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A multi-objective solution algorithm for optimum utilization of Smart Grid infrastructure towards social welfare

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ABSTRACT

This paper proposes an optimization model to maximize social welfare by standardizing the operating conditions with an overall improvement of dynamic stability of power markets endowed with Smart Grid communication technology. The state space based model developed along with the proposed methodology maximizes load catering and simultaneously minimizes the operating standard constrained generation cost to restore power market equilibrium even in the most inadvertent states of the Energy System Network. For optimum utilization of smart metering facility, the model effectively involves resources like demand response, generation surplus and an efficient methodology to optimize the Market Clearing Price (MCP) as well as profit of the market participants by effective categorization. The power market dynamic price equilibrium has been estimated by forming Jacobian of the sensitivity matrix to regulate the state variables for the standardization of the quality of solution. A novel load curtailment strategy has also been proposed to amalgam stability restoring shedding with profit retentive load cut. The model has been tested in IEEE 30 bus system in comparison with standard curtailment based optimization technique to produce encouraging results.

1. Introduction

The synergism of power system with information network has emerged as Smart Grid to undertake the modern power network issues like demand side management, standardization of operating conditions and integration of renewable energy sources. Moreover the Smart Grid is inherently designed to be self-healing to improve reliability and to respond to natural disaster or malicious sabotage [1]. Efficient deployment of information network augmented with Smart Grid can appear to be an invaluable resource to regulate the operational condition of the system and to optimize the system operation to a prolific solution [2,3]. In the quest of optimizing the utilization of these new resources, researchers in the recent past have been proposing indigenous methodologies and solution algorithm. Though the power system planers heavily rely upon the methodologies in [4,5] introduced a distinctive work where operating conditions viz loss and voltage profiles were optimized with a coordination methodology of plug in vehicle charging. A hybrid method has been enunciated in [6] for effective utilization of Smart Grid data viz synchrophasor to improve grid reliability from generation side. Ref. [7] portrayed a framework of future transmission grid while [8–10] identified the challenges associated with the incorporation of Demand Response (DR) in distribution of the existing grid. From this survey, it is quite evident that all the major parts of the grid require extensive reformation for optimization of Smart Grid resources summarized in [11]. All these alterations will lead to a grid capable of monitoring and control and fast responsive devices are to be installed to retaliate almost instantaneously [12] to locate disturbance and to minimize the same. The grid under consideration must possess at least these attributes to negotiate matters like intermittent energy sources, up-gradation of operating conditions and self-regularization. During the incorporation of renewable energy sources the unprecedented intermittent nature and cost curve pose immense difficulty to system optimization. The challenges and possible solutions have been enunciated for the power system networks of Europe in [13]. Refs. [14–16] proposed optimization methodologies to escalate the operational status of power grid subscribing a particular renewable energy source. Ref. [17] depicted a novel algorithm to regulate the system parameters under multiple intermittent sources. The model optimized the system operation by an energy hub concept but the implementation of the same will require efficient infrastructure which may not be available and the model moreover does not incorporate issues like line flow management and load curtailment. Ref. [18]

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dealt with the integration of demand response with irregular energy sources. The multi objective algorithm proposed minimized cost and curtailment but could not maximize load catering policy of the system operator. In addition, issues like payment cost minimization by involving maximum number of consumers as suggested in [19–21] have not been considered. Apart from tribulations associated with intermittent renewable energy sources, Smart Grid has to efficiently employ demand side management technique. The methods proposed in [22–24] effectively utilize demand side bidding or auction strategy or multi-agent policy but the price responsiveness of other available parameters have not been considered. All these efforts concentrated only one of the price responsive parameter and their objective was to minimize the market clearing price rather than maximizing social welfare by catering optimum load at minimum cost. Refs. [25,26] introduced social welfare as an objective but apply less emphasis on sustaining operating conditions of the system or the load shedding technique. The contemporary load curtailment strategies have been illustrated in [27,28] whereas in [29,30] some new strategies have been introduced. Most of these techniques are operating condition constraint Optimal Load Curtailment (OLC) programs could not assure customer a reliable supply with standard operating conditions. In view of this above survey, the need of an algorithm can be felt which can ensure a standard parametric operational condition with an objective of minimizing the price of electricity with optimal load catering without violating the price equilibrium of the market. The algorithm is required to be supported by a pricing model, which not only integrates the demand response and generation characteristics but also involves price sensitivity of voltage profile, line loss, congestion and load curtailment. The existing price forecasting models proposed in [31–39] are optimistic in nature developed to offer solutions under specific operational constraints and these models are only fertile for single objective domain. Moreover they do not consider the dynamic price equilibrium as stated in [40] hence cannot provide an insight of the power market stability. The endeavor of the work presented in this paper has been to develop a state space model of a power system network endowed with smart metering facility not only to forecast price, but also to minimize the same without compromising social welfare, power market stability and thus ensuring sustenance of prolific operating conditions. The convex nature of solution algorithm with nonlinear working surface was compelling in the selection of a stochastic optimization technique like Particle Swarm Optimization (PSO). For comparison of the solution obtained a standard Optimal Power Flow (OPF) [41] has been adopted. The simulations have been carried out in IEEE 30 bus system and the obtained results looked quite promising.

2. Market structure and functioning in Smart Grid

The Smart Grid is an eco-friendly optimization of the present grid endeavored to achieve operational excellence with high degree of reliability. The functional architecture proposed [2] and implemented [10] are based on some basic modification of the present grid organization for proper management of distributed generation with renewable energy sources, improvement of sustainability with self healing activities like congestion, power quality management and encouragement of price responsive demand reduction. The profusion of these activities employs extensive bidirectional communication between wholesale markets/transmission operation and retail markets/distribution operations. Fig. 1 depicts one such architecture enabling the system operator to not only utilize the generator information, but is also to make itself capable of incorporating the demand response of consumers aggregated by local entities like Regional Transmission Organization (RTO), historical and forecasted data, Available Transmission Capacity (ATC) margins etc.

Efficient employment with these new resources as wholesale market product, Independent System Operator (ISO) will be able to reach the furthest corners of the network from generation to load end to maintain profound operating conditions under the worst possible states of the system. In this context ISO will be able to identify the state variable creating imbalance in the power market to de-standardize its operations. The price responsiveness of the state variables of modern power markets has been elaborated in the following section.

3. The proposed price responsive OPF model

3.1. Price sensitivity of demand

The price responsiveness of demand has become an incredible input to the OPF algorithms for their load peak shaving capability in high price conditions [3]. Effective deployment of this resource may lead to the solutions of modern day power network tribulations like network congestion, voltage instability and perturbations in dynamics in power market. The demand elasticity of price is, hence as depicted in [42] an important parameter to be considered for Optimal Power Flow. With the assistance of smart metering this product can be incorporated in optimization to achieve distinction in operating conditions and welfare of the market participants. As shown in Fig. 2, a demand with a marginal benefit above the marginal price will lead to an expansion in consumption until the equilibrium is reached. In Fig. 2a A–B–C represents the bid curve at a particular hour, while X–Y its tangent. The price responsive demand curve (Fig. 2b) shows the nature of the consumer towards price volatility corresponding to the bids. From the bid curve the willingness to pay of the consumers can be determined as

$$\textit{willingness to pay} = \tan\theta = \frac{f(d_1) - f(d_2)}{d_1 - d_2} = \frac{b_1 - b_2}{d_1 - d_2} \tag{1}$$

where d_1, d_2…etc. are the power demands and the bid curve is expressed as a function of demand such as $f(d_i)$. The Market Clearing Price (MCP) corresponding to each point of the bid curve have been plotted in Fig. 2a and b. In this figure it has been assumed that $b_1 = d_1 \cdot MCP_1$, $b_2 = d_2 \cdot MCP_2$, $b_3 = d_3 \cdot MCP_3$. Let us assume that the two curves are fitted with two different polynomials. $k_1x^2 + l_1x + m_1$ represent the bid curve while $k_2x^2 + l_2x + m_2$ represent the price responsive curve where k_1, l_1, m_1 are the coefficients of bid curve and k_2, l_2, m_2 are the coefficients of price responsive curve. Now mapping willingness to pay into price responsiveness of demand

$$\begin{aligned}\tan\theta &= \frac{b_2 - b_1}{d_2 - d_1} = \frac{d_2 \cdot MCP_2 - d_1 \cdot MCP_1}{d_2 - d_1} \\ &= \frac{d_2(k_2d_2^2 + l_2d_2 + m_2) - d_1\left(k_2d_1^2 + l_2d_2 + m_2\right)}{d_2 - d_1} \\ &= k_2\left(d_2^2 + d_2 \cdot d_1 + d_1^2\right) + l_2(d_2 + d_1) + m_2\end{aligned} \tag{2}$$

The willingness to pay is as sensitive to bid curve as is to price responsive curve. Hence, inclusion of demand response or price responsive characteristics into OPF not only incorporates the price dependent consumption characteristics but also involves the willingness to pay of the consumers for a particular alteration in price. In the present work load demand is also scheduled like generation, the load curtailment becomes willingness to pay dependent and involves the consumer more into OPF. In every hour (or a specified period) the consumer with the assistance of smart metering, will be able to modify his stand in the power market enabling Independent System Operator (ISO) to regulate curtailment depending on "willingness to pay" of the consumers.