2011 American Control Conference
on O'Farrell Street, San Francisco, CA, USA
June 29 - July 01, 2011

Market Based Allocation of Power in Smart Grid

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Abstract— **In recent years, the concept of Smart Grid has generated much attention among the producers and consumers of electric power, the policy makers, as well as the researchers. Smart Grid technology promises to revolutionize the way in which electricity is produced, delivered, and utilized. However, it requires technological advancement in a number of interdisciplinary domains before complete benefits of smart grid can be realized. Significant among them are the technological advances to enable substantial increase in the use of renewable energy sources coupled with a massive increase in energy efficiency in not only generation but also in distribution and utilization. In particular, the usage of renewable energy sources is envisioned to result into a massively distributed power generation and distribution system composed of a large number of generating stations operating on disparate renewable technologies. Optimal allocation of existing energy resources becomes a challenge due to massively distributed nature of generation facilities and consumption sites, and due to uncertainty caused by inherent random fluctuations in generation. In this paper, a Market Based technique has been presented for carrying out the optimal allocation for efficient utilization of the energy produced in a Smart Grid. The Market Based Resource Allocation is a distributed technique inspired by the concepts from the economic market where resources are allocated to the activities through the process of competitive buying and selling. In the proposed technique, the energy consumers act as the potential buyers of the energy and the energy producers act as the sellers of energy. The paper evaluates the proposed Market Based technique via a number of simulated scenarios of energy consumers and producers in a Smart Grid. The proposed technique optimizes the energy production cost and the transmission loss of electricity as these costs are reflected in the bidding and asking prices of the consumers and the sellers respectively.**

I. Introduction

THE Smart Grid is a modernized power generation and distribution network that delivers power from the suppliers to the consumers using digital technology and bi-directional communications to reduce cost, save energy and increase reliability and transparency. Essentially, a Smart Grid uses sensors, communications, intelligence, and controls to enhance the overall functionality of the power delivery system. There are many definitions of Smart Grid from the functional, technological and beneficial perspectives. The most common features among the definitions are the utilization of digital signal processing and communication in the power grids for improved efficiency, reliability, security and quality of service. Increasing complexity of the management of bulk power grid, aging assets, environmental concerns and the growth in demand and quality of service have directed the development of the "*Smart Grid*". The Smart Grid can be considered to be multi-faceted solution to the problems faced in the current power grids.

The Smart Grid is expected to utilize the available modern technologies to help the current power grid to function more intelligently and facilitate [1]:

- Enhanced situational awareness and operator assistance.
- Enhanced efficiency by maximizing asset utilization.
- Autonomous control actions to enhance reliability.
- Higher quality of service
- Active participation of the customers by real-time communication.
- Integration of renewable resource, such as solar and wind energy, to address environmental concerns.

Over time, many policy and regulatory initiatives ([2-5]) has increased the momentum towards the *Smart Grid* vision, and that has increased the focus considerably towards different aspects of power generation and distribution including reliability, renewable resources, demand response, electric storage and electric transportation.

According to the author in [6], the use of alternative forms of energy sources based on renewable resources will be a key feature of the future electric grid. Though traditional and renewable sources of energy have financial aspects that make traditional sources cheaper, the price of traditional fuel required to generate energy is expected to rise (Price hike from 1998 to 2008 is already 800% [10]). On the other hand, renewable energy is expected to deliver power for a sustainably longer term [7] at a reduced emission of green-houses gases into the atmosphere. These factors along with long-term non-availability of fuels make it imperative to explore renewable sources for bulk power generation. Reports reflected in [8] and [9] suggest the increase in the popularity of renewable resources in US and abroad. Apart from environmental and overall financial advantages, a lot of renewable energy resources are distributed and local in nature which can potentially provide increased security than bulk energy sources [11]. Usage of these distributed energy resources reduces the dependence on the bulk power generation unit (on which current power grid is hugely dependent) that in turn reduces the effects of transmission network congestion, cascading effects and large blackouts [11].

Although these renewable energy sources such as photovoltaic cells, wind mills, and bio-fuel show great promise when production cost and environmental conditions

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are considered, they pose several challenges to the grid and the grid operations. Some of the issues with these renewable resources are: a) *Transmission system issues:* some renewable energy sources (such as wind mills) can be located far away from the consumption unit and thus require additional transmission infrastructure; b) *Distribution system issues:* the renewable energy resources are essentially geographically distributed and hence incorporating them into the existing power grid requires some changes into the current grid distribution system; c) *Operational issue*: the renewable energy resources are generally intermittent in nature and thus pose additional challenges for the transmission system. In order to achieve maximum asset utilization, an essential feature of the smart grid, and autonomous functioning of the power grid, an allocation technique is required that can carry out decision making for optimal power routing and that can incorporate the distributed and local nature of the production system.

Some of the research in the field of optimization of energy includes those reported in references [15] and [16]. Optimal domestic energy management via linear programming is shown in [15] where power required by each device in a house is optimally met by the available resources. Similar work of power matching can be found in [16] where supply and demand for a number of producers and consumers are matched using Market Based Methods. In [16], the supply and demand matching optimally uses the possibilities of altering the operations of the producer and the consumer in order to match the total supply and demand.

In this paper, a *Market Based Resource Allocation* technique is used to allocate the energy produced from the distributed and central power systems to the consumers (end users) so that the transmission loss is minimized in a distributed manner without altering the requirements of the consumer. This paper focuses on a simplified version of power allocation problem in which the consumers' demands are satisfied by power obtained from producers such that one producer is able to completely satisfy the demand of a customer. Under this assumption, the allocation problem boils down to optimal assignment problem such that every consumer agent is assigned to a generation unit or source of energy so that the overall transmission loss is minimized.

Power allocation is a challenging problem and the key features of power allocation in distributed smart grid systems include dynamic and unpredictable power demand as well as generation, and locations of generation and consumer sites at physically and administratively distributed space. A Market Based Resource Allocation technique is a distributed resource allocation technique that is inspired by the economic market. There exists no rigid definition of these "Market Based" or "auction like" or "economically inspired" techniques but rather there are certain features in the market that have inspired the development of such techniques [12]. These features include decentralization, interaction among agents and the knowledge of the resource that is required to be allocated.

II. PROBLEM DESCRIPTION

Resource utilization is one of the important aspects of the Smart Grid. The available electrical energy at a particular instant of time can be regarded as the available resource for the Smart Grid that needs to be intelligently allocated among a number of prospective consumers, which can be considered as the end users of energy. The resources to be allocated include the generated electricity from the central power plants along with the distributed energy resources from sources such as wind mills and the photovoltaic cells on the roof-tops of the consumers. Incorporation of the renewable, geographically distributed resources requires the allocation to be performed in a distributed manner. At every instant of time, each consumer has a certain requirement of electrical energy that is required to be met by the available energy from the sources. Although the energy requirement of each of the consumers can be met from a number of sources and even different combinations of the sources, the most efficient allocation technique would result in the minimization of the cost. The "cost" can be modeled in a number of ways depending on the problem being solved. In this paper, the cost is considered to be a function of *transmission loss*. The transmission cost, in this paper, is assumed to be the product of the distance between the source and the consumers and the power transmitted between them. It may be mentioned that the proposed technique would be applicable to any non-linear relationship between the distance of transmission, power transmitted, and transmission loss.

The future grid can be thought of as being organized in clusters, and composed of generation units and end users. Each of these clusters can be considered as a node. These clusters or nodes consist solely of generation units, solely of end users or a combination of both. Depending on the scale of the problem, these nodes can represent a region, a city, or even smaller entities. In this paper, each of the nodes is considered to be either solely generation units, considered as seller agents, or solely end users, considered as buyer agents. This assumption is justified because the net power of a node would either make it a buyer or seller of power.

In the proposed Market Based Resource Allocation method, the producers and the consumers are represented by provider agents and the consumer agents respectively. Each of the provider and the consumer agents bid for their selling and buying price and through the competition among these agents, resource is allocated that reduces the transaction price to the highest extent. This results in reduction of the transmission loss and energy production costs because the buying and the selling price of the different agents are a function of these parameters. The optimization problem can be formulated as follows:

The grid is assumed to consist of $R = \{R_1, R_2 \ldots R_m\}$; "*m*" provider/seller agents and $S = \{S_1, S_2 \ldots S_n\}$; "*n*" consumer/buyer agents. Each provider agent is characterized by its *selling price*. Accordingly, each consumer agent is characterized by its *bidding price* and its demand for resources d_i, $i = 1,2,3\ldots n$. There is a dealer in the market that helps in the transaction of resources and sharing information of price to the buyer agents. The role of the dealer can be assumed by the distribution units in the grid. The objective of the resource allocation problem is to minimize the following:

$$\min \sum_{i=1}^{n}\sum_{j=1}^{m} D_{ij} P_{ij} \tag{1a}$$

$$\text{s.t. } P_{ij} \in \{0, d_i\} \tag{1b}$$

where D_{ij} is the distance between i^{th} buyer and j^{th} seller and P_{ij} is the electrical power transferred between them. The equation (1b) shows that the problem to be solved is essentially an assignment problem, that is, each of consumers or end users are assigned to one particular generation unit or source of electrical energy. Here, i^{th} buyer either gets its entire demand d_i or none from the j^{th} seller.

In this paper, the proposed market based technique is applied to different scenario problems. Fig. 1 shows a particular scenario problem in which there are *5* energy sources (called providers) and *5* consumer units are assumed to be located in a distributed fashion. Each energy source has an energy producing capability and each consumer has a demand that changes with time. The problem thus is to assign the resources dynamically at every time instant so that the overall cost is minimized. In this respect, the problem is similar to the classical Quadratic Assignment Problem [17], a well studied problem in optimization literature, which is computationally NP-hard, and which rapidly becomes computationally intractable with growing size of the problem. In the power allocation in electrical grids, the difference stems from the fact that it is dynamic in nature, and QAP needs to be solved every time demand changes.

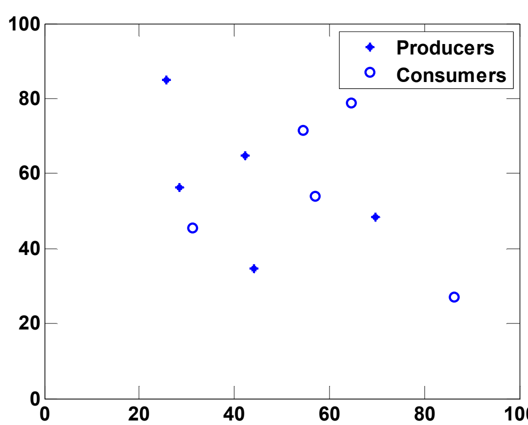

Fig. 1 Sample Scenario of distributed resource and consumers

III. APPROACH

The paper proposes a Market Based Resource Allocation technique with auction based method for resource allocation. A market can be considered to be a system with locally interacting agents (components) that achieve some overall global behavior. In a market, the simple interactions among individual agents i.e., buying and selling, lead to a desirable global effect such as stable prices and fair allocation of resources. The ability of the Market Based method to facilitate fair allocation of resources with limited information makes them an attractive solution for many complex problems.

There are overall two categories of market-based models that are generally used in grid resource management viz. commodity market model and auction models. In commodity market model, the providers specify their prices and charge the consumers according to their consumption. The consumers and the providers in auction models act independently and settle for a selling price privately. The auctions are used for the resources that have no standard values and the prices change dynamically according to the supply and demand at a specific instant. The auction methods are decentralized; they require little information and are easy to implement [13]. There are four basic types of auctions based on the interaction between the consumer and the provider: the ascending auction, descending auction, the first price and second price sealed auction, and the double auction [14].

Motivated by its successful applications in grid based environments, the paper uses the Market Based Auction Method for resource allocation in the power grid network. In the auction method, the goal of both the provider and the consumer agents is to maximize their own profit margins. The goal of each consumer agent is to buy the required resources at the cheapest price while the provider agent intends to sell its resources at the highest price to maximize its profit margin. The auctioneer or dealer maintains a list of current bids for buying and asking prices from the consumers and providers respectively.

The market based approach works in an iterative fashion where agents adjust their bidding and selling prices based on current allocations decided by the dealer in each iteration. In the next iteration, agents try to re-adjust the allocation in a manner that improves the overall utility.

A. Consumer/Buyer Agent's Strategy

Each of the consumer or buyer agent calculates the cost of acquiring the required resource from the all the generation units or the seller agents it is connected to. In this paper, it is considered that all the consumer agents are connected to every seller agents. The cost of acquiring the resource from a particular generation unit or the seller agent is a function of the distance (D_{ij}) between the consumer "i" and the seller agent "j" and the price, "p_j", of the resources for the particular seller agent "j", and is given by:

$$Cost_{ij} = \alpha D_{ij} + \beta p_j \tag{2}$$

where "α" and "β" are constants. This cost reflects the price the consumer agent has to pay to procure resources from a given seller agent. Using the distance in the cost function helps minimize the distance through which power has to transmit thus reducing the power loss. Each consumer agent "i" maintains a cost vector given by $Cost_i$ whose elements are obtained by (2). To maximize its own profit margins, each consumer agent "i" ($i = 1,2\ldots n$) would bid for the resource that results in minimum cost, i.e., $min(Cost_i)$ for a particular "i". More than one consumer bidding for the same resource becomes very likely in such bidding strategies. The information about the other consumer agents bidding for the same seller agent is made available to the consumer agents via the dealer in the market. In such cases, the bidding amount for the most preferable resource (seller agent) "j" for a consumer agent "i" depends on the number of consumers competing for the "j", and is given by:

$$bid\_value_{ij} = Cost_{i2} - Cost_{ij} \tag{3}$$

where $Cost_{i2}$ is the cost associated with the second most preferable seller agent for buyer agent "i", and is obtained by the 2nd minimum element of the vector $Cost_i$. $Cost_{ij}$ is the minimum cost, associated with the most preferable seller agent "j", incurred by the consumer agent "i". The bid value in (3) signifies the importance of the seller agent "j" for the consumer agent "i", and suggests that the value of the optimum request of consumer "i" is the difference between the costs associated with its second best and best request. So if the difference between $Cost_{i2}$ and $Cost_{ij}$ is high, the bid value for the seller agent "j" increases which signifies that the importance of the seller agent "j" is high because if the agent's request is not fulfilled, then the cost associated with the second best request is a lot higher. Conversely, if difference is low, then the bid value decreases which means the valuation of the optimum request is lower because even if the agent's optimum request is not met, its second best request is not that bad.

B. Seller Strategy

The seller agent is considered to maintain a very simple strategy. The initial selling price p_j for the seller agent "j" is considered to be a very low value and its price increases as the number of requests to the seller agent "j" increases. The evolution of price over iteration from t to t+1 is given by:

$$\left(p_j\right)_{t+1} = \left(p_j\right)_t + (k-1)\gamma \tag{4}$$

where k is the number of consumers bidding for the seller agent "j" and γ is a constant that governs the change of price rate. Equation (4) suggests that if only one consumer bids for the seller "j" then its price will remain unchanged. When more than one consumer bid for the seller, its price will go up. If no consumer bids for the seller agent "j", its price will go down.

C. Dealer

The role of the dealer is to inform the consumers about the total number of consumers bidding for a particular seller agent and facilitate the transaction. The dealer assigns highest bidder for a particular seller agent "j" to the buyer agent "i" and the transaction price is the cost of acquiring the resource from the seller agent "j" for the highest bidder given by (2).

IV. Simulation Results

The above presented market based technique is verified via extensive simulations carried out using a number of scenarios. A comparison of the proposed method has been carried out with an integer programming method that provides globally optimal solution. In our first problem scenario, we consider equal demand of all the consumers and equal production capability of all the seller agents or generation units. We carry out simulations for cases: i) 5 consumers and 5 producers (5X5), ii) 10 consumers and 10 producers (10X10), iii) 15 consumers and 15 producers (15X15), iv) 20 consumers and 20 producers (20X20), v) 25 consumers and 25 producers (25X25); vi) 30 consumers and 30 producers (30 X 30); vii) 50 consumers and 50 producers (50 X 50); and vii) 100 consumers and 100 producers (100X100). It is considered here that all the seller agents have the capability to supply power to any of the consumer agents. In each of the cases the demanded power for each consumer was considered to be 5 units .The optimal cost given by Eq. (1a), in units, obtained for all the scenarios and their comparison with the integer programming method is shown in Table I. It is clear from the Table I that the solutions obtained from the proposed market based method are very close to the globally optimal results.

Table I

Scenario	*Market Based Cost*	*Integer Programming Cost*
5X5	575.11	575.11
10X10	849.13	849.13
15X15	1237.5	1237.5
20X20	1320.2	1320.2
25X25	1665.1	1655.8
30X30	1698.2	1614.6
50X50	2461.7	2396.4
100X100	4664.7	**

** Matlab showed "Out of Memory" error on the computer used for the simulation.

For higher dimensional problems, it is seen that the market based technique obtains slightly different solutions with respect to the global ones. 25X25 is an example of this. The optimal allocation of power via assignment between the consumers and the producers using distributed Market Based Method and integer programming method are shown in Figs. 2 and 3 for the case 25X25. Solving the assignment problem using centralized integer programming method for higher dimensional problems require a lot of computational memory which can be avoided when solving the problem in a distributed manner. Table I shows one such example where integer programming method failed due to memory problem when solving the assignment problem for the 100X100 case.

This example shows that centralized optimization techniques are not scalable, and often become intractable for higher dimensional problems.

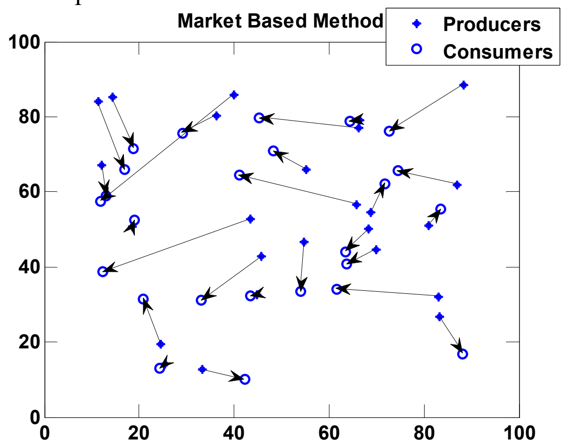

Fig. 2 Optimal Assignment in 25X25 case (Market Based Method)

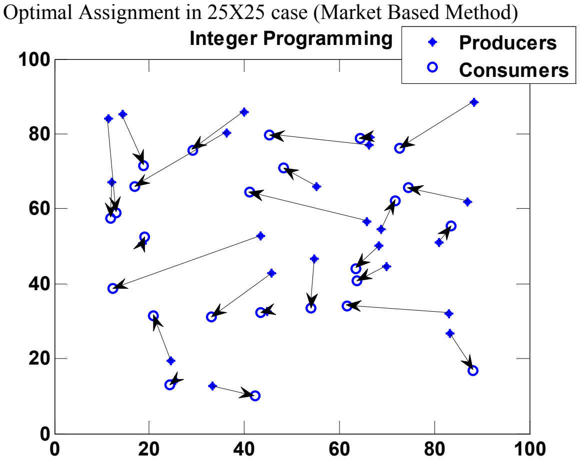

Fig. 3 Optimal Assignment in 25X25 case (Integer programming)

The second scenario where we applied this method concerns a more realistic problem in Smart Grid environment where the requirement of power is different for different consumers and their requirements change with respect to time. To simulate such environment, in a 15X15 case, the demand of all the consumers is randomly generated and the capacities of energy production of the seller agents or the generation units are considered to be such that each seller agent is capable of supplying energy to any consumer agent. Furthermore, one seller unit would supply power to just one consumer unit. In different time steps, the consumer demands are considered to change in a random fashion. Table II shows the demand of all the 15 consumers at six different time steps. The optimal allocation of power in such a scenario is shown in Fig. 4. Fig. 4 (a), (c), (e), (g), (i) and (k) shows the optimal allocation of power using Market Based Methods in six different time steps. Their corresponding Integer programming optimal allocations are shown in Fig 4. (b), (d), (f), (h), (j) and (l). Table III shows the comparison of the optimal result of Market Based method and the Integer Programming method for the six different time steps. It can be seen that the optimal results obtained from the Market Based Method are either same or very close to the optimal solution obtained from the integer programming method.

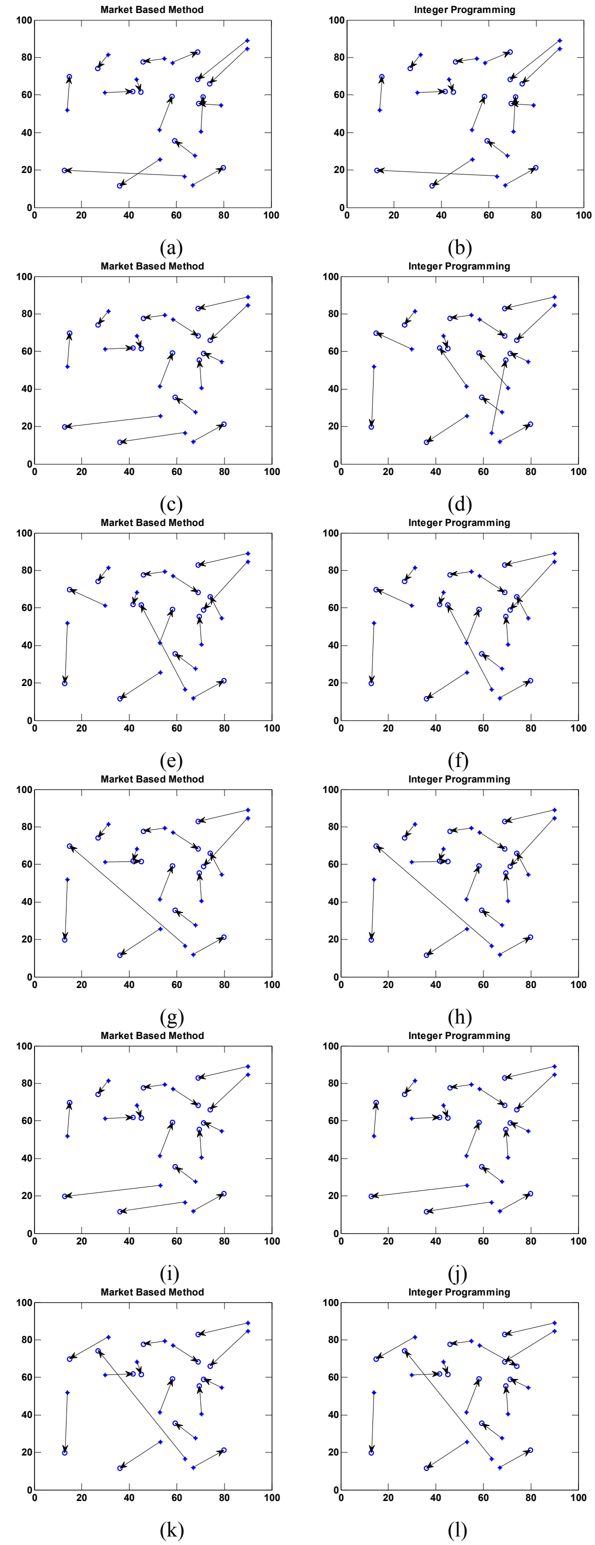

Fig. 4 Optimal Assignment in 15X15 case for 6 different time steps; (a), (c), (e), (g), (i) and (h) shows the optimal power allocation using Market Based Methods; (b), (d), (f), (h), (j) and (l) shows the optimal power allocation using Integer Programming method.

TABLE II
DEMAND OF CONSUMERS AT DIFFERENT TIME STEPS

Consumers	*Time Step 1*	*Time Step 2*	*Time Step 3*	*Time Step 4*	*Time Step 5*	*Time Step 6*
1	8.04	2.94	6.83	1.25	6.87	5.66
2	2.53	3.96	8.88	5.10	8.23	8.19
3	2.22	2.22	7.64	9.28	9.52	4.57
4	1.22	9.16	6.1	2.56	2.38	9.16
5	3.84	5.81	4.75	9.33	1.26	1.43
6	1.44	7.44	7.32	6.57	8.83	4.66
7	5.85	2.63	4.27	9.66	7.49	6.61
8	7.80	0.89	0.74	3.30	2.52	7.20
9	2.08	7.84	8.71	7.23	8.70	5.62
10	6.53	6.85	0.21	6.79	3.52	4.43
11	4.77	9.13	3.12	0.78	3.75	7.68
12	9.11	5.81	9.27	5.70	1.98	2.89
13	5.92	5.28	8.14	7.35	8.14	8.97
14	4.51	1.65	5.47	6.46	9.92	2.10
15	7.64	7.5	7.67	6.23	9.22	7.14

TABLE III
15X15 SCENARIO

Time Steps	*Market Based Cost*	*Integer Programming Cost*
1	1098.2	1098.2
2	1237.1	1219.5
3	1471.9	1471.9
4	1585.6	1585.6
5	1299.2	1299.2
6	1289.5	1279.6

V. CONCLUSION AND FUTURE WORK

In this paper, an allocation technique is presented for optimal routing of power from distributed sources in a Smart Grid that minimizes the transmission loss. A Market Based Allocation technique with auction method is proposed to dynamically allocate power in a Smart Grid environment. Simulation results using different scenarios and a comparison with integer programming method that provides globally optimal solutions demonstrate the effectiveness of the proposed resource allocation technique. Two particular characteristics of the proposed method make it specifically suited for its application in Smart Grid systems: i) its ability to be applied in distributed, networked systems and its scalability; and ii) its ability to carry out re-allocation in dynamic scenarios. The realization of Smart Grid is still in its nascent state and it requires simultaneous efforts in a number of technological domains. The ability of the Smart Grid system to intelligently and optimally allocate and re-allocate power among the consumer forms the central aspect of such systems. The proposed method, based upon market based technique, demonstrates its potential to be applied in massively distributed smart grid systems.

It may be mentioned that the work is a preliminary study that uses very simplified scenarios. Future work includes incorporation of more realistic power generation and distribution constraints. Furthermore, implementation of the proposed market based technique in a distributed environment where buyers and sellers interact with only local entities is another direction for future research.

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