Determination of Spot Price and Optimal Power Flow in Deregulated Power System

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Abstract

In this paper, determinations of spot price with optimal power flow and important factors that may affect generating companies’ profit margins through wholesale electricity trading are discussed. These factors include spot price, generators’ efficiencies and capabilities, types of generators owned, fuel costs, transmission losses and settling price variation. It demonstrates how proper analysis of these factors using the solutions of Optimal Power Flow (OPF), can allow companies to maximize overall revenue. And through this OPF analysis, companies will be able to determine, for example, which generators are most economical to run, best locations for generators to be situated at, and also the scheduling of generators as demand changes throughout the day. It illustrates how solutions of OPF can be used to maximize companies’ revenue under different scenarios. In this paper above tasks are demonstrated on 124-bus Indian utility real-life system and results have been presented and analyzed. All simulations are performed by using Power World Simulator software.

Keywords: OPF, Electricity Market, Spot Price

1. Introduction

In the past, the electricity industry was government-controlled and also monopolistic. However over the past decade, the industry in many countries including part of India had undergone significant changes and was restructuring for a free market, also known as deregulation (Xie 2000). This led to a competitive market whereby customers are able to choose their electricity supply from a number of generating companies and retailers. In this deregulated market, it is essential for generating companies to plan their operations efficiently, so as to minimize operating costs while maximizing their profit margins (Geerli 2003).

There are many factors involved in the successful operation of a power system. The system is expected to have power instantaneously and continuously available to meet power demands. It is also expected that the voltage supplied will be maintained at or near the nominal rated value. Not only must the demands be met at all times, the public and employees should not be placed in hazard by operations of the system. At the same time proper operating procedures must be observed to avoid damage to equipment or other facilities of the system. All of these operating requirements must be achieved simultaneously (Miller 1970).

Other than those mentioned above, one of the most important factors is the operating cost. Generation and distribution of power must be accomplished at minimum cost but with maximum efficiency. This involves the real and reactive power scheduling of each power plant in such a way as to minimize the total operating cost of the entire network. In other words, the generator’s real and reactive powers are allowed to vary within certain limits so as to meet a particular load demand with minimum fuel cost. This is called the Optimal Power Flow (OPF) or sometimes known as the Optimal Power Dispatch or Economic Dispatch (ED) problem (Happ 1974).

The objective of this paper is to demonstrate how generating companies can utilize solutions of OPF to minimize costs while maximizing profit margin in a deregulated wholesale market environment. Thus,
there is a need to understand how the local electricity market operates.

2. Modelling of Optimal Power Flow Problem

In the solution of OPF, the main objective is to minimize total operating costs of the system. In OPF, when the load is light, the cheapest generators are always the ones chosen to run first. As the load increases, more and more expensive generators will then be brought in. Thus, the operating cost plays a very important role in the solution of OPF (Momoh 1997).

In all practical cases, the cost of generator $i$ can be represented as a cubic function of real power generation expressed in $$/hr,

$$C_i = (\alpha_i + \beta_i P_i + \gamma_i P_i^2 + \xi_i P_i^3) \times \text{fuel cost}$$

(1)

Where $P_i$ is the real power output of generator $i$, and $\alpha$, $\beta$, $\gamma$ and $\xi$ are the cost coefficients. Normally, the cost coefficients remain constant for a generator. The last term in the equation is the fuel cost, expressed in Rs. /MBtu.

Another important characteristic of a generator is the incremental cost, also known as marginal cost. It is a measure of how costly it will be to produce the next increment of power. The incremental cost can be obtained from the derivative of $C_i$ of equation (1) with respect to $P_i$,

$$\frac{\partial C_i}{\partial P_i} = (\beta_i + 2\gamma_i P_i + 3\xi_i P_i^2) \times \text{fuel cost}$$

(2)

Which is expressed in Rs./MWHr.

The transmission losses become a major factor in a large interconnected network whereby power is being transmitted over long distances. A common function to represent total system real power losses in terms of the total real power output is the Kron’s loss formula,

$$P_L = \sum_{i=1}^{ng} \sum_{j=1}^{ng} P_i B_{ij} P_j + \sum_{i=1}^{ng} B_{ii} P_i + B_{\infty}$$

(3)

Where $P_L$ is the total real power losses, and $B_{ij}$ are the loss coefficients or B coefficients (Grainger 1994).

Optimal dispatch can be seen generally as a constrained optimization problem. When solving a constrained optimization problem, there are two general types of constraints, which are equality and inequality constraints. Equality constraints are constraints that always need to be enforced.

The constrained optimization problem can be solved using the Lagrange Multiplier method, and for simplicity, only the maximum and minimum real power limits are included as the inequality constraints.

The total operating cost of all generators in a system is given by,

$$C_i = \sum_{i=1}^{ng} C_i$$

(4)

Where $ng$ is the number of generator buses.

The total real power generation is then given by,

$$\sum_{i=1}^{ng} P_i = P_D + P_L$$

(5)

Where $P_{\text{min}} \leq P_i \leq P_{\text{max}}$, $P_D$ is the total real power demand, and $P_L$ is the total system real power loss [9].

The Lagrange Multiplier can then be expressed as,
\[ \ell = C_1 + \lambda (\sum_{i=1}^{n} P_i - P_i + \mu_{i(max)} (P_i - P_{i(max)})) + \sum_{i=1}^{n} \mu_{i(min)} (P_i - P_{i(min)}) \]  

(6)

Where the term second term is the equality constraint, while the last two terms are inequality constraints in equation (6) (Momoh 1999).

Note that both \( \mu_{i(max)} \) and \( \mu_{i(min)} \) are equal to zero if \( P_{i(min)} \leq P_i \geq P_{i(max)} \), which means that the inequality constraints are inactive. The constraints will only be active when violated, which means \( P_i > P_{i(max)} \) or \( P_i < P_{i(min)} \). This is known as the Kuhn-Tucker necessary conditions of optimality, following the conditions below,

\[ \frac{\partial \ell}{\partial P_i} = 0 \]  

(7)

\[ \frac{\partial \ell}{\partial \lambda} = 0 \]  

(8)

\[ \frac{\partial \ell}{\partial \mu_{i(min)}} = P_i - P_{i(min)} = 0 \]  

(9)

\[ \frac{\partial \ell}{\partial \mu_{i(max)}} = P_i - P_{i(max)} = 0 \]  

(10)

The optimal solution can then be obtained by solving for the condition, \( \frac{\partial \ell}{\partial P_i} = 0 \) (Sun 1984).

3. The Spot Price

A centralized economic dispatch is employed to determine the market clearing price, the power generation and demand levels of all units and consumers. The competition in the electricity market must be encouraged for investments to the new technology and more productive electrical source.

The participants in deregulated power market are independent power producer, Distribution Company. Bids are for supplying loads because all participants in the power system each other effect. The bids are been received by independent system operator. Independent System Operator (ISO) analyzes the power system situation, develop strategies and define transactions among participants by looking for the minimum price that satisfies the power demand (Davison 2002).

According to many system operations each power production participant defines its own resource scheduling and sends a bid to the ISO for supplying other loads. The participants submit hourly offers that contain quantity and price, and they receive dispatch instructions from the ISO for each 5-min period. ISO determines transaction between participants according to their bids and power demand (Rodriguez 2004, Aganagic 1998, Wen 2001 and Chattopadhyay 2001). Transaction payments are defined as the product of the spot price and power transactions for each participant.

In a real competitive power market, no participant can absolutely control the power system operation. It means that the participants can not significantly affect the existing spot prices by adjusting their bids but mostly match the spot price with their marginal costs. Therefore the minimum power system operation cost and the maximum participant benefit are reached at the same time in a real competitive power market.

Electricity in the National Electricity Market (NEM) can be either traded through retail or wholesale trading or even through contracts. Note that this paper only emphasizes on the wholesale trading of the spot market. All wholesale electricity must be traded through the spot market; generators are paid for the electricity they sell to the pool while retailers and wholesale end-users pay for the electricity they use from the pool. It is a process whereby prices for electricity are set and then settled. This pool is the way which short-term operation of the power system is centrally.

In this spot market, generating companies can choose whether to commit their generators and make it
available for dispatch. Once they have decided to commit, they must submit a bid for the opportunity to run their generators. A bid is the “sell offer” submitted for a particular amount of electricity selling at a particular price. Generating companies can change their bids or submit re-bids according to a set of bidding rules. After receiving all the bids, NEM will then selects the generators required to run and when to run at different times of the day, based on the most cost-efficient supply solution to meet specific demand. This ensures electricity is supplied at the lowest possible price. As mentioned above, the spot market allows instantaneous matching of supply against demand.

4. Test Case

In a competitive electricity market, there will be many market players such as generating companies (GENCOs), transmission companies (TRANSCOs), distribution companies (DISCOs), and system operator (SO). Similarly Andhra Pradesh State Electricity Board (APSEB) is divided into Andhra Pradesh Generating Company (APGENCO), Andhra Pradesh Transmission Company (APTRANCO) and Andhra Pradesh Distribution Company (APDISCO). All are operating with independent companies under the government of Andhra Pradesh. APDISCO is again divided into four companies as Northern Power Distribution Company Limited (NPDCL), Central Power Distribution Company Limited (CPDCL), Eastern Power Distribution Company Limited (EPDCL), and Southern Power Distribution Company Limited (SPDCL).

At present APGENCO is operating with Installed Capacity of 8923.86 MW (Thermal 5092.50MW and 3831.36MW) along with Private sector of 3286.30MW and Central Generating Stations (CGS) share of 3209.15MW.

For this case study total APGENCO, Private sector and Two Generating stations (bus 1 (2600MW), bus 115 (1500MW)) from CGS is considered. APTRANSCO is considered at 220kV level. Each DISCO is considered as one area.

A 124-bus Indian utility real-life power system is used for portfolio analysis in different operating scenarios. The generators’ efficiencies and capabilities, types of generators owned, fuel costs, transmission losses and spot price variation are some of the factors that can affect generating companies’ profit margins in a deregulated market environment. This section demonstrates that through proper analysis of these factors, generating companies can utilize solutions of OPF to maximize their profit margins through the wholesale spot market.

This analysis is discussed under different case studies as follows
Case 1: All the generators are operating without considering Minimum MW limit, with Maximum MW limit and with CGS Share.

Case 2: All the generators are operating with considering Minimum and Maximum MW limit and with CGS Share.

Case 3: All the generators are operating with considering Minimum and Maximum MW limit and without CGS Share.

Case 4: Some expensive Generators are shutdown, remaining all the generators are operating with considering Minimum and Maximum MW limit and without CGS Share.

The generators’ bids are assumed to be 10% higher than the generators’ costs and the spot price is determined by the highest generator’s bid.

Profit (Rs./MWhr) = Spot Price (Rs./MWhr) – Cost (Rs./MWhr)

Profit (Rs./Hr) = Profit (Rs./MWhr) x Gen MW

Results of Total Generation, Load, Losses, CGS Share, Spot price, Cost of Generation, Profits of Generator are given in Tables from 1 to 6. Power Exchange from 400kV lines, Cost functions of Generators are given in Tables 7 and 8.

In case 1, the OPF program set most expensive generators generation to zero. In case 4, Spot price is
reduced by shutting down the most expensive generators. The generators which are not committed to
dispatch are not shown in Tables.

Compared to all the Cases in Case 1 cost of generation is less because of considering the CGS share, in
Case 2 also CGS share considered but by imposing of Minimum MW limits to generators some of
expensive generators are committed to dispatch.

Comparing with Case 4, in Case 3 Spot Price, Cost of Generation and Profits are more because some more
expensive generators are committed to dispatch and losses are reduced. Case 3 will give more profits to
generator companies and Case 4 will give benefit to the consumer.

Results showed that profits are positively-related to the spot price and the load demand. In other words,
profits increase as the spot price increases with the load demand. This is because the spot price is
determined from the highest generator’s bid, and expensive generators are required when the load demand
is high, which will set a high spot price.

It is also realized that cheaper generators will have higher profit margins regardless of the spot prices.
Therefore, it is advantageous for companies to own a greater number of cheap generators along with a few
expensive ones. Those expensive generators can be used as backup units for emergencies and perhaps also
used to set high spot prices which are beneficial to the cheaper generators.

5. Conclusion

This paper demonstrated that the proper scheduling of generators by using OPF minimized the total system
losses and therefore increased generators efficiencies. It shows that the OPF algorithm had solved the case
more cost-efficiently. Therefore increases the revenues of company in deregulated power system. It is also
realized that cheaper generators will have higher profit margins regardless of the spot prices. Therefore, it is
advantageous for companies to own a greater number of cheap generators along with a few expensive ones.
Those expensive generators can be used as backup units for emergencies and perhaps also used to set high
spot prices which are beneficial to the cheaper generators. From these results, it can be concluded that types
of generators owned by companies and that spot price variation can greatly affect their overall revenue. The
results are certainly useful in an online environment of deregulated power system to perform the
transactions between buyer and seller for APGENCO, APTRANSCO, and APDISCOMs.

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Figure 1. 124-bus Indian utility real-life Power system.

Table 1. Details of Total Generation, load, Losses, CGS Share, Spot price and Cost of Generation

<table>
<thead>
<tr>
<th>Case</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
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<td>Total MW Load</td>
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<td>Total MW Losses</td>
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<td>CGS Share</td>
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<td>Spot Price (Rs./MWHr)</td>
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<td>6385.69</td>
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<td>Cost of Generation (Rs.)</td>
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Table 2. Details of Area wise generation and load

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<td>Generation MW</td>
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### Table 3. Generator Costs, Bids, Spot Price and Profits of Case 1

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<th>Gen MW</th>
<th>Cost Rs./Hr</th>
<th>Cost Rs./MWHr</th>
<th>Bid Rs./MWHr</th>
<th>Profit Rs./Hr</th>
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Total Generation (MW) 7874.44
Total Profit (Rs./Hr) 146810414.31

### Table 4. Generator Costs, Bids, Spot Price and Profits of Case 2

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Total Generation (MW) 7874.44
Total Profit (Rs./Hr) 146810414.31
### Table 5. Generator Costs, Bids, Spot Price and Profits of Case 3

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Total Generation (MW) 8970.04  
Total Profit (Rs./Hr) 36422883.28
Table 6. Generator Costs, Bids, Spot Price and Profits of Case 4

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