Techno-economical Study of Power System Market- A Game Theory Approach

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***Abstract*—The renewable energy penetration in power system has perpetrated new dimensions in the existent electricity market which warrants its restructuring. Continuous research is on regarding formulations of polices to meet the long-term techno-economical electricity management challenges in this heuristic and diversified scenario. The advancement and development in this new era revolve mainly around the operational complexity of Unit Commitment and the dispatch related economic issues. In this evolution of power systems is studied as a conventional Grid, a Micro Grid and a Renewable integrated Grid. Game theory, for the most prevalent Renewable integrated Grid, has been applied to demonstrate its techno-economic evaluating strategy. The major concern of the modern Smart Grid system is to achieve a "No-regret" solution under self-enforcement conditions. The game theory, considering a Micro Gird and a Conventional Grid as the two players, has been performed with the help of game theory matrix. The aim is to illustrate the optimal payoff according to their different actions of Cooperation and Non-cooperation in the game.**

Keywords—game theory; power system market; micro grid; conventional grid

I. Introduction

In 20th century, the continuously increasing demand of the electrical power requirements and ongoing liberalization process has created a need to expand electricity power networks structure throughout the world. However, due to advancement in Conventional Grid operation the complexity has increased in view of environmental problems. Rise in the cost of rapidly depleting resources have convoluted prominently making it difficult to cater reliability, safety, and diversity [1] to the customers [2]. Against this backdrop, researchers in 21st century suggested the idea of a Micro Grid which is defined as a group of interconnected loads and distributed clean energy resources act as a single controllable system providing heat and power for a local region [3], [4], [5]. The need of the day is that the conventional power Grids collaborate with Micro Grid in the form a Smart Grid to achieve economy, better ride through capabilities, peak load shavings and clean energy [6] leading to increased utilization rate, technological innovation and scope of distributed energy.

The Smart Grid has heterogeneous nature, which motivates the researchers to developed advanced techniques and strategies for overcoming the different technical as well as electricity management challenges at various levels such as bidding, control, implementation and design etc. [7]. For the sake of environmental problems and world welfare the future Smart Grid system can improve the robustness, reliability, efficiency and various integrating advanced techniques of power systems disciplines by using the applications of game theory in power system market [8].

The game theory is a better expected way to establish a significant analytical as well as conceptual framework with a set of mathematical tools in the construction and design of the future Smart Grid in the power system [8], [9]. From several years, game theory has been adopted in a wide range of disciplines spreading from economics and politics to psychology [10]. Most recently, game theory has been applied in deregulated electricity power system industries [11] as the conventional economic modeling approach posed certain shortcomings including limited ability to model all the intrinsic characteristics of electricity markets.

The major objective in deregulated environment in power sector is to provide better market efficiency by maximizing the profit of power producers and, at the same time, reducing electricity price to the end user via introducing competition [12]. This competitive environment enables power market participants to maximize their profits via logically deciding their pricing with the help of game theory. To achieve this, strategically chosen methods are applied to attained Nash equilibrium with pareto optimal solution in deregulated power system [13]. Game theory is a tool for rational decision making in conflicting situations. It has long been commonly used in economics, social sciences and biology to model decision making situations where the outcomes are contingent upon the interacting strategies of two or more agents with conflicting, or at best, self- interested motives [14], [15].

This paper is organized as follows. Section II describes the game theory, its evolution and the basic elements. Section III deals with the concept of power system market model. Section IV presents a game theory-based solution methodology for a power system market. Section V concludes the paper.

II. Game Theory

Game theory is the study of economic and mathematical models of conflict and cooperation among intelligent rational decision-makers to find optimal choice of their actions. They can be of two types namely cooperative and non-cooperative games [13], [14], [16]. Cooperative game is a game where groups of players may enforce cooperative behavior; hence the game is a competition between coalitions of players, rather than between individual players. A non-cooperative game is the one in which players make decisions independently [16].

A. Evolution Of Game Theory

In 1713, the first known solution to such a game was reported from James Waldegrave to Pierre-Remond de Montmort regarding a two-player type of the card game Le Her [17]. In 1913, the most famous axiomatisation of set theory was introduced by the German mathematician Ernst Zermelo, for games like chess, now called as extensive form games [18]. Then, the four notes on strategic games were published by the great French mathematician and probabilist, Emile Borel during 1921 to 1927 [19].

In the early 20th century, game theory was recognized as a formal discipline. The great mathematician John von Neumann proposed a non-cooperative game of two people in 1928 [20]. In 1930, R. A. Fisher applied the game theory to explain the approximate equality of the sex ratio in mammals [21]. In 1944, the book "Theory of Games and Economic Behaviour" was written by John von Neumann and Oskar Morgenstern symbolized the setting up of the game theory.

In the early 1950s a legendary figure John Nash proposed a central solution concept for non-cooperative game theory of equilibrium, that is now called as the Nash equilibrium. In parallel, non-cooperative game theory started to grow and cooperative game theory enjoyed its peak. During this time, John F. Nash used laborious mathematical language and simple words to exactly define Nash Equilibrium [22], which was a noteworthy breakthrough in game theory domain.

H. W. Kuhn in his papers discussed about the problem of Information and Extensive Games comprising of the formulation of extensive form games which is presently used. He also worked on basic theorems belonging to this class of games during 1950 to 1953. The legendary scholar in this field, Shapley, published a paper on Stochastic Games that brings together a novel and significant model of games [23]. In 1961, the great author R. C. Lewontin made the first unambiguous application of game theory to evolutionary biology as Evolution and the Theory of Games [24]. In 1972, the well-known certified journal International Journal of Game Theory was founded that took care of the maturity of game theory.

For their pioneering analysis of equilibria in the theory of non-cooperative games in 1994, the Nobel Prize in Economics was awarded to John Nash, Reinhard Selten and John C. Harsanyi. For having enhanced the understanding of conflict and cooperation through game-theory analysis in 2005, Thomas C. Schelling won the Nobel Prize in Economics with Aumann. For the theory of stable allocations and the practice of market design in 2012, Al Roth won the Nobel Prize in Economics with Shapley. From then on, game theory was firstly widely used in economics. As time went on, it was gradually applied in other subjects, such as politics, biology, computer science, military, transportation, etc.

B. Basic Elements of Game Theory

In game theory, game includes basic three important elements: players, actions, and payoffs of the utilities [14]. The working functions of these three elements and their possible explanations are described in the text to follow.

a) *A set of player,* $\mathrm{P} = \{\mathrm{P}_1, \mathrm{P}_2, \mathrm{P}_3, ..., \mathrm{P}_n\}$ is a finite set of n, indexed by i.

b) *A set of actions,* $\mathrm{A} = \{\mathrm{A}_1, \mathrm{A}_2, \mathrm{A}_3, ..., \mathrm{A}_n\} \in \mathrm{A}$ is available to each player to determines its possible strategies.

c) *A payoff utility,* $U = \{U_1, U_2, U_3, ..., U_n\}$ represents the possible payoff preferences of each player and shows what will it receive at the end of the game.

Best response in a game is defined as $\mathrm{A}_i * \in \mathrm{B}R_i(\mathrm{A}_{-i})$

$\mathrm{A}_1*, \mathrm{A}_2*, \mathrm{A}_3*, ..., \mathrm{A}_n*$ is pure strategy Nash equilibrium for n players; if for each player i, $U_i(\mathrm{A}_i*, \mathrm{A}_{-i}*) \geq U_i(\mathrm{A}_i, \mathrm{A}_{-i}*)$. Where, U_i is player i action of G_i; A_i is the action of one player; A_{-i} is the action of the rest of all players.

III. Power System Market model

Modern power industry operation is extremely complex to understand from the business perspective. Electrical power is quite different than the other tradable commodities like wheat, oil etc. The technical difference is that, it is based on real-time generation, transmission, distribution and consumptions mainly due to its storage-less nature. This peculiar inherent difference creates a convoluted restructuring related change in the operational strategies as well in the philosophy of planning to meet the desired challenges continuously [11].

The restructuring has been accompanied by a variety of new problems in completive power market. However, many parts of the world have progressively moved towards competitive markets as a means to produce and to obtain electricity along with many of the support services necessary to satisfy load demand [13].

There are three different types of power system market.

a) *Physical power market*: In this category, the exchange of electrical power takes place only physically. This market comes under spot marketing for immediate delivery. The major volume of energy is traded based on this technique due to which it is considered as the core of all the power markets. Every generating company gets the market clearing price and every consumer has to pay the price thus decided, provided all the operations are done without any congestion. Here, everyone has a risk of losing revenue. Also, there is a possibility of high price volatility [25].

b) *Financial power market*: It is not an actual electrical power trading, but it is a contractual agreement sharing about the upcoming risk between the two parties. If anything happened unfavorable, then both the parties share and face the loss mutually. In this, derivatives of risk management tools for product/time/place are used in Forwards, Futures, Options and Swaps to settle the risk [26].

c) *Balancing power market*: Ancillary service management in power market refers to balancing power market. The physical market is based on forecasted load in which all the calculations are done for day ahead market. But for the energy transaction, there is a mismatch between actual and forecasted load in the real time operation. Hence, balancing power market needs to take care of generation or load mismatch [27]. There is a separate provision in the power market for balancing power market and apart from physical spot market, the generators have to submit separate bid in this market [25].

Power system reliable operation is one of the important issues in power industries [28]. The aims are to provide a techno-economical methods and algorithms to manage the total costs in electricity generation and transmission markets. Its management begins with traditional power systems and builds into the fundamentals of power system operation, economic load dispatch, optimal power flow, and unit commitment [29].

Within strictly regulated frameworks in which vertically integrated utilities handled all or most of the activities from generation to transmission up to loads. The conventional power Grid is basically the interconnection of various power system elements such as synchronous machines, power transformers, transmission lines, transmission substations, distribution lines, distribution substations and different types of loads [6]. The generators are located far from the power consumption area and electric power is transmitted through long transmission lines. Such situations are comparatively easier to manage as shown in Figure 1.

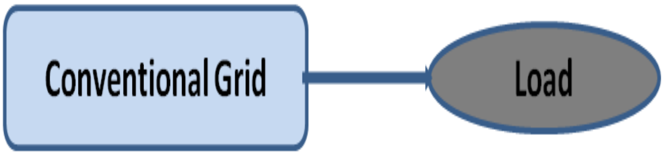

Fig. 1. Block diagram of Conventional Grid in power system

The major drawbacks of the Conventional Grid are high cost of operation and difficult operation. They become more prominent when users additionally expect safety, reliability and diversity [7]. Improved operation becomes further complex due to resource shortage and prevention of environmental deterioration resulting from the rapid industrial development and expansion of electrification.

With the advent of rapid development of Renewable Energy Resources (RER), Islanded Micro Grid concept has come up as a relief for distant load locations. Micro Grids either implement a single locally available source or a combination of multiple available RERs. It has proven its efficiency for location specific applications [4], [5]. It is economical for domestic purposes and realizes reliable supply of energy in various forms. The concept of distributed energy got thus evolved providing clean energy. The high initial installment cost of Micro Grids is recovered over a certain span of time [8]. The common sources typically consist of wind turbine and photovoltaic along with the storage etc. Indeed, Micro Grids have received great importance due to tremendous application potential in remote locations shown in Figure 2.

Fig. 2. Block diagram of Islanded Micro Grid in power system

Micro Grids, in collaboration with Conventional Grid in power supply, can reasonably allocate electric power within a broader scope and increase the utilization rate of distributed energy and clean energy with the help of the sound power transmission and distribution system of large power networks [3], [5]. Nowadays, due to the increased application of power electronics devices, Micro Grids are able to operate in both Grid-connected and island modes as shown in Figure 3.

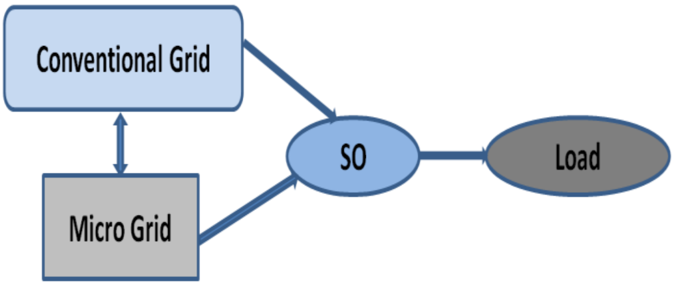

Fig. 3. Block diagram of Smart Grid in power system

The Smart Grid is a decentralized system where power can be derived from various sources in a controlled environment. A Smart Grid is capable of monitoring the activities of the Grid-connected system, a consumer preference etc and provides real-time information at all times of all the events. Much impetus is gained by Smart Grid solutions through technological innovation for solving power supply problems in remote areas and in autonomous regions [4]. Addition of a System Operator (SO) between Grid and load creates provision for cooperation between Micro Grid and Conventional Grid can enlarge the participation of distributed energy and clean energy, which is conductive to optimization of energy structure, energy conservation and emission reduction in the power sector as well as enhancement of social welfare [30].

IV. Game Theory For Power System Market Model

The prime objectives in power management are to minimize the total production cost of power generation, to maximize the profit of power producers while satisfying various generators' constraints and catering to the need of load demand over a scheduled time frame.

Roles of System Operator are to determine apt price points at every instant, to reject infeasible bids, to maintain economy and reliability and to make the system demand responsive by companies' profit and customers' payoff. Optimal biding strategy can be developed by hybrid evolutionary game theory and coalitional game strategy. The coalitional games are of three types; (i) Request Exchange Stage (ii) Merge-and-split stage and (iii) Cooperative transaction stage [8]. The major goal in power system is to achieve using Nash Equilibrium technique a techno-economical day ahead unit commitment schedule for renewable integrated Grid systems.

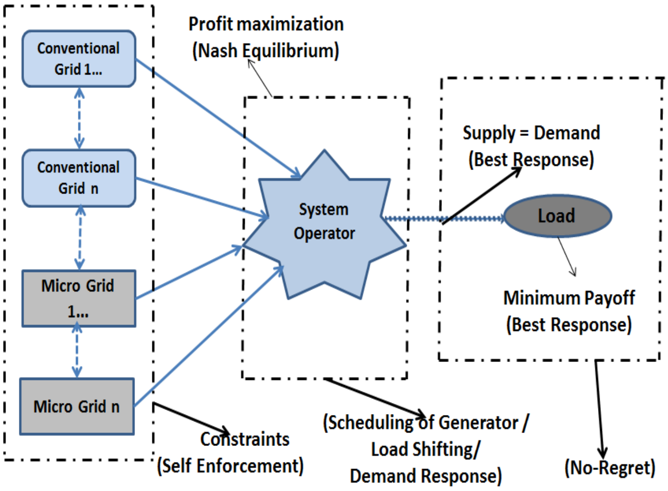

Fig. 4. Block diagram of Smart Grid in power system using game theory.

Independent System Operator receives bids from Pool participants and defines transactions among participants by looking for the minimum price that satisfies the demand in the Pool. As restructuring evolves, pricing of electricity becomes a major issue in electric industry. In power systems, emphasis is given to maximization of benefit from the perspective of participants rather than maximization of system wide benefits. The objectives are achieved by game theory to maintaining self-enforced constraints by Gencos. Maximizing profit for Gencos by System Operator is done by means of scheduling the generators, shifting the loads incorporating demand response. Obtaining no regret operating conditions by maintaining power balance intact and minimizing the payoffs. The general representation of the arrangement is shown in Figure 4.

The economic problem that is needed to be solved, makes the market design complex. However, it seems that the game theoretical approach may reduce the complexity to a significant extent [31]. To explain the approach, a simple example for two-player game is shown in Table I. One player is a Micro Grid (P_1) and other player is a Conventional Grid (P_2). They have only two options. Either they are cooperative or non-cooperative. This creates four possibilities of actions i.e., (C, C), (C, NC), (NC, C) and (NC, NC). The corresponding payoffs of the utilities can either have high profit or low profit. If P_1 chooses action C then P_2 can choose C or NC, then in case of (C, C), the payoff will be (0, 0) whereas in the other case (C, NC), the payoff will be (1, 0). Similarly, If P_2 chooses action NC then P_1 can choose C or NC. Then, in case of (NC, C) the payoff will be (0, 1) and in other case (NC, NC), the payoff will be (1, 1). Here, 1 represents high profit and 0 represents low profit.

TABLE I. PAYOFF MATRIX OF GAME THEORY

Game theory between Micro Gird & Conventional Grid	*Cooperation (C)*	*Non-cooperation (NC)*
Cooperation(C)	(C,C)	(C, NC)
Non-cooperation(NC)	(NC, C)	(NC, NC)

Therefore, by the game theory approach in power system market the Micro Grid and the Conventional Grid can know their exact payoffs and can act accordingly to the meet the desired requirements.

V. CONCLUSIONS

This paper presents the basic features of a power system market explaining how the market works to address the key objectives with game theory, how it has evolved over time, and whether it is suited to handle the large changes that may take place over the next decades. In the competitive power market, pricing in restructured system has become a major issue in the power industry and additional mathematical support is needed to define pricing strategies to address to the issues. If we analyze the problem without a game-theoretical approach, any one participant may obtain lower benefits than the others.

The game theory approach can be used in power system to solve the various problems optimally. Some of the areas where it can be implemented in future are; bidding strategies, load and demand balancing, hybrid energy system management, modeling and analysis of systems, economy and cost estimation etc.

ACKNOWLEDGMENT

The authors would like to acknowledge Homi Bhabha Teaching Assistant Fellowship and Technical Education Quality Improvement Program Phase III, Institute of Engineering and Technology, Lucknow (Dr. APJ Abdul Kalam Technical University, Lucknow) for funding this research.

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