to be computed incrementally by OPF. Capacity addition by DG will affect the economic dispatch and hence LMP costs. Hence, the problem becomes nonlinear and iterative. The study is useful for determination of viable DG capacity in a typical distribution system.

The paper is organized as follows. Section-2 describes the role of DG in the deregulated environment. SMD market and LMP calculation are discussed in section 3. DG planning under SMD is considered in section-4.GA and GA based OPF explained in section-5. Results are presented in section- 6. Section -7 concludes the paper.

II. DISTRIBUTED GENERATION IN DEREGULATED ENVIRONMENT

In addition to meet future energy needs, DG will have vital role in a deregulated environment. It can provide independence and flexibility to the consumers in planning and developing the installation as per the criticality of the load. It can minimize the investment made over Transmission and Distribution (T&D) [6]. infrastructure by locating it near the load. It has potential to serve as an ancillary service. Many new DG models are commercialized in United States and Europe. The liberalization of wholesale and retail electric markets is giving rise to customer choice and new offerings by unregulated energy retailers. Due to the continuous improvements in DG technologies, it is possible to provide cost effective electricity to the customers. In wholesale power markets, customer owned DGs can respond to the extreme price swings so as to reduce the volatility in prices. During peak hours and emergencies, a part of the total load can be transferred to an isolated generator, relieving the utility's burden to some extent. Furthermore, the parallel operation of DG with the utility is much more flexible than that of the standalone system.

In competitive electricity markets, DG can compete with the centralized power generation and hence market regulations should ensure that there should be standard operational practices and reliability requirements so as to have fair competitive environment for DG. Various electricity market models like pool model, SMD are in operation in different parts of the world. Since the cost of electricity from the grid is dependent upon the market model, the model will influence the DG planning.

III. STANDARD MARKET DESIGN

LMP provides market participants a clear and accurate signal of the price of electricity at every location on the grid. These prices, in turn, reveal the value of locating new generation of upgrading transmission systems. Under SMD, the term 'multi-settlement market' implies that the energy market consists of day ahead and real time markets, each producing its own separate and unique financial settlements[7]. The day ahead market produces generation and load schedules one day ahead before operating day. The real time market reconciles any differences between the amounts of scheduled day ahead and real time conditions. The DGs can participate in the real time market.

In this work market operates under SMD framework. Hence, the knowledge of LMP at every node is used to take a decision for the placement of a DG.

A Locational Marginal Pricing

LMP is the lagrangian multipliers associated with the active power flow equations for each bus in the system. LMP at any node in the system is the dual variable for the equality constraint at that node [8]. LMP is generally composed of three components, a marginal energy component, a marginal loss component and a congestion component. Considering the case of real power spot price at bus i, higher LMP implies a

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greater effect of active power flow equations of the node on total social welfare of the system. It thus provides indication that for the objective of social welfare maximization, injection of active power at that node will improve the net social welfare. As the DG is assumed to inject real power at a node, the node with highest LMP will have first priority for DG placement.

The determination of LMPs is similar, but not identical, in the day ahead and real time markets. Day ahead LMPs are output from the day ahead market clearing process. Generation, demand, external contracts and increment/decrement positions that are in the day ahead market settle at prices determined by day ahead LMPs. The real time market balances supply and demand as the system operates. Real time LMPs are based on current power system operating data. Deviations between day ahead and actual real time positions settle at prices determined by real time LMPs.

$LMP_i = LMP^{energy} + LMP_i^{cong} + LMP_i^{loss}$

Where,

LMP^{energy}-The component of the LMP that reflects the marginal cost of providing Energy from a designated reference location.

LMP_i^{cong}–The component of LMP at a ith Node that accounts for the costs of congestion, as measured between that Node and a Reference Bus.

LMP_i^{loss}–The component of LMP at a ith Node that accounts for the marginal real power losses as measured between that Node and a Reference Bus.

B OPF Formulation

The heart of the above algorithm is OPF program. The OPF schedules the MW generations throughout the system to minimize cost of generation or social welfare cost. In particular we consider the objective function to be the total cost of real power generation. The problem is formulated as follows.

1) Proposed OPF problem formulation

In any optimization problem, the OPF problem is formulated as a minimization or maximization to a certain objective function in which it is subjected to a variety of equality and inequality constraints. The proposed objective function is the Minimization of Generation Fuel Cost [9]. The main objective is to minimize the fuel cost of thermal units. OPF generation fuel cost function can be expressed by a quadratic function as follows.

$$\text{Minimize } (F_T) = \sum_{i=1}^{Ng} Fi\ (PGi)$$

where,

$$F_i(P_{Gi}) = a_i + b_i P_{Gi} + c_i P^2_{Gi}$$

where,

$$P_G = [P_{G1}, P_{G2}, \ldots\ldots\ldots\ldots\ldots, P_{Gn}]^T$$

2) The constraints

The control variables for OPF include active power at all generator units, generator bus voltages, transformer tap positions and switchable shunt reactors. OPF constraints are divided into equality and inequality constraints. The equality constraints are active/reactive power equalities. The inequality constraints include bus voltage constraints and generator reactive power constraints. Reactive source reactive power capacity constraints and the transformer tap position constraints, etc. Therefore, the above objective function is subjected to the below constraints.

3) Equality constraints

The equality constraints of OPF reflect the physics of the power system. They are enforced through the power flow equation. The net injection of the real and reactive power at each bus is to be zero as shown.

The power flow equation of the network

$P_{gi} - P_{Li} - P(V,\Theta) = 0$ (active power balance equations)

$Q_{gi} - Q_{Li} - Q(V,\Theta) = 0$(reactive power balance equations)

where,

V and Θ are voltage magnitude and phase angles at different buses.

4) Inequality constraints

The inequality constraints of the OPF reflect the limits on physical devices in the power system as well as the limits created to ensure system security. The types of inequality constraints are bus voltage limits at generations, maximum line loading limits and limits on tap settings. The inequality constraint on active power generation P_{gi} at each PV bus are,

Real power generation limits:

$P_{gi}^{min} \leq P_{gi} \leq P_{gi}^{max}$

Reactive power generation limits: $Q_{gi}^{min} \leq Q_{gi} \leq Q_{gi}^{max}$

Bus voltage limit: $V_i^{min} \leq V_i \leq V_i^{max}$

Line flow limit: $S_{ij} \leq S_{ij}^{max}$

$S_{ji} \leq S_{ji}^{max}$

IV. DG PLANNING UNDER SMD

The placement of DG can be considered on the basis of nodal LMPs. To start with, the base case OPF of a system is solved. LMPs at system nodes correspond to the price of a unit power received at the node. The node with the highest LMP is a clear candidate for locating the DG since it will yield highest returns. In the formulation, DG is considered as a negative load and it is assumed that it will be paid at the rate of LMP. The algorithm is as follows.

Step 1: Initialize the installed DG at each node for each DG type to be equal to zero, iteration = 0

Step 2: Run base case security constrained OPF to minimize the total cost of generation or maximize the social benefit function. Consequently, all generation available for scheduling is scheduled optimally.

Step 3: Find the node with the highest LMP.

Step 4: If the maximum LMP is lower than minimum viable DG cost ($ / MWh) option, terminate the algorithm. Else proceed to step-4.

Step 5: Choose suitable (acceptable) type of DG and locate it at the node with maximum LMP. Initially selection of DG type may reflect preference of the planner. Also once, a particular type of DG is selected at a given location, other DG options at that site may be inhibited.

Step 6: Increment the installed DG at the max LMP node either by a small value, e.g., 1 MW or a value based on the judgment of planner.

Step 7: Iteration + 1, run new OPF to obtain new set of LMPs and go to step 2.The process terminates when the cost of energy ($ / MWh) supplied by cheapest available DG is higher than the maximum LMP ($ / MWh) in the system. At this point, no incremental addition of DG in the system is economically viable. It should be noted that in step-5, the emphasis is placed on incremental addition of the DG capacity.

V. GENETIC ALGORITHM

A simple Genetic Algorithm is an iterative procedure, which maintains a constant size population P of candidate solutions. During each iteration step (generation) three genetic operators (reproduction, crossover, and mutation) are performing to generate new populations (offspring), and the chromosomes of the new populations are evaluated via the value of the fitness which is related to cost function. Based on these genetic operators and the evaluations, the better new populations of candidate solution are formed

We use genetic algorithm because the features of Genetic algorithm are different from other search techniques in the several aspects. First the algorithm is a multipath that searches many peaks in parallel and hence reducing the possibility of local minimum trapping. Secondly, GA works with a coding of parameters instead of the parameters themselves. The coding of parameter will help the genetic operator to evolve the current state into the next state with minimum computations. Thirdly, GA evaluates the fitness of each string to guide its search instead of the optimization function [11]. The genetic algorithm only needs to evaluate objective function (fitness) to guide its search.

Step-by-Step Algorithm for Genetic Algorithm Based OPF

1. Read the database for the generator data, bus data, capacitor/reactor data, transformer data and transmission line data [9].
2. Assume suitably population size (pop _size), maximum number of generations or populations (gen_max).
3. Set valid number of population counter. pop_vn=0.
4. Randomly generate the chromosomes.
5. Run power flow using the Newton-Rapson method for each set of generating patterns Pgi corresponding to a particular generation and after that determine, slack bus generation, bus voltage magnitudes and phase angles at all the buses. Also calculate power flow in each transmission line of the system.
6. Check the constraints, if any of the above limits is violated, go to step 4.
7. If all the above constraints are satisfied, increment pop_vn by 1. If pop_vn less than or equal to pop_size, go to step 4, otherwise go to next step.
8. Calculate and then store the total cost of generation corresponding to each valid generation pattern of chromosome.
9. Find and store minimum cost among all valid individual parents and corresponding generation pattern.
10. Check if random no. $r_i < c_r$ (crossover rate) for i=1 to pop_size, select i^{th} chromosome. Apply the crossover operator to that individual.
11. Run power flow using Newton-Raphson method for each set of new generating patterns and hence determine, slack bus generation, bus voltage magnitudes and phase angles at all the buses. Also calculate power flow in each transmission line of the system.
12. Check system constraints as mentioned in 6.
13. If all the constraints are satisfied, the individual of the new population becomes valid otherwise it becomes invalid.
14. Apply the mutation operator to the calculated generation patterns.
15. Run power flow using the Newton raphson and check all the constraints as mentioned in step 6.
16. If all the constraints are satisfied go to next step otherwise go to step 4.
17. Calculate the total cost of all valid patterns.
18. Find the optimum solution among all population groups.

VI. SIMULATION RESULTS AND DISCUSSION

In this section, we present case study for MATPOWER IEEE 30 bus system [12].The nodal LMP at each bus is calculated by using the standard OPF formulation of MATPOWER package. The costs per unit value are available for the capacity and type of DG in the below table or they should be calculated for particular sites under consideration. The penetration level can be defined on the base case and peak case. The peaking cost of energy at customer level due to various types of DGs along with the DG lifetime and its initial cost are tabulated below. The cost of energy is computed using a discount factor of 11.1%.

TABLE 2: COST OF ENERGY WITH VARIOUS TYPES OF DGS

DG Type	Initial Cost ($ / kW)	% Efficiency	% Availability	Life in Yrs	Cost of Energy at Customer Level ($/MWh)
Reciprocating Engine	433	40	97	20	110
Mini Gas Turbine	420	29	97	20	120
Fuel Cell	750	42	97	10	131

Using GA number of values that can be accessed between the minimum and maximum limit is decided by the number of bits selected for that parameter. So the accuracy of the parameters optimized depends on the number of bits selected. In this paper, 12 bits are considered for each generator power output i.e. we get 2^{12} values. Similarly the adequate numbers of bits are considered for the remaining parameters such as voltages, transformer taps, shunts and DG. Similarly, for each voltage 8 bits, for each transformer tap 5 bits, for each shunt 3 bits and for each DG 8 bits are considered [13].

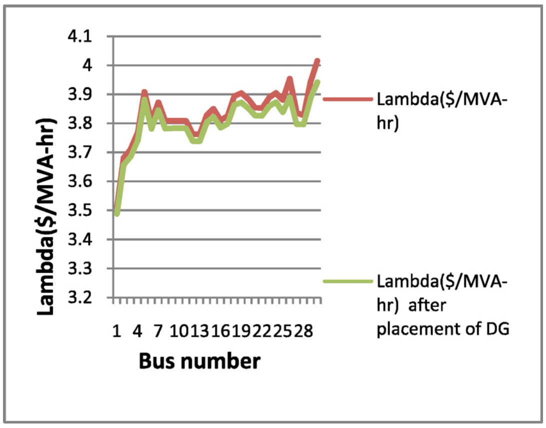

Fig. 1: LMP's for IEEE 30 Bus System by GA without DG and after Placement of DG

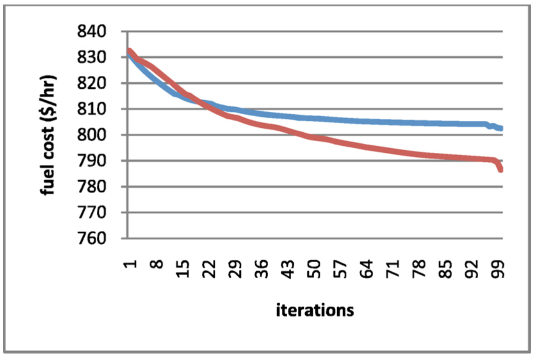

Fig. 3: Fuel Cost without DG and after Placement of DG with GA for IEEE 30 bus Systems

From the above graph we can observe that fuel cost has reduced after placement of DG.

TABLE 3: OPTIMAL LOCATION BASED ON LMP AND SIZE OF DG BY GA FOR IEEE 30 BUS SYSTEMS

Optimal Bus Location for DG Placement Based on LMP	Optimal Size of DG by using GA in (p.u.)	DG Type
30	0.019765	Mini gas turbine
26	0.009647	Reciprocating Engine
19	0.009206	Mini gas turbine

From the above table it is observed that the most suitable DG types are selected based on data given in table 1.

TABLE 4: FUEL COST FOR IEEE 30 BUS SYSTEM BY GA WITHOUT DG AND AFTER PLACEMENT OF DG.

Fuel Cost without DG by GA in $/hr	Fuel Cost with GA After Placement of DG in $/hr
803.083177	789.441332

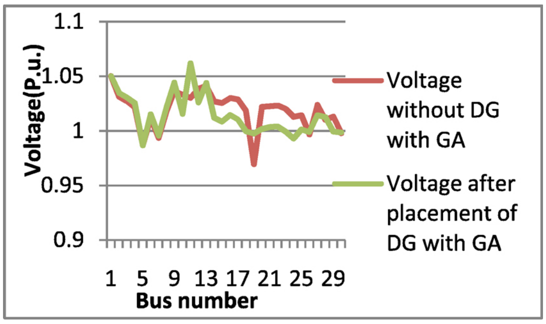

Fig. 2: Voltages in (p.u.) for IEEE 30 bus System by GA without DG and after Placement of DG

VII. CONCLUSIONS

1. An algorithm is proposed for solving the DG placement and penetration problem which tells that the cost of grid electricity is higher than the DG electricity cost.

2. LMP is used as an indicator of grid electricity cost at a node as it is sensitive to generation cost, losses and location of the node in the system.
3. The optimal placement and penetration depends on the cost characteristics of DG as well as those of central generations. The DG with incremental cost lower than the central generation have a higher penetration in the system, and similarly, the one with higher incremental cost have the lower penetration. Considerable reduction in central generation dispatch is observed with high DG penetration.
4. The base case OPF of a system is solved. LMPs at system nodes correspond to the price of a unit power received at the node. The node with the highest LMP is a clear candidate for locating the DG since it will yield highest returns. The optimal location is founded based on LMP values.
5. The OPF problem by placing DG at exact locations in deregulated environment is solved by using GA. It is observed that GA gave best results for optimal size of DG, minimum fuel cost, and reduction in losses and improved voltage profile.

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