Multi-Agent Coalition Formation in Power Transmission Planning: a Bilateral Shapley Value Approach

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Abstract

Deregulation and restructuring have become unavoidable trends to the power industry recently, in order to increase its efficiency, to reduce operation costs, or to provide customers a better service. The once centralized system planning and management must be remodeled to reflect the changes in the market environment. We propose and have developed a multi-agent based system to assist players, such as, owners of power generation stations, owners of transmission lines, and groups of consumers, to select partners to form coalitions. The system provides a *cooperation plan* and its associated *cost allocation plan* for the user to support its decision making process. Among several coalition formation and cost allocation criteria, we have selected the Bilateral Shapley Value (BSV) as the theoretical foundation to develop the system. We have tested the multi-agent system with a classical transmission expansion example.

1. Introduction

Since the late 1980's, the electric utility industry has been facing the pressure of deregulation and restructuring. Two of the major changes were that the owners of the transmission lines could participate in the market to make decisions on behalf of themselves, and that the old boundary lines have been removed to offer consumers more alternatives, for example, in the U.S., consumers were allowed to purchase electricity from power stations located in other states.

As deregulation and restructuring have become inevitable trends in the modern utility industries, there is a need for more efficient methods or systems to facilitate a *just and stable* searching method to find new partners, as well as a *fair* system to identify the contribution from each participant.

Deregulation and restructuring have been adopted in several states, for example, California, and countries, for example, Australia; market structure of such states or countries have been changed significantly. In most cases, a more decentralized system or negotiation infrastructure has replaced the original system. Since this issue was very important, Wu et al. [18] have developed a decentralized algorithm to optimize multilateral trading among the participants. For transmission planning, Bushnell and Stoft [2], and Chao et al. [3] have shown that investment incentives and market mechanisms have been important to guarantee a fair and just outcome.

Planning for transmission expansion involves decisions from the players over several scenarios, which include the network topology, suppliers, customers, and/or owners of transmission lines. It is common that when adding a new transmission line, costs should be shared by all the players who will have a benefit. The decision making process about whether to add one more line or not and how to allocate costs is still an open research area.

This problem is very similar to the logistics planning problem in which the numbers and locations of the manufacturing plants or warehouses and retail stores are fixed. Therefore, to design a new logistics system, which includes decision of the routing and number of trucks, has become the core of the problem. In other words, the goal of solving such a problem is to satisfy the demands of a new set of consumers with the lowest costs to both owners of the transmission lines and owners of power units. To solve such problems, a solution needs to guarantee that the other operational constraints, such as, capacity of power transmission, can be satisfied.

Several techniques have been used to assist the planning of transmission expansion. For example, techniques based on mathematical programming, such as Branch-and-Bound [4, 5, 12], techniques based on sensitivity analysis [1, 13], and techniques that use a hybrid of neural networks and genetic algorithms [19]. Normally, planning for expansion is a combinatorial problem, and that makes it very difficult to find reasonable solutions within short computational time if the number of nodes or number of participants is large.

Using game theory to assist in the formation of coalitions is one approach to solve the transmission expansion

Bus From/to	Cost (Units)	Susceptance (1/Ω)	Capacity (MW)
1/2	40	2.50	100
1/4	60	1.67	80
1/5	20	5.00	100
2/3	20	5.00	100
2/4	40	2.50	100
2/6	30	3.33	100
3/5	20	5.00	100
4/6	30	3.33	100
5/6	61	1.64	78

Table 1. Six Bus Problem

problem. In particular, Gately used the Shapley value to set up regional cooperation for investment in expansion and cost allocation [6]. Gately's approach was a centralized one, where a central planner is needed to be in charge of cost allocation.

Recently, researchers in Distributed Artificial Intelligence (DAI) have started to study how coalitions are formed and what negotiation or bargaining algorithms are useful in helping people to better understand the process of coalition formation to design better negotiation strategies. Cooperative game theory has proved to be useful when combined with a DAI approach to address and solve some pending issues in deregulated power transmission markets [6, 11]. For example,

- Determining the members of coalitions and which coalition will be formed
- Implementing a protocol to support bargaining and negotiation
- Allocating total expansion costs to all the players (agents) of the expansion game

In this paper, we propose and have developed a multi-agent system to prove that some of the above issues can be solved by such multi-agent approach. The multi-agent system simulates the power industry and models each player, such as, an owner of a power station, as an agent. In the system, agents communicate with each other, based on Bilateral Shapley Values (BSV) to search for potential partners to form coalitions where they can protect their long-term interests.

The agents of this system have to work collaboratively to finish certain tasks, for example, determining the new transmission lines to add to the system and forming coalitions to reduce the overall costs. Each agent is assumed to be rational, that is, maximizing its own utility, and to be an independent and autonomous agent, who is not willing to accept any plan that generated by a centralized planner.

The network expansion model, which governs the network expansion of electricity transmission will be discussed in section 2. Coalitions in network expansion planning will be covered in section 3. The process of decentralized coalition formation among agents will be analyzed in section 4. Implementation of the multi-agent system will be discussed in section 5.

This paper is concluded with a discussion about the limitations of a multi-agent approach and recommendations for future research.

2. Network Expansion Model

We have used a simple example, a six-bus system, to illustrate the planning process of network expansion as shown in Figure 1. The limits of power transmission and power generation are provided on the same figure. The details of the model and the example can be found in [5, 17].

There are several techniques that can be used to rank the possible locations to add new lines to an existing system. For this study, we followed the heuristic approach suggested by [13, 17], which is a quadratic linear programming problem, to identify whether a solution is feasible or not. The general formulation can be expressed as:

$$\min \frac{1}{2} \sum_{j=1}^{M} c_j P_j^2 \qquad \textbf{(1)}$$

subject to

$$\mathbf{B}\Theta + \mathbf{K}^{\mathrm{T}} \mathbf{P}_{\mathrm{D}} = \mathbf{P} \qquad \textbf{(2)}$$

$$\left| \mathbf{B}_{\mathrm{L}} \mathbf{A} \Theta \right| \leq \overline{\mathbf{P}}_{\mathrm{L}} \qquad \textbf{(3)}$$

where c_j is the cost of adding line *j* to the network, P_J is the active power (in p. u.) flowing through the added line *j*, i.e., the *j*th element of $\mathbf{P}_{\mathrm{D}}$, and $\mathbf{P}_{\mathrm{D}}$ is the flow vector for the possible lines. *M* is the number of possible new lines, **B** is the matrix whose elements are the imaginary parts of the nodal admittance matrix of the existing network, Θ is the phase angle vector, $\mathbf{K}^{\mathrm{T}}$ is the transpose of the node-branch connection matrix, **P** is the nodal injection power for the overall network, $\mathbf{B}_{\mathrm{L}}$ is a diagonal matrix whose elements are branch admittance, $\overline{\mathbf{P}}_{\mathrm{L}}$ is the branch active power vector, and **A** is the network incidence matrix.

The data for Garver's six bus problem are presented in Figure 1 and Table 1. The solid lines and doted lines in Figure 1 represent the existing lines and candidate lines, respectively. The minimization algorithm is run recursively until there are no overloads, P_j, in the system. Although the optimum value is not always guaranteed, the simplicity of the heuristic algorithm makes it a valid first approach to solve a highly combinatorial complicated problem like this one.

Since the objective function (1) has taken into account the effect of the power transmission cost, the candidate line with the largest power flow is the most effective in the expanded network[1]. Constraint (2) expresses the total nodal injection power as a function of the existing and the potential network (after adding new lines) parameters, and constraint (3) reflects the thermal limits of the existing network lines.

3. Coalitions in Expansion Planning

To solve the transmission expansion planning problem in a decentralized environment, we treat it as a cooperative game. The purpose of the game is to expand the transmission grid with the minimum possible costs, subject to the constraints (2) and (3), as well as with a "fair" allocation of total costs among the players based on their contributions.

By DAI terminology, a player is called an agent. An agent in the game can be either a generator (a power station), a load (a group of consumers), or an independent third party (for example, an independent system operator). A typical agent is considered to be an independent entity: a customer load or a set of customer loads, a generator or a set of generators, or a combination of both. For simplicity, we do not consider fractional bus loading or fractional generator output. We also assume that any set of generation units and loads attached to the same bus belong to a single agent. Thus, we cannot have two agents sharing the same bus. Therefore, we have a maximum of six agents in the expansion game corresponding to the six-bus example as shown in Figure 1.

A coalition is defined in this paper as a set of agents and their associated transmission line(s) which connect these agents. They must satisfy four conditions:

1. There must be at least one generator, one load, and one transmission line included in the agents.
2. Generators have to meet the total demand, i.e. the loads have to be always satisfied by the outputs from generation stations plus the losses due to transmission.
3. Existing line(s) thermal limits cannot be exceeded.
4. There must be one or more transmission lines (either existing or possible candidates) which connect all the agents.

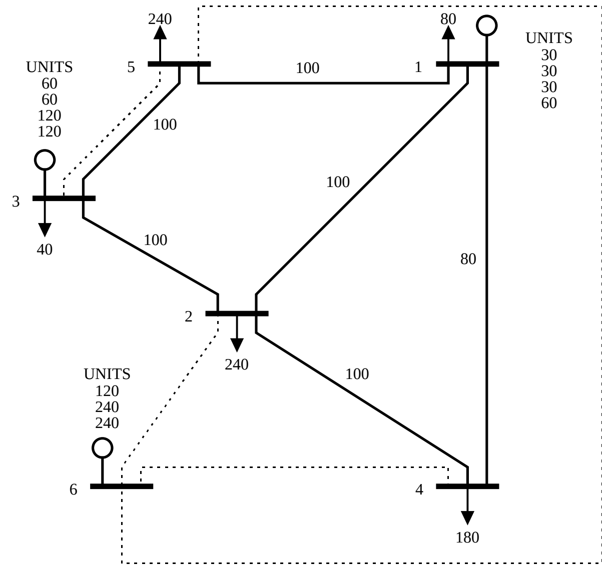

Figure 1. Six bus problem

A self-contained single agent can also be regarded as a coalition, called a trivial coalition. Such trivial coalitions do not need not meet all the four conditions.

Once a coalition is formed, then it will be represented by one autonomous agent. Within each coalition, it can develop its own expansion plan, and the expansion plan of this coalition can be determined again by the minimum algorithm described by (1), (2) and (3). Figure 2 shows two examples of feasible coalitions in the Garver test case.

When we allow generation rescheduling, that is, the real power generation output can be ranged form 0 to the maximum capacity (150, 360, and 600 MW respectively in Figure 1), the optimal solution of the minimum algorithm for the grand coalition has a cost of 130 units, and circuit additions are $n_{26} = 3$ circuits, and $n_{35} = 2$ circuits.

We will use the bus notation when referring to coalitions. For example, when we say coalition {1,2} we are referring to a coalition that combines all generators and loads on buses 1 and 2, and all the lines that interconnect these buses.

4. Decentralized Coalition Formation between Transmission Expansion Agents

The use of decision techniques to analyze DAI problems, like the one discussed in Section 3, started in the early

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[1] See [18], pp.394-400, for a very detailed explanation.

1990s. However, the Shapley Value [15] has been used to solve such problems [6]. The Shapley Value calculates a fair division of the utility, based on individuals' contributions, among the members in a coalition. It is a solution concept for a n-person cooperative game. The Shapley Value can be considered as a weighted average of marginal contributions of a member to all the possible coalitions in which it may participate. It assumes that the game is super-additive and the grand coalition is possible to be formed. Readers are referred to [7, 15] for a more detailed explanation. The mathematical expression of the Shapley Value, is given by:

$$\phi_i = \sum_{S, i \in S \subset N} \frac{(|S|-1)!(n-|S|)!}{n!} [v(S) - v(S - \{i\})] \quad \textbf{(4)}$$

where, i is a player, S is a coalition of players, $|S|$ is the number of players in coalition S, n is the total number of players, N is the set of all players, and $v(S)$ is the characteristic function associated with coalition S.

In order to avoid the combinatorial complexity of a Shapley Value calculation, Ketchpel introduced the Bilateral Shapley Value (BSV) [8]. Klusch and Shehory [9, 10] adapted this approach for a completely decentralized and bilateral negotiation process among rational agents. In particular, the algorithm for coalition formation they provided is also useful in the power transmission planning area [11].

Let $S \subseteq P(A)$ be a coalition structure on a given set of agents $A = \{a_1, \cdots, a_m\}$, where $C = C_i \cup C_j \subseteq A$, and $C_i \cap C_j = \phi$. Therefore, C is a (bilateral) coalition of disjoint (n-agent) coalitions of C_i and C_j $(n \geq 0)$. The Bilateral Shapley Value for coalition C_i in the bilateral coalition C is defined by

$$\varphi_C(C_i) = \frac{1}{2} v(C_i) + \frac{1}{2}(v(C) - v(C_j)) \quad \textbf{(5)}$$

Both coalitions C_i, C_j are called founders of C, and $v(C)$ denotes the self-value of coalition C[2]. Both coalitions C_i, C_j are willing to form coalition C, if

$$v(C_i) \leq \varphi_C(C_i) \text{ and } v(C_j) \leq \varphi_C(C_j) \quad \textbf{(6)}$$

In fact, a super-additive cooperative game is played between C_i and C. (6) reflects the individual rationality and (5) implies the collective rationality.

It can be seen that the founders will get half of their local contributions, and the other half obtain from cooperative work with the other entity. The second term of the BSV expression, as in (5), reflects the strength of each agent based on its contribution. Therefore it can remove the "free-rider[3]" problem, which is common in value allocation in transmission expansion.

In summary, the process of coalition formation among agents is based on the approach of Klusch and Shehory in [10]. The process has the following four steps:

Step1. Self-Value Calculation

Each bus is represented by one agent. Each individual agent collects and analyzes information to determine its initial self-value. A self-value (cost) determines the maximum value (minimum cost) that the agent should get (pay) when expanding its own lines. If the agent is not willing to join a coalition, such as agent 1 and 3 in Figure 1, the self-value is set to zero. If the agent must form a coalition to achieve its goal, such as agents 2,4,5, and 6, the self-value of agent a_i can be chosen as

$$v(\{a_i\}) = \max_j v(\{a_i, a_j\}) \quad \textbf{(7)}$$

For simplicity, we assume that an individual agent can be included in some two-entity coalitions. (7) reflects what initially agent a_i will pay for all the construction costs of the coalition $\{a_i, a_j\}$ to encourage the formation of a coalition.

There are other values for an agent to choose as its self-value. However, the lower boundary of the self-value for agent a_i is

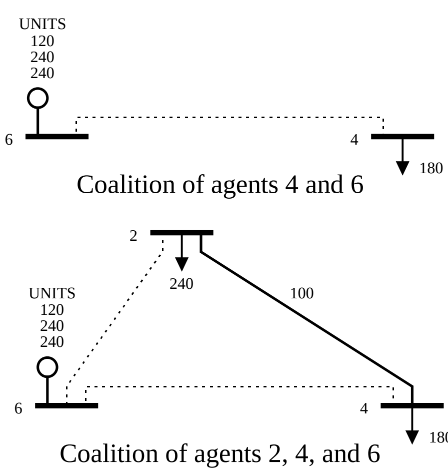

Figure 2. Two examples of coalitions

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2 Note that $\varphi_{\{C,\phi\}} = v(C)$, and $v(\phi) = 0$.

3 The free-rider concept address the issue of new agents that take advantage of the work done by the existing ones, without paying and compensation to them.

$$\min_{a_i \in S} v(S) \quad \textbf{(8)}$$

If (8) is set as its self-value, every coalition $S - \{a_i\}, S \subset A$ is willing to form coalition S with a_i. No matter what self-value is chosen, the algorithm can not guarantee that an agent with non-zero self-value will be included in a coalition.

Step 2. Communication and Security Check

Each agent sends its self-value and the candidate coalition to an independent coordinator. The coordinator will check the security of the coalition according to the security constraints. If a candidate coalition is identified to be detrimental to the security of the system, the independent coordinator informs the founders of the coalition to cancel the candidate coalition. After a security check, the coordinator broadcasts the information of each coalition to all the agents.

Step 3. BSV Calculation

After receiving messages from the coordinator, each agent proceeds to calculate BSVs to rank the order of forming coalition with other agents. Then each agent determines a rational list of preferred agents, *L*, to form coalitions, i.e. an ordered list of local agent's BSVs for two-entity coalition.

Step 4. Bilateral Negotiation

for each agent:

(1). Initially, set $i = 1$.

(2). Sends an offer to the ith agent in the agent's preference list, i.e. $L(i)$.

(3). Waits for replies and offers from other agents.

(4). If an offer from the agent $L(j)$, $j \le i$ is received, $i = j$. If an offer from the agent $L(j)$, $j > i$ or from an agent outside the preference list L has been received, replies a dissent message to that agent. If no more offer from other agents has been received, replies a consent message to agent $L(j)$ and informs coordinator the candidate coalition with agent $L(j)$.

(5). If a consent message from agent $L(i)$ has been received, informs the coordinator about the candidate coalition with agent $L(i)$. If a dissent message from agent $L(i)$ has been received, and $L(i)$ is not the last agent in the preference list, let $i = i + 1$ and go to (2)

for coordinator:

When the coordinator receives messages from the founders of a candidate coalition, sends a message to both of them to stop negotiation, and removes from its own preference list the agents within the candidate coalition, and then go to Step 2.

When every agent reaches the end of the list *L* and no coalition is possible, the process terminates.

It is perfectly possible that two agents can reach an agreement that is satisfactory to both of them, but which may be detrimental to the security of the system. This is the reason why an independent coordinator is needed to check and to guarantee that the reliability of the system and quality of service can be achieved. The coordinator is assigned other duties in the process. It is responsible for gathering information of the network and sending the information to all the agents. In the process, the synchronization in the multi-agent system is actually done by the coordinator.

The process produces a coalition structure that is a set of coalition trees in which the founders of a coalition are the sons of the coalition. The coalition structure is not unique for a given power expansion planning. If the grand coalition is formed, the coalition structure will only contain a single tree.

For power expansion planning, the grand coalition will not necessarily be formed. However, the process does not guarantee that any individual agent belongs to a coalition in the coalition structure.

Cost allocation according to coalition structure is given by

Coalition	*Value*	*Coalition*	*Value*
1	0	{2, 5, 6}	-334
2	-90	{3, 5, 6}	-101
3	0	{4, 5, 6}	-304
4	-60	{1, 2, 3, 6}	-30
5	-40	{1, 2, 4, 6}	-120
6	-60	{1, 2, 5, 6}	-273
{2, 6}	-90	{1, 4, 5, 6}	-243
{3, 5}	-40	{2, 3, 4, 6}	-120
{4, 6}	-60	{2, 3, 5, 6}	-100
{5, 6}	-183	{3, 4, 5, 6}	-161
{1, 2, 6}	-60	{1, 2, 3, 4, 6}	-90
{1, 3, 5}	-20	{1, 2, 3, 5, 6}	-80
{1, 4, 6}	-60	{1, 2, 4, 5, 6}	-272
{1, 5, 6}	-183	{2, 3, 4, 5, 6}	-160
{2, 3, 4}	-60	{1, 2, 3, 4, 5, 6}	-130
{2, 4, 6}	-150		

Table 2. Coalition expansion values

1. if $S \subset A$ and S is a root of a coalition tree, the cost shared by coalition S is

$$\varphi(S) = v(S)$$

2. if $S_i, S_j \subset A$ and S_i, S_j are the founders of coalition S, the cost shared by coalition S_i is

$$\varphi(S_i) = \tfrac{1}{2} v(S_i) + \tfrac{1}{2}[\varphi(S) - v(S_j)]$$

Note that cost allocation is different from (5) and the values are also different.

For the six bus problem, the cost function $v(S)$ of all valid coalitions and the self-value of each individual agent is given by the Table 2. The values (costs) are negative (positive) to reflect that the line expansion produces a negative value (positive cost) to the agents.

5. Implementation

Integrated Development Environment for Agent Systems (IDEAS) [9] has been selected to implement the multi-agent system to support coalition formation. IDEAS is implemented in Tcl (Tool Command Language) with the Tk Toolkit for the X Windows System running on UNIX platforms. An agent in IDEAS runs as a separate process in UNIX. The internal links among the local agents are made possible via UNIX pipes while the agents establish their communication with other known agents at remote sites for cooperative works by TCP-sockets via the Internet.

The *User Agent Manager* (UAM) is the user interface of IDEAS where user can use it to input parameters or view the outcomes as shown in Figure 3. Each line in the Local Agent List illustrates the address/ specification/status of an independent agent. Each agent can be activated or deactivated by the UAM. The UAM can send messages to every agent. Figure 4 shows the final cost allocation result using BSVs. The negotiation procedure of the six-bus problem is illustrated in Figure 5. When the coordinator sends the START message to all six agents, agents begin to negotiate with each other.

For example, the preference list of agent 1 is empty, therefore it sends a COMPLETE message to the coordinator. Agent 4 sends a REQUIRE message to agent 6 and it also receives a REQUIRE message from agent 6. After calculating BSV and identifying that the condition of super-additive is satisfied, agent 4 and agent 6 then form a coalition.

After the coalition is formed, agent 4 becomes the representative of the coalition, and it sends a COMPLETE message to the coordinator. After that, agent 2 sends a REQUIRE message to agent 6. Since agent 6 already

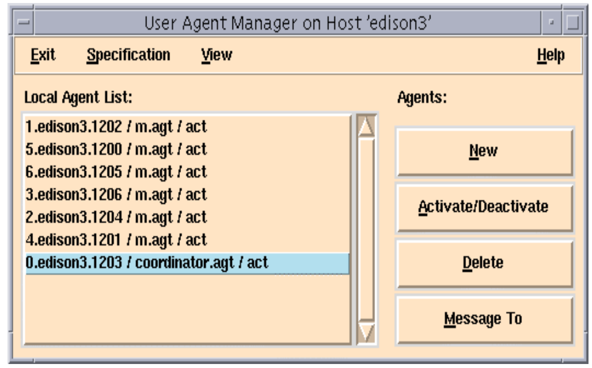

Figure 3. The User Agent Manager of IDEAS

agreed to form coalition with agent 4, it has to turn down the invitation from agent 2 by sending a REFUSE message to agent 2. The other reason is that agent 4 is before agent 2 in the preference list of agent 6. When the coordinator receives COMPLETE messages from all the agents, the process stops. The coordinator updates the information in its own belief base and sends another START message to kick off the next round of negotiation.

The log file of the communication messages that agent 2 has received is presented in Figure 6. From the log file it is easy to see that each message contains the information about the sender and receiver, the message type, the message reference number and the priority of the message, etc. Figure 7 shows the final results of the coalition formation. From Figure 7, we can see the sequence of coalition formation. In the beginning, agent 3 and agent 5 as well as agent 4 and agent 6 form the first two two-agent coalitions. Then, each two-agent coalition in the second round joined another agent to form a three-agent coalition. Finally, both three-agent coalitions joined together to form the grand coalition.

Notice here that no global agent or central mediator exists. Each agent in IDEAS is autonomous and works in a completely decentralized environment. For *belief representation and reasoning,* each agent maintains its own belief base which written in BinProlog [16]. Agent *plans*

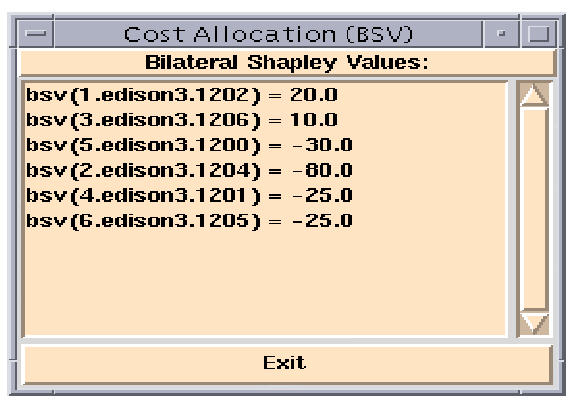

Figure 4. Result of cost allocation

can be specified by the appropriate developed rules for message evaluation. *Actions* can be defined in Tcl as well as in C. IDEAS provides some predefined standard actions for communication and managing the agents belief base etc. For further details, please refer to [9, 20].

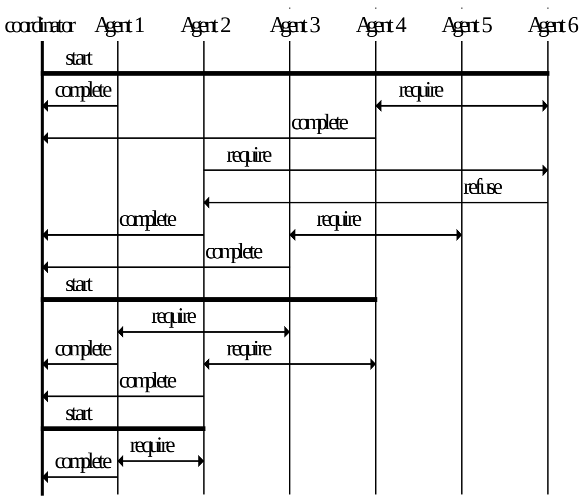

Figure 5. The negotiation procedure of six bus problem

The ability to support decentralized decision making is the most important issue to develop systems that simulate deregulated markets where the players have the right to evaluate and select partners to form coalitions, as well as to determine how to allocate profits or costs among themselves. IDEAS provides a full range of features, supported by a set of components that are needed for building comprehensive and decentralized multi-agent systems. Such ability to support decentralized decision making is the most important issue for selecting IDEAS to implement a multi-agent system that supports coalition formation Therefore, the determination of coalition formation and cost allocation in the new power market is better done locally, but in a coordinated way.

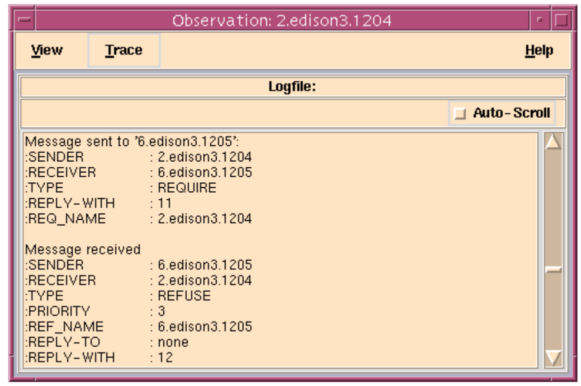

Figure 6. The log window of agent 2

6. Conclusions

The multi-agent system developed for this project was proved to be able to assist in the decision making for coalition formation and cost allocation for electric utility industry. The multi-agent was capable of making decisions for coalition formation and cost allocation, with very limited coordination and synchronization provided by the coordinator, in a fully decentralized environment. Furthermore, it is easy to implement and to run on the Internet. Therefore, the users do not need to rent dedicated lines to support the communications. We could see that such multi-agent systems can easily be applied to solve the problems where formation of coalition is essential and the environment is geographically dispersed, for example, global logistics planning or coalition formation of shipping and transportation firms.

The coalition formation in the multi-agent system is a hill climbing process. In each step of the coalition formation, the payoff for each agent to should not be worse than the payoff of the previous step. However, such requirement may not be able to find the best solution for all the participants, it may get trapped in local minimum. In our future research, we will test other algorithms, such as, simulated annealing, to give the system greater flexibility.

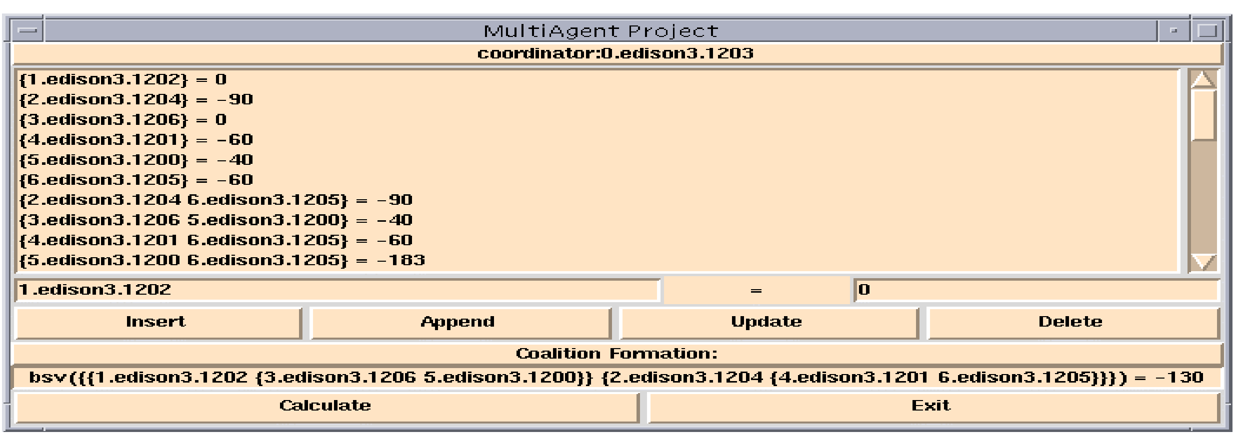

Figure 7. Result of coalition formation

When the negotiation process reaches the end, the cost or payoff for each agent must be allocated by a recursive algorithm, which is based on the coalition structure and the contribution from each agent that led to the final grand coalition. However such negotiation may not consider all the possible coalitions. Therefore an agent who is willing to form a coalition with some particular partners may not be guaranteed to be feasible. Therefore, how to give agents additional flexibility, so that they can select partners not purely based on the profits or sharing of costs will be one of the items for us to improve our system.

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