A Market-based Approach for Optimal Operation of Customer-owned DG Units in Smart Grids

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ABSTRACT

This study presents a multi-objective model for distribution system operation regarding utility and customer benefits in the smart grid environment. A methodology to purchase power from customer-owned distributed generation (DG) units based on the multi-objective decision making approach is proposed in the paper. The objective of the algorithm is to find the operation schedule of DG units that result in maximum profit for utility and customers at the electricity market, taking into account the technical benefits of DG installation. An improved non-dominated sorting genetic algorithm (NSGA- II) is developed to solve the problem. The effectiveness of the proposed model and search method is assessed and demonstrated by numerical studies. The results presented are evaluated in the IEEE 30-bus test network.

INTRODUCTION

Distributed Generations (DGs) are defined as electric resources interconnected to the distribution networks. The DG units have been, in the last decade, in the spotlight of the power industry and scientific community and constitute a new paradigm for onsite electric power generation. There are three key factors deriving this change namely, environmental concerns, technological innovation and new government policy [1].

Recent developments in traditional power systems which involve emerging smart technologies and communication techniques will convert the present electricity grid into smart grids. Envisaging smart grids as the future of electric grids, one can say that a smart grid is an infrastructure able to accommodate all centralized and distributed energy resources (DER), including intensive use of renewable and distributed generation (DG), and demand response, seeing consumers as active players, in the context of a competitive business environment[2].

Under restructuring of electric power industry, different participants namely generation companies and consumers of electricity need to meet in a marketplace to decide on the electricity price. In competitive electricity markets, the cost of purchasing energy from the transmission system and from DG units should be considered in order to retain a proper assessment of the penetration level of distributed generations in a distribution system. Greater efficiency may then be achieved by matching demand and supply in a decentralized fashion such that consumers and producers make decisions based on their own utility-and profit-maximizing objectives [3].

This paper discusses the effects of emerging smart grids on the customer's behaviour as private investors and owners of DG units. In this study, the DG units are considered to be controllable and their generated power is dispatchable. The optimization problem is solved from a technical point of view with objective functions consisting of minimizing the power losses and maximizing the loadability of the network. From economical point of view, the optimization problem is solved based on profit maximization through maximizing utility and customer benefit objectives. In this paper, the NSGA-II, which incorporates the concept of Pareto optimality into its search algorithms and can find optimal trade-offs among the multiple conflicting objectives simultaneously, has been implemented [4]. A max–min approach based on fuzzy satisfaction approach is used to select the best multi-objective DG operation solution [5].

PROBLEM FORMULATION

The proposed optimization model for optimal operation of customer owned DG units is formulated and presented in this section. The model includes two main perspectives. The first perspective contains only the technical impacts of DG units in the distribution system. In this context the solutions to the problem obtained from the proposed multi-objective method determine the optimum generated power of DG units. The steady state voltage profile, system losses, and voltage stability margin are the technical impacts of DG units evaluated in the paper. These indices are briefly defined and discussed in the Refs.[6-7].The objective of the technical perspective is to minimize the power loss in the system and to maximize the loadability margin in the system. The objective functions from the technical point of view are as follows:

$$F_1=LLRI \tag{1}$$

and

$$F_2=-VSMI \tag{2}$$

LLRI, is the Line Loss Reduction Index and VSMI is the static Voltage Stability Margin Improvement index [6-7]. These indices take the distribution network without DG as benchmark. Static voltage stability margin or maximum loadability margin is the margin between the operating point of the system and the maximum load for which voltage collapse occurs in the system. The loss reduction benefit also plays an important role in the economic evaluation of DG benefits.

The second perspective implies the economic benefit of DG installation to the utility and customers. In the evaluation of objective functions, the DG owners attain benefits from the generated power while their costs comprise of investment and operational costs. The benefit of the utility is resulted from power loss reduction in the system and its cost is purchasing power from DG owners. In this evaluation, the utility purchases the power from DG owners considering an award policy to encourage customers to connect DG to improve network performance and efficiency. The objective functions which present the customer and utility benefits are expressed as follows:

$$f_{customer\_benefit} = \sum_{dl=1}^{N_{dl}} \left(\sum_{i=1}^{N_{DG}} P_{DGi,dl} \cdot (C_e \cdot PLF_{dl} + C_{aw} \cdot ALF_{dl}) \cdot T_{dl} - \sum_{i=1}^{N_{DG}} P_{DGi,dl} \cdot C_{LC} \cdot T_{dl} \right) \quad (3)$$

and

$$f_{utility\_benefit} = \sum_{dl=1}^{N_{dl}} \left(\Delta loss_{dl} \cdot C_e \cdot PLF_{dl} \cdot T_{dl} - \sum_{i=1}^{N_{DG}} P_{DGi,dl} \cdot (C_e \cdot PLF_{dl} + C_{aw} \cdot ALF_{dl}) \cdot T_{dl} \right) \quad (4)$$

where PLF is price level factor; ALF is Award Level Factor; C_e is electricity price; C_{aw} is award policy price; C_{LC} is operation cost of DG units; dl is the demand level and T_{dl} is duration of each demand level. The formulated problem and the solution approach were implemented in Matlab. The decision variables are the generated power of each DG unit and the purchase price.

PROPOSED APPROACH

Multi-objective optimization is the process of simultaneously optimizing various conflicting objectives subject to a set of constraints. Multi-objective optimization problems are solved by two fundamentally different groups of techniques. The first one uses a priori preference information and single objective optimization techniques. In contrast, the second group of techniques proposes a true multi-objective approach. The multi-objective solution is a solution that is non-dominated by any other solution; such solution is called Pareto optimal and the entire set of non-dominated solutions is called Pareto optimal front. Pareto optimal solutions set are often preferred to single solutions because they can be practical when considering real-life problems since the final solution of the decision maker is always a trade-off [4].

In this paper, NSGA-II is applied to find trade-off optimal solutions of DG operation pattern. The ultimate goal of the operator is to choose the “most preferred” solution among the Pareto optimal front. A fuzzy satisfying method is used in this paper to find the ‘the best’ solution. The principles of this method are as follows: for each solution in the Pareto optimal front, X_n, a membership function is defined as μ^f_k. This value, which varies between 0 and 1, shows the level of which X_n belongs to the set that minimizes the objective function f_k. A linear membership function is used in the present work for all objective functions, as follows [5]:

$$\mu^{f_k(X_n)} = \begin{cases} 0 & f_k(X_n) > f_k^{max} \\ \dfrac{f_k^{max} - f_k(X_n)}{f_k^{max} - f_k^{min}} & f_k^{min} \le f_k(X_n) \le f_k^{max} \\ 1 & f_k(X_n) < f_k^{min} \end{cases} \quad (5)$$

A conservative decision maker tries to maximize minimum satisfaction among all objectives or minimize the maximum dissatisfaction. The final solution can then be found as:

$$\max_{n=1:N_p} (\min_{k=1:N_o} \mu^{f_k(X_n)}) \quad (6)$$

To represent the dynamics of loading conditions, the daily demand variation is divided in multiple levels. Each level is a measure of how many hours at least a specified amount of energy must be supplied. The price of electricity purchased from the main grid is determined by the market. This value changes during each demand level.

All DG units are considered to be of such technologies and resources that they can be dispatched. For example, gas-turbine DG units would be typical examples. This is not limiting the ability of the model for considering other DG technologies. The DG units have been represented as PV buses, which allow them a more active role in the network.

RESULTS AND DISSCUSSIONS

The proposed evaluation method has been applied on the well-known IEEE 30-bus test system as shown in Fig.1. The load flow data of the system is included in [8]. A loading condition of 283.4MW and 126.2MVAr is assumed as the base case. The voltage limit of ±5% is applied at load buses. The DG units are already installed in the weak buses of the system. These buses are 26, 29, and 30. The maximum capacities of DG units installed in these buses are assigned 20, 10 and 25 MW, respectively.

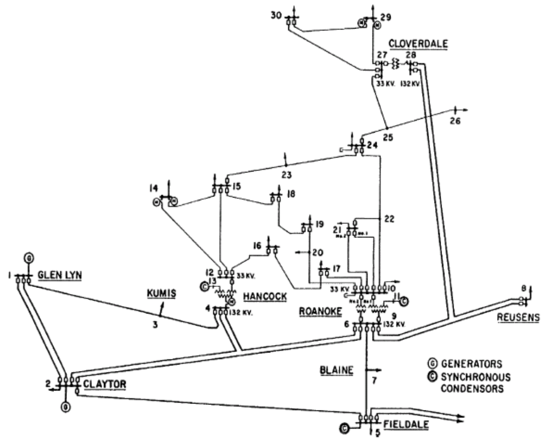

Fig. 1. IEEE 30-bus system.

In this work, four demand levels, i.e., low, medium, base and high are considered with demand level factors as presented in Table.1. The electricity market price and assigned award policy are assumed to be 70$/MWh and 10$/MWh for the base demand level.

Table.1: Data used in the study.

Demand Level	Demand Level Factor	Duration (Hour)	Price Level Factor	Award Level Factor
1 (low)	0.75	2920	0.7	0.2
2 (medium)	0.87	2920	0.85	0.5
3 (base)	1	2847	1	1
4 (high)	1.25	73	1.45	-

The Pareto-optimal fronts from the technical point of view and the economical point of view for low demand level are depicted in Figs.2 and 3 respectively.

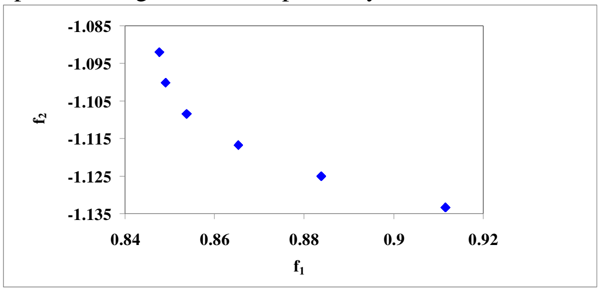

Fig.2.Pareto optima front of Technical Perspective (Demand Level 1)

In this study, the operation and installation costs of DG units is considered as a total cost or levelized cost of 55 $/MWh. Generally the levelized cost of DG generation is a function of several parameters such as: installation cost, operation cost, DG maintenance cost, the operation period and DG life time [9].

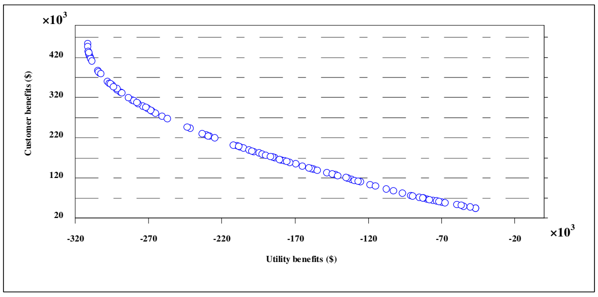

Fig.3.Pareto optima front of economic Perspective (Demand Level 1)

According to the fuzzy satisfaction decision making approach, the best solution of the Pareto optimal front from economic perspective for each demand level is presented in Table 2.

Table.2. Pareto-optimal solution of economic perspective

Demand level	Utility benefit ($)	Customer benefit ($)	Purchase price ($/MWh)
1	210240	-199728	50
2	178120	1027840	62
3	227760	2772978	74.5
4	114975	109573	85

The optimal generated power of each DG unit for economic perspective is presented in Table 3.

Table.3. Generated power of each DG unit (MW) in optimal solution

Demand level	DG at bus 26	DG at bus 29	DG at bus 30
1	3.16	2.94	7.6
2	15	10	25
3	15	10	25
4	15	10	25

From Tables 2 and 3, it is revealed that in low demand level; due to low purchase price and high DG operation cost; the customer gains no benefit and so will operate with minimum generation. As purchase price increases, the DG owners operate with full capacity and this is desirable from utility point of view to overcome the demand in the system.

In the competitive market, the utility is considered to be a participant in the electricity market and it purchases power from the market. During hours where the electricity prices are the highest (during peak load or generation scarcity), it will be cost effective for the utility to purchase the electricity produced by customer-owned DG units. The benefits for the utility of avoiding spot electricity purchases are obtained by the difference between the wholesale electricity price and the tariff offered to the DG owner for its output.

From Table 2, the offered purchase price at high demand level is at least 15 $ lower than the spot market price which is 100 $/MWh in this case study. The attained benefits at this demand level cover the extra associated costs of utility in other demand levels. The total benefits of utility and customer in Table 2 show that DG installation is profitable for both parties.

Figs. 4 to 7 illustrate the power generation of DG units for different demand levels. Four different perspectives are implemented: Technical perspective; utility and customer benefit perspectives, individually and simultaneously.

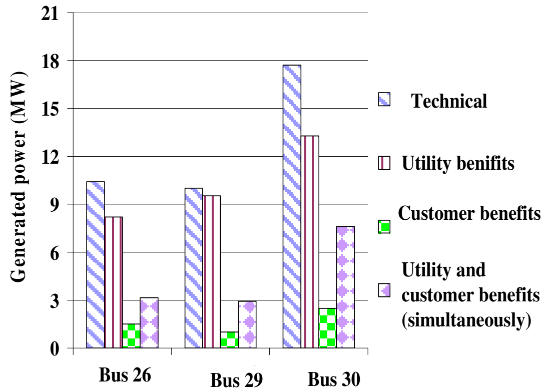

Fig.4 : DG generated power from technical and economical perspectives (Demand level 1)

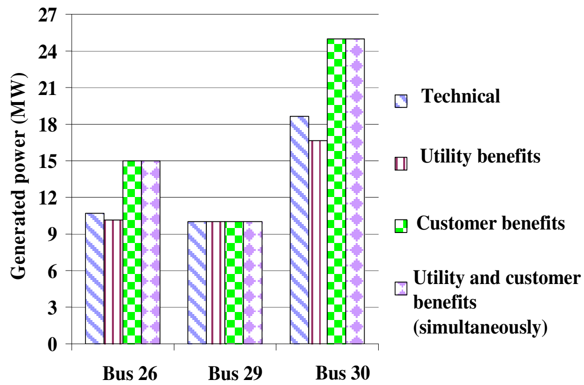

Fig.5 : DG generated power from technical and economical perspectives (Demand level 2)

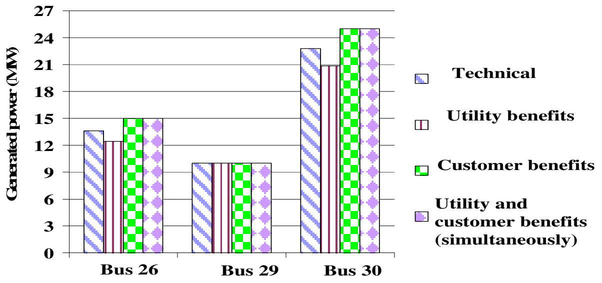

Fig.6 : DG generated power from technical and economical perspectives (Demand level 3)

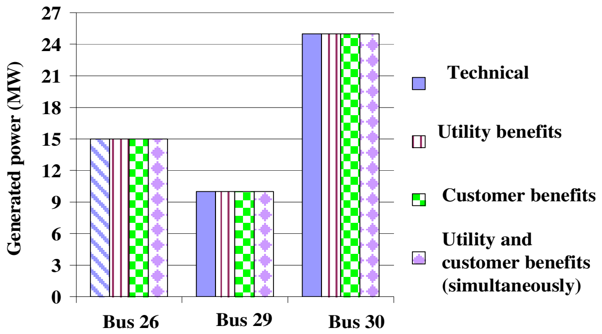

Fig.7 : DG generated power from technical and economical perspectives (Demand level 4)

As shown in Figs. 4 to 7, for different demand levels, the DG generation pattern from technical perspective is in line with the utility benefits point of view and that from customer benefit point of view is in line with the simultaneous benefits of utility and customer. In addition at high, base and medium demand levels, the DG generation pattern from technical perspective follow the same pattern as economic perspective. In low demand operating condition, there is a significant difference between the generation patterns from different perspectives.

It should be noted that, the operating DG units at the maximum capacity with the maximum profits are the main objectives for customers who own the DG units. A key element of competition is the information utilities provide to customers to enable them to manage their energy generation in the smart grid environment. In this regards, utility offers a specific purchase price to encourage the customer to follow a generation pattern which covers the technical needs of the utility. Regulatory and market design agencies hope these price signals will delay the need to build new power stations or at least reduce the amount of electricity that has to be bought from more expensive sources.

According to the results obtained, the proposed DG generation pattern considering the optimum obtained results is generation with the maximum capacity for medium, base and high demand levels. However the power generation at low load level is considered as 50 % of maximum capacity of DG unites. Accordingly, the assigned power purchase price as tariffs offered to DG owners are the optimum purchase price obtained and presented in Table 2.

CONCLUSIONS

The results show that the incentive provided to DG developers has a major impact on their opinion of optimal operation of DG units. It is demonstrated that the inclusion of customer-owned DG units offers technical benefits such as voltage profile improvement, line loss reduction, and relief of overloading power demand. The results obtained from economic evaluation of customer-owned DG implementation to the system reveal that if a proper power purchase policy is executed by the utility, not only do utility and customer both attain the benefits, but also the customer is encouraged to stay in service to overcome the system's peak load.

Furthermore, it is indicated that by developing of the smart technologies in the power systems all of the consumers with any type of electricity demand as investors of distributed energy resources can actively participate in the electricity markets and trade electricity at the spot prices. This will increase the efficiency of the markets and the benefits of the consumers.

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