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Chapter 2

Game Theory Application in Smart Energy Logistics and Economy

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Abstract

In many parts of the world, energy sectors are transformed from conventional to the smart deregulated market structures. In such smart deregulated market environment, cooperative game theory can play a vital role for analyzing various smart deregulated market problems. As an optimization tool, cooperative game theory is very useful in smart energy logistics and economy analysis problem. The economy associated with smart deregulated structure can be better optimized and allocated with the help of cooperative game theory. Initially, due to regulated structure, there is no cooperation between different entities of energy sector. But after new market structure, all the entities are free to take their own decisions as an independent entity. Transmission open access of energy logistics is also comes into the picture, as all the generators and demands have the same right to access the transmission system. In this market situation, multiple utilities are using the same energy logistic network. This situation can be formulated as a cooperative game in which generators and demands are represented by players. This chapter deals with energy logistic cost allocation problems for a smart deregulated energy market. It is cooperative in nature as all the agents are using the same energy logistic network.

Keywords: smart grid, cooperative game theory, Shapley value, Nucleolus approach, transmission usage cost allocation, transmission loss allocation

1. Introduction

Cooperative game theory is a decision-making tool that helps game players (decision-makers) to take decisions under various strategic situations. It is a branch of applied mathematics that is utilized for a wide range of applications in the field of technology, science (social, political,

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behavioral), economics, biology, and philosophy. In strategic situations, game theory helps to mathematically model the behavior of various players [1].

Power sector is restructured in many parts of the world. Under this new structure, power sector is working under market forces. Its structure is transformed from regulated (government-controlled) to deregulated (market-controlled) one. The whole power sector is divided into three basic entities, i.e., generation company (GENCO), transmission company (TRANSCO), and distribution company (DISCOM). Other than these three basic entities, various new entities also emerged such as independent system operator (ISO), power pool, power exchange, etc. These entities ensure the reliable and secure operation of new restructured power sector. Private industries also participate in these sectors as independent players, such as independent power producers (IPPs) in GENCO and various distribution franchises in DISCOMs. The aim of restructuring is to bring competition and operating efficiency in power industry that result in reliable, economic, and quality power supply to consumers. Further, restructuring initiated the implementation of smart grid technology.

Conventional grid can be converted into smart grid with the incorporation of following characteristics:

- Self-healing from faults
- Incorporation of demand response programs for enabling consumer's active participation
- Robustness against any kind of cyber and physical attack
- Able to supply quality power as per the customer's requirements
- Able to incorporate all generation sources, i.e., conventional and renewable
- Enable incorporation of storage devices
- Enable restructuring to develop new markets, services, and products
- Operate economically by optimizing resources

From the abovementioned characteristics, it is clear that the smart grid system is completely working under market forces. Different entities aim to enhance their profits. Therefore, cooperative game theory can be applied by different market entities to increase their revenues.

The development of game theory and its applications also reflected in many energy market modeling and analysis problems. In 1999, for energy market modeling and analysis, IEEE Power and Energy Society published a landmark tutorial on game theory application in power systems [2]. During the past 20 years, many researchers implemented game theory for various power system problems, and this trend is also reflected in the journal and conference publications.

There are various technical and economic issues in smart grid system that requires fair and unbiased solution. Thus, cooperative game theory is utilized by various entities around the world for solving critical technical as well as economic issues.

This chapter deals with various smart energy logistics and economy problems solved by using cooperative game theory.

2. Smart grid

According to Brian Seal, senior project manager, power delivery and utilization, Electric Power Research Institute (EPRI), "Smart grid is a marketing term that is devoid of technical definition." A variety of operational and energy measures such as smart appliances, smart meters, renewable energy resources, and energy-efficient technologies are part of smart grid. There are different technologies, which are incorporated by different utilities in all the three energy sectors, i.e., generation, transmission, and distribution [3].

2.1. Smart technologies in generation sector

Various techniques incorporated for smart operation of generation system should be able to understand the unique nature of energy generation of resources. This understanding is very helpful for optimizing the energy generation. Further, multiple feedbacks from different points in the grid are helpful to maintain the desired voltage, frequency, and power factor standards.

For making generation sector smart, utilities are incorporating novel technologies in the system, continuously. Some of these technologies are as follows:

2.1.1. Incorporation of distributed generation and microgrid

As name indicates distributed generation incorporated various energy resources those are distributed in their nature. It includes technologies such as microturbines, energy storage, electric vehicles, solar energy, fuel cells, and micro wind turbine [4].

For efficiently incorporating the abovementioned distributed energy sources, microgrid technology can be utilized. It provides a better way to incorporate renewable energy sources in smart grid. **Figure 1** presents the general structure of microgrid technology [5].

As seen from **Figure 1**, a microgrid consists of photovoltaic source, wind turbine, microturbine, fuel cell, electric vehicle technology, battery energy storage, diesel generator, and electrical loads.

2.1.2. Frequency regulation management

Due to the incorporation of a large number of green and distributed energy sources in the smart grid, more fluctuation is occurred in the base load generation. Therefore, extra regulation will be required to maintain the balance in supply frequency. Flywheel plant technology is incorporated in the smart grid system to maintain the frequency regulation. In the case of excess power generation, extra energy is supplied to the flywheels for storage [6].

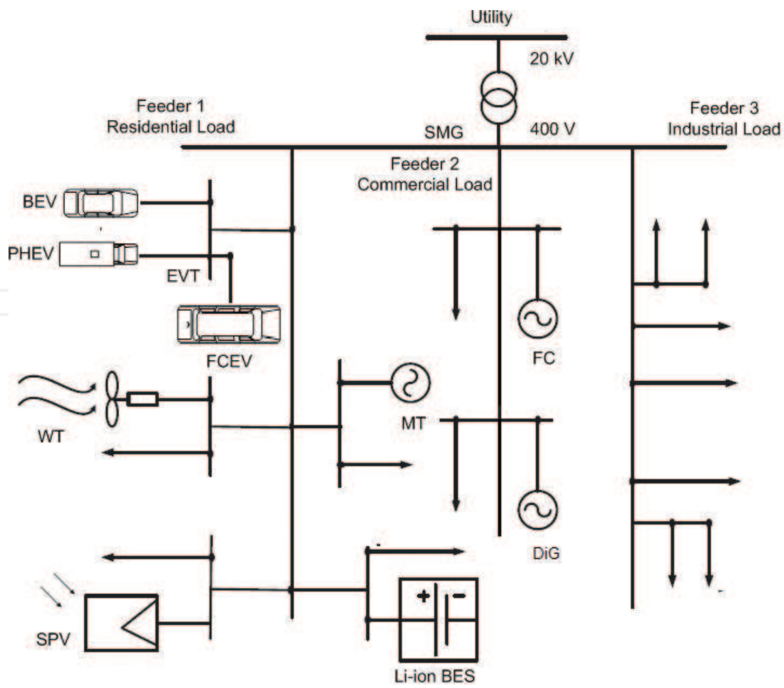

Figure 1. Microgrid [5].

2.1.3. Generation control

The time frame of the generation area under consideration is very important from the point of view of generation control. For generation and load control, supervisory control and data acquisition (SCADA) system provides the data for every second. Generation control is directly affected by the use of smart meter technology at the end-customer's location [6].

2.2. Smart technologies in transmission sector

Transmission system transfers a large amount of power at various voltage levels from generation point to the substations. For supplying resilient power supply to the energy markets, a reliable transmission system is the first requirement. To achieve this goal, under smart grid environment, synchrophasor technology is emerged as vital component. Different building blocks of a smart and reliable transmission system are as follows: wide area communication networks, phasor measurement units (PMUs), phasor data concentrators (PDCs), and smart substations [7].

2.2.1. Phasor measurement units

For enabling complete power system monitoring and control, the modern metering devices such as phasor measuring units (PMUs) are installed by different utilities. These are the most accurate and time-synchronized devices that provide voltage and current measurements. It directly measured the voltage phase of the bus at which PMU is installed. Further, it also measured the current phasor of few or all the transmission lines connected to the PMU installed bus.

2.2.2. Phasor data concentrators (PDCs)

As shown in **Figure 2**, isolated PMUs are utilized to develop a wide area monitoring system (WAMS). PMU fed Global Positioning System (GPS) time-stamped measurement signals to phasor data concentrator (PDC). The main function of PDC is to collect and sort the phasor measurements obtained by PMU. It is clear from **Figure 2** that signal processor converted PMU data into useful information, which is available on human machine interface (HMI) system. By using HMI system, an operator can easily access the important information of the system state [7].

2.2.3. Smart substation

A smart substation refers such a system, which control and monitor both critical and non-critical operational information. Information about system power factor, breaker status, and transformer operation and battery condition comes under operational information.

2.3. Smart technologies in distribution sector

For making distribution sector smart, techniques incorporated should be such that which makes distribution system self-healing, self-optimizing, and self-balancing. Further, it also includes superconducting cables and automated monitoring and control tool.

Different techniques such as smart controllable load, smart meters, electric vehicle technology, etc. are incorporated in the distribution sector to make it smart [8].

2.3.1. Smart controllable load

Variable load is the key challenge in the power system. Due to this, the large number of power system problems like generation control, frequency regulation, stability problems, etc. arises.

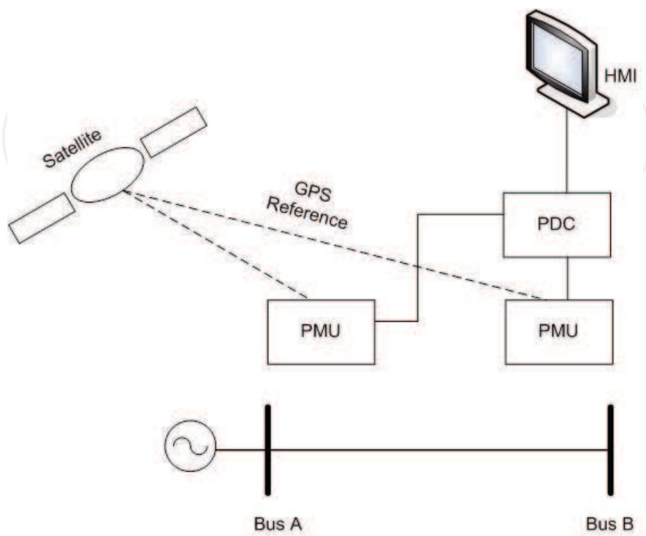

Figure 2. Layout of PMU with GPS time-stamped signal [7].

Therefore, the key aim of smart grid technology is to make variable load more controllable and flexible. For that purpose smart meter technology is very useful because it has an ability to disconnect the load remotely. It requires two basic components [9]:

1. Two-way communication system
2. Loads equipped with controls

2.3.2. Smart meters

Conventional energy meters do not have communication capability and need to be read manually. Smart meter technology equipped with two-way communication system. It measures demand on second-by-second basis and provides consumer access to their energy demands. Further, utility used smart grid technology to remotely disconnect loads. Communication system is the key for smart meter technology. Possible options for communication technology are as follows [9]:

1. Use existing customer broadband connections
2. Broadband over power line (BPL)
3. Meshed wireless

2.3.3. Electric vehicle technology

Electric vehicle technology is the key driver for widespread implementation of controllable electric load. But recharging of electric vehicles also requires load control. There are three basic types of electric vehicle [9]:

1. Battery electric vehicle
2. Hybrid electric vehicle
3. Fuel cell electric vehicle

3. Cooperative game theory

Game theory is a decision-making tool. It is the field of applied mathematics that deals with the conflicts of interests of persons or group of persons. These conflicts of interest are included in the term "Game." Game theory is broadly categorized into two sections: coalition or cooperative games and strategic or noncooperative games. In general, cooperative games are utilized for optimal allocation or assignment problems, while noncooperative games are utilized for analyzing oligopolistic models by using Nash equilibrium. Player refers to the person in both types of games. There is a key assumption in game theory that all the players behave rationally. Therefore, each player earns the profit from the game [10].

Cooperative game theory has different approaches such as core, Nucleolus, Shapley, Owen, solidarity, and Aumann Shapley.

3.1. Terminology used in cooperative game theory

Cooperative game theory provides an optimal and fair allocation between its players. An allocation game is defined by a couple (N, v). Let $N = \{1, 2, 3, \ldots\ldots n\}$ represents the set of n number of players, where n being equivalent to $|N|$. v is the characteristic value or function value. A group of players S that coordinate together are represented as a subset of $N, S \subset N$. A set N represents the grand coalition, and null set denotes an empty coalition. Players can be grouped in various ways that depends on their interest and convenience. Here, 2^N represented the collection of coalitions in N. Each player belongs to only one of the coalitions. Further, players of a certain coalition are related to each other. But these players are not related to the participants of other coalitions [11].

A real valued function $v\colon 2^N \to R$ is the game on N. It allots a value to each group and satisfies $v(\emptyset) = 0$. Characteristic value $v(S)$ provides the maximal value incurred by the coalition S by cooperation between coalition players [12]. A payoff vector is $\{x_1, x_2, x_3, \ldots x_n\}$, where x_n is the payoff concerned to agent n that represented the result of the game. The three rationalities represented in Eqs. (1)–(3), namely individual, group, and global rationalities, must be satisfied for fair and equitable allocation to all the players [11]:

$$x(i) \leq v(i); \quad i \in N, \tag{1}$$

$$x(S) \leq v(S); \quad S \subset N \tag{2}$$

$$x(N) = v(N); \tag{3}$$

$$(\text{With})\ x(S) = \sum_{i \in S} x(i);$$

Imputation is a payoff vector that satisfied the individual and global rationalities. Further, if imputation satisfied the group rationality, then the solution is laid in the core. Group or individual rationality verifies that a group of players or individual players must not have higher value than their stand-alone value. Global rationality ensures that the value obtained by the cooperation to all the players should be matched to the total value to be covered. It is known as break-even condition or Pareto optimum. In addition to this, if allocated value is less than the sum of individual allocations, then the solution of cooperative game is stable. As a result, all the participants are incentivized to stay in the group, leaving no significance for any participant to pull out.

3.2. Different approaches of cooperative game theory

Various cooperative game theory approaches are utilized by the researchers to find the optimal solution. Some of them are as follows:

3.2.1. The core approach

The core of the game (N, v) is the set of all the solutions presented by Eq. (4) such that

$$x(S) \leq v(S); \forall S \subset N, \quad \text{With } x(S) = \sum_{i \in S} x_i \tag{4}$$

Therefore, the core is nothing but the subset of the group of imputations. It is the simplest cooperative game theory approach. This approach is related to a group of imputations that leaves no choice for an optimal solution to its participants and does not permit any type of subsidies between coalitions.

3.2.2. Shapley value approach

Shapley value approach is a cooperative game theory approach that is utilized for fair allocation between players. This fair solution is obtained by the cooperation between different players. The basic concept utilized by Shapley value is that the allocated value to a particular player is the average of the value in all available coalitions. It fulfills all the required characteristics for fair allocation. Further, the solution is symmetric and additive in nature [13].

It is a priori value, which adds by each player to the grand coalition of cooperative game through a particular characteristic function. For calculating this value, all the available combinations should well think out. The net contribution of each player to the grand coalition is depended on the entry of that particular player. The addition of all of these contributions provides the Shapley value. It is represented by $\varnothing_i(v)$ for player i, as shown in Eq. (5):

$$\varnothing_i(v) = \sum_{s, i \in S} \frac{(|S| - 1)!(|N| - |S|)!}{|N|!} [v(S) - v(S - \{i\})] \tag{5}$$

where

$|S|$ represents the number of players in coalition S; $|N|$ represents the total number of players; and $v(S)$ represents the characteristic function associated with coalition S.

3.2.3. Nucleolus value approach

The concept of Nucleolus, as introduced in 1969, is characterized by two features: every game has one and only one nucleolus, and unless the core is empty, the nucleolus is in the core [14]. In Nucleolus solution, the dissatisfaction for every coalition is minimized till the solution becomes fair and acceptable for all the coalitions and the players as well. A measure of inequality of an imputation x for a coalition S is defined in Eq. (6) as the excess:

$$e(x, s) = v(S) - \sum_{i \in S} x_i \tag{6}$$

This gives hint of the amount by which the coalition falls short of its potential. The largest dissatisfaction is calculated and is reduced. After this, the next largest dissatisfaction is taken up and reduced. This can be solved as a solution of a set of linear programming problem. An imputation in this case lies within the core if all the surpluses are either negative or zero. Thus, the advantage of the nucleolus solution is that it is part of the core. Thus, no other payoff vector can dominate the nucleolus over any association. When a payoff vector is not dominated, then it is more expected to be accepted by players [15].

4. Cooperative game theory application in smart energy logistics and economy

Conventionally, power sector is regulated by the government. All the three major sectors, i.e., generation, transmission, and distribution, are operated by government-owned entities. Therefore, it is impossible to implement cooperative game theory. In the 1990s, after deregulation, power sector is completely transformed. Three major sectors are transformed into private entities. Further, various private players also come in these sectors. Now, the number of players is increased, and cooperative game theory can be utilized to raise the profit of different players.

Deregulation brings transmission open access into the picture, because different entities have the same rights to access the transmission system. Therefore, the operating condition in which multiple entities utilized the same transmission network can be modeled as cooperative game theory problem. In this game, different generators and demands are represented as players. Therefore, different transmission access problems such as transmission usage and usage cost allocation, transmission loss, and loss cost allocation can be optimized with the help of cooperative game theory because all the participants utilized the common network [10]. Cooperative game theory provides the optimal allocation of all the abovementioned problems in a fair and equitable way.

4.1. Optimal transmission usage cost allocation

The smart deregulated market structure of energy sector requires economic efficiency. In this regard, the solution approaches of cooperative game theory behave well in terms of economic efficiency, fairness, and stability [16]. In [17], Shapley and Nucleolus approaches are utilized for transmission usage cost allocation. To accommodate all the loads in the pool market, Shapley value allocated the transmission usage cost to demands. Shapley value is the most preferable approach when the solution lies in the core. It uniformly and fairly allocated the transmission usage cost among the players [18]. Shapley value has a drawback that it explodes when the number of players in the game is very large. Aumann Shapley approach overcomes this drawback by reflecting the marginal contribution of a player to the cumulative system savings [19].

4.1.1. Characteristic function

There is no unique way of characterizing the cost of coalition, i.e., $v(S)$. For transmission usage cost allocation game, the characteristic value specifies the minimal cost that will be incurred by each coalition [13]. In cooperative game theory, $v(S)$ is defined as per the choice of user either on the basis of cost or on the basis of transmission usage. In [20], the basis of transmission network usage cost has been chosen. A power flow tracing method is used to evaluate characteristic value $v(S)$ as well as stand-alone cost $v(i)$ of player i of a system [15]. The work follows the ratio for cost allocation between generators and loads as 23:77% in pool market [21].

The characteristic function of the cooperative game, developed in [20], is presented in Eq. (7):

$$v(s) = \sum_{l \in N_L} (P_{m-n}) * C_{m-n} \quad (7)$$

where $v(S)$ is the fixed cost of providing transmission service to coalition S, P_{m-n} is the power flow in the line $m-n$, N_L is the number of lines, and C_{m-n} is the cost of the line $m-n$.

4.1.2. Cooperative gaming for optimal usage cost allocation in 6-bus system

The 6-bus system is considered as pool market for realizing Shapley value and Nucleolus approach of cooperative game theory. Therefore, bilateral contracts are not allowed, and the whole power is traded in a mandatory pool with the pool operator having a wide knowledge of the generator's data. In this attempt cooperative gaming is allowed among loads, and they behave as the players in the pool market.

If all the three loads are going to cooperate with each other, then the possible coalitions are 7, including the single-player coalition. The evaluated characteristic values using power flow tracing algorithm [20] for seven coalitions are presented in **Table 1**.

For power flow tracing, Newton-Raphson load flow runs with different collations. The load flow results are presented in **Table 1**. Afterward, Shapley and Nucleolus approaches are utilized for optimally allocating transmission usage cost to loads. **Table 2** presents a comparison between Shapley and Nucleolus values.

Results are obtained that satisfy all the three conditions of gaming, i.e., individual rationality, group rationality, and the global rationality of game theory. Thus, the accomplishment of group rationality proves that the solution lies in the core. As allocated payoff vector is part of the core, hence more likely to be accepted by the players.

Characteristic value of coalition in the 6-bus pool market (sr. no.)	Coalition	Characteristic value [Rs./hr.]
1	L4	161.107
2	L5	374.46
3	L6	229.04
4	L4 L5	547.069
5	L4 L6	396.05
6	L5 L6	614.79
7	L4 L5 L6	759.08

Table 1. Characteristic value of coalition in the 6-bus pool market.

Shapley value and Nucleolus value allocation for loads (Sr. no.)	Load	Stand-alone cost [Rs. /hr]	Shapley value allocation [Rs./hr.]	Nucleolus value allocation [Rs./hr.]
1	L4	161.107	158.402	158.9663
2	L5	374.46	374.45	373.5036
3	L6	229.04	226.23	226.5914

Table 2. Shapley value and Nucleolus value allocation for loads.

Individual rationality: $x(i) \le v(i)$

$$x(L4) \le v(L4), \text{i.e.}, 158.402 < 161.107$$

$$x(L5) \le v(L5), \text{i.e.}, 374.45 < 374.46$$

$$x(L6) \le v(L6), \text{i.e.}, 226.23 < 229.04$$

Group rationality: $x(S) \le v(S)$

$$x(L4L5) \le v(L4L5)$$

$$x(L4) + x(L5) \le v(L4L5)$$

$$158.402 + 374.45 < 547.069$$

$$532.852 < 547.069$$

Global rationality: $x(N) = v(N)$

$$\sum_{i=L4,L5L6} x_i = v(L4L5L6) = 759.082$$

From the above, it is clear that the results obtained from the Shapley and Nucleolus approaches lie in the core. Therefore, fair and equitable solution is obtained.

4.2. Optimal transmission loss allocation

In [22], authors developed a Shapley value and Nucleolus approach-based transmission loss allocation method under smart energy market structure. Generally, 7% transmission losses are occurred in practical power system. Therefore, in this study authors also considered total 7% transmission losses.

4.2.1. Characteristic function

For transmission loss allocation game, the characteristic value specifies the minimal loss that will be incurred by each coalition [13]. In [23], particular loss allocation index (PLAI) method is utilized to evaluate characteristic value as well as stand-alone value, i.e., transmission loss of a system. In this method authors allocated 77% losses to loads and 23% losses to generators [21].

The characteristic function of the cooperative game for loss allocation in [22] is derived by PLAI as shown below.

For loads, particular loss allocation indices (PLAI) are presented in Eq. (8):

$$PLAI_{ln}^{L_T} = \frac{P_{A_{ln}}^{L_T}}{PF_{ln}} p_{ln} \tag{8}$$

where $PLAI_{ln}^{L_T}$ is the losses occurred in transmission line due to load L_T, $P_{A_{ln}}^{L_T}$ represents the transmission line usage allocated to load L_T, PF_{ln} represents the power flow in respected transmission line calculated by load flow, and p_{ln} represents the transmission losses.

4.2.2. Cooperative gaming for optimal loss allocation in 6-bus system

An algorithm used in [24] is used for calculating transmission loss allocation by using Shapley and Nucleolus approaches. Results are shown for 6-bus system. **Table 3** provides transaction data for 6-bus system.

Now, **Table 4** presents the characteristic values for transmission loss allocation using Nucleolus approach.

Table 5 provides the transmission loss allocated to users using Nucleolus approach.

Transaction data of 6-bus system (in per unit) (trans. no.)	User	Supplier	Transaction quantity
1	D4	G1	0.731
2	D5	G2	0.725
3	D6	G3	0.714
1 and 2	D4,D5	G1,G2	1.461
1 and 3	D4,D6	G1,G3	1.448
2 and 3	D5, D6	G2,G3	1.444
1,2, and 3	D4,D5,D6	G1,G2,G3	2.184

Table 3. Transaction data of 6-bus system (in per unit).

Transaction losses of 6-bus system (in per unit) (transaction combination)	Active power losses
1	0.031
2	0.025
3	0.014
1 and 2	0.061
1 and 3	0.048
2 and 3	0.044
1,2, and 3	0.084

Table 4. Transaction losses of 6-bus system (in per unit).

Comparison between Shapley and Nucleolus approach (in per unit) loads	Stand-alone loss	Shapley value allocation	Nucleolus value allocation
L4	0.031	0.03	0.03
L5	0.025	0.03	0.0297
L6	0.014	0.0182	0.0187

Table 5. Comparison between Shapley and Nucleolus approach (in per unit).

5. Conclusion

The present energy sector involves a large number of stakeholders. Therefore, cooperative game theory application in modeling of smart energy market and economic analysis is increasing day by day. In addition to this, implementation of smart grid increased the applicability of cooperative game theory manyfolds because it is driven by the market forces. The huge amount of economy is involved in smart energy sector; thus, cooperative game theory plays a vital role to allocate this economy between various shareholders in a fair and equitable way.

This chapter provides an overview of smart grid structure along with various cooperative game theory applications in the present smart deregulated environment. For nondiscriminatory transmission open access, the problems of transmission usage, cost, and loss allocation and pricing must be dealt fairly. Due to the conflicting nature of these problems, power system becomes more complex. As a result cooperative game theory approaches such as Shapley value and Nucleolus approach are very useful to deal the abovementioned problems. This chapter discusses the transmission usage cost and loss allocation problems with the help of Shapley and Nucleolus approach. A sample 6-bus system is utilized to show the applicability of cooperative game theory approaches on the smart deregulated market structure.

The futuristic application of cooperative game theory problem may be to solve the cost optimization problem of distributed energy sources and microgrid. Further, various open access problems such as usage cost and loss allocation can be performed by incorporating the cost of smart grid technologies such as phasor measurement units. Additionally, other cooperative game theory techniques such as Aumann Shapley can also be implemented to solve large energy sector problems.

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Conflict of interest

The author declares that there are no conflicts of interest regarding the publication of this chapter.

Appendix

6-Bus system data

The data of test system, namely 6-bus system used in this work, is given below [25]. It contains three generator busses and three load busses. The data are at 100 MVA base. **Tables 6** and **7** present the line data and bus data of the 6-bus system, respectively.

Line data of 6-bus system (in per unit) (line no.)	From bus	To bus	R	X	Susceptance
1	1	2	0.1	0.2	0.02
2	1	4	0.05	0.2	0.02
3	1	5	0.08	0.3	0.03
4	2	3	0.05	0.25	0.03
5	2	4	0.05	0.1	0.01
6	2	5	0.1	0.3	0.02
7	2	6	0.07	0.2	0.025
8	3	5	0.12	0.26	0.025
9	3	6	0.02	0.1	0.01
10	4	5	0.2	0.4	0.04
11	5	6	0.1	0.3	0.03

Table 6. Line data of 6-bus system (in per unit).

Bus data of 6-bus system (in per unit) (bus no.)	Bus type	Voltage	Angle	PL	QL	PG	QG
1	1	1.05	0	0	0	0	0
2	2	1.05	0	0	0	0.5	0
3	2	1.07	0	0	0	0.6	0
4	0	1	0	0.7	0.7	0	0
5	0	1	0	0.7	0.7	0	0
6	0	1	0	0.7	0.7	0	0

Table 7. Bus data of 6-bus system (in per unit).

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