

# Market Mechanism of Smart Grids: Multi-agent Model and Interoperability

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**Abstract**—In order to reach the target of reducing green house gas emission, technologies such as renewable energy sources and plug-in hybrid electric vehicles (PHEV) have to be widely adopted. For the sake of accommodating such intermittent generators and flexible loads, the transmission and distribution network of the current electric power system will be adapted toward the next generation electricity infrastructure, namely the Smart Grid, with the capability of real-time pricing, dispatching and management of demand-side response. In this paper, we describe the overall model of the Smart Grid from both the architectural as well as the functional prospects. Moreover, the basis of the potential of the Smart Grid, a retailing spot market of electric energy is proposed. Its interoperability with other stakeholders in the electric power infrastructure, which is modeled as a cooperating multi-agent system, is elaborated.

**Keywords**—multi-agent, electricity market, smart grid, microgrid, renewable energy, demand response

## I. INTRODUCTION

In the prospect of the Smart Grid, a substantial amount of electricity will be fed into the power system at low voltage level. The lower parts of power grid are expected to evolve from a hierarchical top-down structure into a network of microgrids [1], where vast number of components influence each other. A combination of technologies, such as RES, demand response, real-time pricing and intelligent control, opens the possibility of optimization regarding economics, dependability and sustainability.

On the other hand, the electricity supply will no longer be in the hands of a small group of big market players, but be spread out over a vast number of small ones. This will give rise to new business models in electricity production and consumption. In regions with highly deregulated energy system, market mechanisms should be used for planning of large-scale production via day-ahead power exchange trading, and for real-time balancing via auctions held by the Transport System Operators (TSO).

The Smart Grid can also be viewed as a combination of several domains of major functionalities featured with different characteristics, uses, behavior and requirements. Each of those functionalities is consisted of many tasks that are performed by agents with associations between each other.

Agents may be devices, computer systems, software programs or the organizations that own them. Agents have the capability to make decisions and exchange information with other agents through communication links. Tasks are performed by the agents within a specific domain. Some tasks are finished by a single agent, others by cooperation of several agents. Associations show either electrical connections or communications links. In Figure 2, the electrical connections are shown as dashed lines and the communications links are shown as solid lines. Each of these associations may be bi-directional.

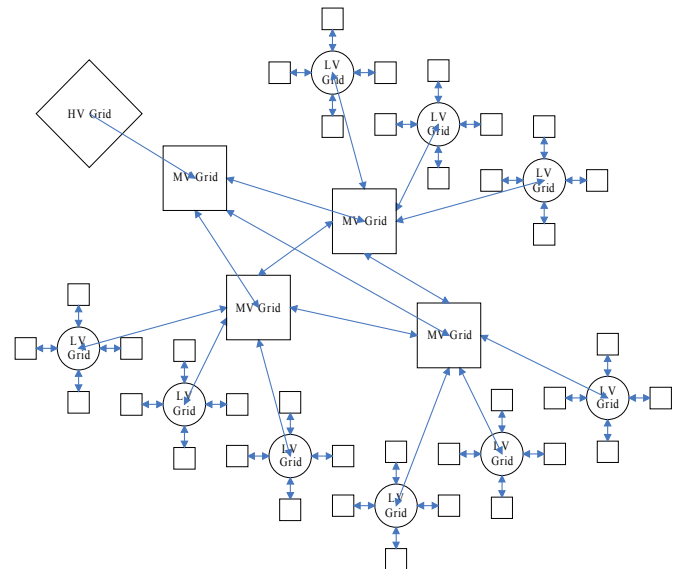


Figure1. Overall Structure of Smart Grid.

The functionalities of the Smart Grid can be grouped into seven major domains, which are briefly listed below.

### 1. Customer

Agents in this domain enable customers to manage their energy usage and generation. Some of them also provide control and information to agents of other domains. The three types of electricity users, household,

commercial building and industrial facility, may also generate, store, and manage their use of energy. The typical energy needs of each type are less than 20kW for households, 20-200kW for commercial buildings, and over 200kW for industrial facilities. There are multiple agents with different tasks in each type, where the energy management system (EMS) may reside in a meter or an independent gateway.

The EMS may communicate with agents of other domains via the advanced metering infrastructure (AMI). It may also communicate to agents within the same domain across a local area network (LAN). There may be more than one EMS—and therefore more than one communications link—per customer. EMS is the entry point for tasks such as remote load control, monitoring and control of distributed generation, in-home display of energy usage, reading meters, and integration with building management systems. The EMS may provide auditing/logging for cyber security purposes.

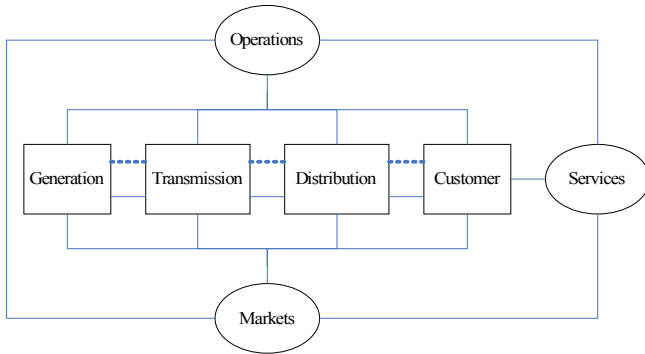


Figure2. Major Functions of Smart Grid.

## 2. Markets

Agents in this domain exchange price and balance supply and demand within the power system. Communication between the agents in market domain and those in domains supplying energy are critical, which include the generation domain and distributed energy resources (DER). DER may reside in the transmission, distribution, and customer domains. Suppliers of more than 300 megawatts to be bulk generation; most DERs are smaller and is typically served through aggregators. Communications for market interactions must be reliable, traceable and auditable. They must support e-commerce standards for integrity and non-repudiation.

The challenges in the markets domain are: extension of price and DER signals to each of the agents in customer domain; simplification of market rules; expanding the capabilities of aggregators; interoperability across all providers and consumers of market information; managing the growth (and regulation) of retailing and wholesaling of energy, and evolving communication mechanisms for prices and energy characteristics between and throughout the market and customer domains.

## 3. Services

Agents in the Services domain support the business processes of power system producers, distributors and customers. These processes range from traditional utility services such as billing and customer account management. The agents associate with others in the market, operations and customer domains. Communications with the operations domain are critical for system control and situational awareness; communications with the market and customer domains are critical for enabling economic growth through the development of “smart” services, which may be performed by the electric service provider, by existing third parties, or by new participants drawn by the new business models.

The challenge in this domain is to develop the communication mechanisms that will enable a dynamic market-driven ecosystem while protecting the critical power infrastructure. These mechanisms must be able to operate over a variety of networking technologies while maintaining consistent messaging semantics.

Function Domains	Key Agents
Generation	Plant Control Agent
Transmission	Intelligent Electronic Device / Field RTUs, Transmission Actuator
Distribution	Field Devices, Workforce Tools, Distribution Engineering Agent
Operations	ISO/RTO, Utility EMS, SCADA, Wide Area Measurement and Control, Distribution Management Agent, Utility Transportation Apps, Load Management Agent, Geographic Information Agent, Customer Information Agent, Outage Management Agent
Markets	Wholesale Market Agent, Retail Market Agent
Customer	Meter, Display, DER Controller, Smart Appliance, Energy Storage, PEV, AMI / Customer EMS, Facility EMS / Gateway, End Use Measurement Device / Sub Meter, Electric Vehicle Service Agent, Energy Services / HAN Interface
Services	Aggregator, Demand Response Agent, Public Information Agent, Meter Info Collector, Accounting and Billing Agent

## 4. Operations

Agents in this domain are responsible for the smooth operation of the power system. The majority of these

functions are the responsibility of a regulated utility. The smart grid will enable more of them to be outsourced to agents of the service domain; others may evolve over time. No matter how the service and markets domains evolve, there will still be basic functions needed for planning and operating the service delivery points of a independent system operator (ISO).

## 5. Generation

The generators of electricity in bulk quantities may also store energy for later distribution. This domain is electrically connected to the transmission domains and shares communication links with the operations, markets and transmission domains. Agents in this domain must communicate key performance and quality of service issues such as scarcity (especially for wind and sun) and generator failure.

New requirements for this domain include green house gas emissions controls, increases in renewable energy sources, provision of storage to manage the variability of renewable generation.

## 6. Transmission

Transmission is the bulk transfer of electrical power from generation to distribution through multiple substations. A transmission network is typically operated by a regional transmission operator (RTO), whose primary responsibility is to maintain stability on the electric grid by balancing supply and demand across it. This domain may contain DERs such as electrical storage or peaking generation units. Energy and ancillary services (capacity that can be dispatched when needed) are procured through the markets domain, scheduled and operated from the operations domain, and finally delivered through the transmission domain to the customer domain.

Most behaviors of the agents in this domain take place in a substation. It uses transformers to change voltage from high to low or the reverse across the electric supply chain. Substations are usually equipped with switching, protection and control agents. They are typically monitored and controlled through a supervisory control and data acquisition (SCADA) system composed of communication links, monitoring and control agents.

## 7. Distribution

This domain associated the transmission domain and the customer domain. It is the metering points for consumption, distributed storage, and distributed generation. The physical distribution network may be arranged in a variety of structures, including radial, looped or meshed. The reliability of the distribution system varies depending on its structure, the types of agents deployed, and the degree to which they communicate with each other and with the agents in other domains.

In the smart grid, the agents in distribution domain will communicate more closely with those in the operations domain in real-time to manage the power flows associated with a more dynamic markets domain and other

environmental and security-based factors. The communication will effect localized consumption and generation. In turn, these behavioral changes due to market forces may have functional and structural impacts back on the distribution domain.

## II. ELECTRICITY MARKET STRUCTURE AND MECHANISM

In this section, the pivotal components and mechanisms of a prevailing electricity market are delineated and modeled as Multi-agent System (MAS). Such a market arrangement is based on bilateral trading between generators, suppliers, traders, and customers, which take place in the Forward Markets before gate closure. Power Exchanges (PX) among these four organizations are set up to facilitate this, although it is clear that market forces will cause liquidity to gravitate to one or two of them. The Balancing Mechanism (BM) works as a market where Independent System Operator (ISO) buys and sells Increments (incs) or Decrements (decs) of electricity in order to balance the system as a whole. However, individual generators and suppliers may be out of balance.

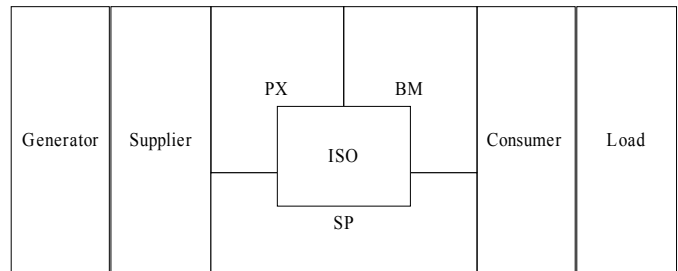


Figure3. Electricity market structure.

During Settlement Process (SP), the ISO will compare the Contract Positions (quantities contracted) with the Actual Position (quantities generated or consumed) for each of the consumers and generators to calculate the imbalances. The imbalance may be a Spillage (if a plant generates more than it contracted or if a load consumes less than it contracted) or a Top-up (if a plant generates less than it contracted or if a load consumes more than it contracted). For both types of imbalance, there is a price: if an agent is spilling, it will receive payment for the marginal generation at the System Selling Price (SSP); if an agent is topping up, it will pay at the System Buying Price (SBP). The spread between the two prices is intended to provide a penalty for being out of balance: SSP (SBP) is expected to be considerably lower (higher) than the prices in the forward markets.

Such an electricity market arrangement is a costly system, partly a reflection of the inherent complexity of its rules and partly because of the costs and risks of doing business in a market overshadowed by intentionally penal imbalance prices [2]. This is a trading environment in which the big players enjoy special advantages: their diverse portfolios make them less susceptible to the vagaries of the imbalance settlement process. The obvious losers from all this are CHP and RES, which are inevitably relatively small, and in the case of some CHP plant and wind generation, especially exposed to the

penalties of the imbalance settlement process. Aggregation in the supply business prompted by high costs has reduced the number of potential customers for embedded generation and added to these difficulties. The Government has responded to the plight of RES by introducing financial incentives in the form of Renewable Obligation Certificates (ROCs) which place a premium on renewable generation, negating the detrimental effects of the very market arrangement.

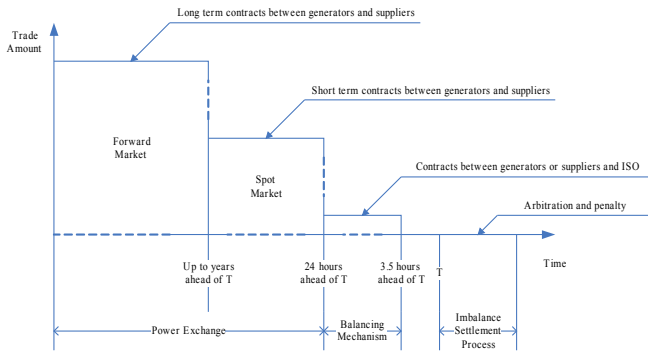


Figure4. Electricity market mechanism.

Here comes the critical issue of how to facilitate RES deployment into the distribution system with market forces. While it can be easily seen that due to the unpredictable nature of RES, microgrids consist of clustered micro-sources and loads, behaving as fluctuating Virtual Power Plants (VPP) or virtual loads, are not applicable in bulk energy trade of PX with bilateral contracts. However, the fast response of microgrids will allow their competence in BM with short-term supplementary services. Moreover, the considerable high SBP will guarantee an obvious profitability of the winning VPP in balancing market during SP. From the inside of microgrids, SBP and SSP will be regarded as bids offered by outside consumers and suppliers. The uniformity of overall future market and regional spot market can be realized by transferring SSP (SBP) to  $P_{oc}$  (outside consumer buying price) and  $P_{os}$  (outside supplier selling price). Therefore, the economic incentive for facilities to equip RES will be enhanced, besides the benefit from ROCs. One of the indispensable conditions for such a market arrangement to be deployed is to establish the electronic market and delegate agents, as well as their coordination mechanism, which can enable the active involvement of various RES and flexible loads into the competition derived from the electricity market. A multi-agent system carrying out the required functionality is elaborated in the following part.

Moreover, there is a need for an innovative common pricing model across all domains that use price. Price is no longer a simple number, but will be a compound carries information about amount, timing and carbon characteristics. A potential paradigm could be and , where is the price of energy sold by Suppliers or bought by Consumers; is the amount of energy being traded with the unit of kWh; is the specified interval of delivery. While most illuminating of all, is the Carbon Efficiency of electricity suppliers and is the

Energy Efficiency of power consumers. The carbon efficiency is the quotient of carbon emission among electricity generation in the unit of ton/kWh, and the production efficiency is the rate of production output over energy consumption in the unit of Euro/kWh. In this case, high emission generators and low efficiency loads can be directly regulated with the entrance standards of the electricity market. Further, when carbon efficiency is divided by production efficiency, another index called the Carbon Intensity can be issued, which reveals the emission characteristics of a certain energy consumer in a specified energy purchase. Such an index with the unit of ton/Euro will be capable of associating the macro-economic object of a region or a country and the micro-economic behavior of an industry or an enterprise through the management of electricity market. After all, the very interoperable pricing model is a key to Demand-Response, Dynamic Pricing, and energy trading including forward markets. A multi-agent system carrying out the required functionality is elaborated in the following part.

### III. REAL-TIME SPOT MARKET

In the hierarchically distributed environment of the smart grid, for each resource (load or generator), agents should be introduced, which are responsible for managing their functions respectively. On one hand, Generator Agent (GA) controls the output of its associated DER to ensure that the demand of Load Agents (LA) is satisfied. On the other hand, LA determines the maximum unit price it is willing to pay for a quantity of power required during a specific period of time, based on internal prediction algorithms that incorporate real-time and historical data. At the same time, the GA interacts with its affiliated DER to determine unit production cost, preferred markup, and the quantity of power available for supply. Production costs are calculated based on operation, fuel, and maintenance overheads. During some certain time period, GA and LA coordinate with each other to achieve their objectives. Primarily, both LA and GA wish to maximize their utility. LA wants to minimize their cost by purchasing energy below their unit price, whereas GA wants to maximize their profits by selling energy above the unit cost and maximizing markup. For the problem of energy allocation, auction-based mechanism has been shown to work well, which implement bilateral contracts between GA and LA.

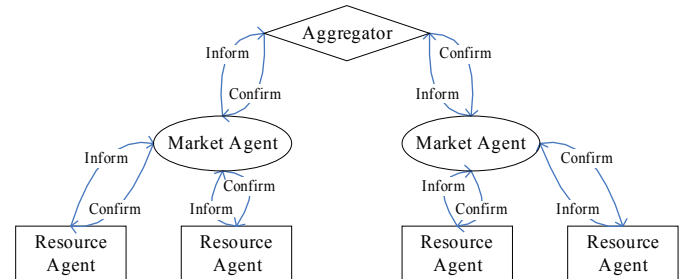


Figure5. Real-time Spot Market Architecture.

Let's consider a simplified model of microgrid, which is composed of two distributed generators  $G_1$ ,  $G_2$  and two loads  $L_1$

,  $L_2$ . Here we do not take storage devices in to account, because they behave either as load or as generator at any certain moment. Each of the above actors participating in the market competition of electric energy within the microgrid has its own capacity  $Q$  (either demand quantity or supply quantity) and initial price  $P$  (either price to buy or price to sell).

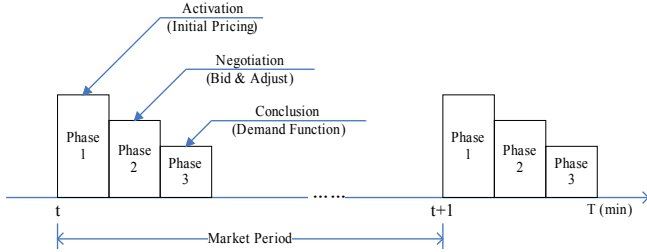


Figure 6. Market procedure of a microgrid.

As such a simple model, the environment within a microgrid can be partially accessible, which means load agents can acquire all the information from generator agents, e.g.  $P_{G1}$ ,  $P_{G2}$ ,  $P_{OS}$  (price of outside supplier) and  $Q_{G1}$ ,  $Q_{G2}$ ,  $Q_{OS}$  (quantity of outside supplier), while generator agents can acquire all the information from load agents e.g.  $P_{L1}$ ,  $P_{L2}$ ,  $P_{OC}$  (price of outside consumer) and  $Q_{L1}$ ,  $Q_{L2}$ ,  $Q_{OC}$  (quantity of outside consumer); same kind of device agents (either loads or generators) should be unperceivable to each other, due to their private ownership and rivalry relationship for resources (either consumers or producers) within the microgrid. Moreover, although all the above variables alter during each market period, they will not change during each single bidding round, which results in a static environment [3]. These facts are the fundamental basis for the coordination system based on MAS to be built.

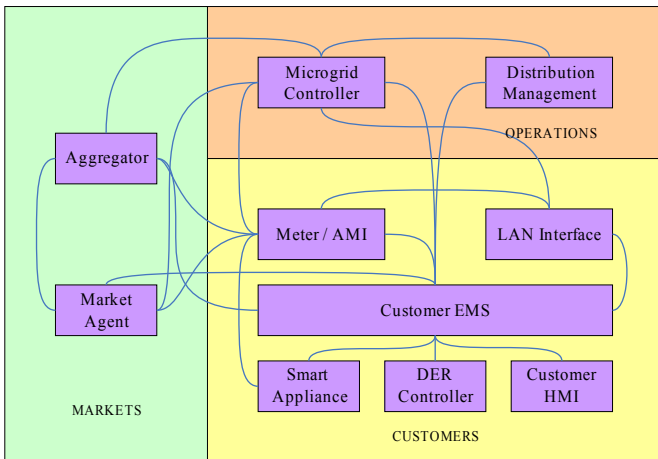


Figure 7. Market Interoperability.

Since market prices can fluctuate significantly, undesirable stabilities in trading may occur. Consequently, a single microgrid could be best served by bilateral contracts, while the

distribution system could also use pool-based mechanism. In essence, each bilateral contract guarantees the energy allocation of one bidder within a group, which is facilitated by an auctioneer. The auctioneer specifies the quantity of goods and a starting unit price. Bidders make bids after analyzing the feasibility of the auctioneer's parameters. In practice, there are two possible auction scenarios in microgrids: GA act as auctioneer, auctioning energy to participating LA; or LA act as auctioneer, auctioning the right of providing energy to participating GA. Concentrating on four types of auctions [4]: First-price Sealed-bid (FPSB), Vickrey, English and Dutch, the first one is the most suitable mechanism in our application on microgrids, as explained later.

#### IV. AGENT ARCHITECTURE AND BEHAVIORS

In order to design the specific software architecture for each agent in our coordination system, agent behaviors that take place in each phase of a Market Period (MP) should be considered in detail. A critical point must be clarified is that any Resource Agent (RA), when is newly added into the microgrid, must send its ID to the Market Agent (MA) they subordinate to as an Resource Added Message (RAM), before being activated in its first MP. Moreover, any RA, when is about to be removed from the microgrid, must also send a Resource Removed Message (RQM) to its MA. These operations will help MA keeping a complete updated Resource List (RL) which is composed of the ID and status of all RA with in the microgrid. Such a list can greatly facilitate the negotiation among agents.

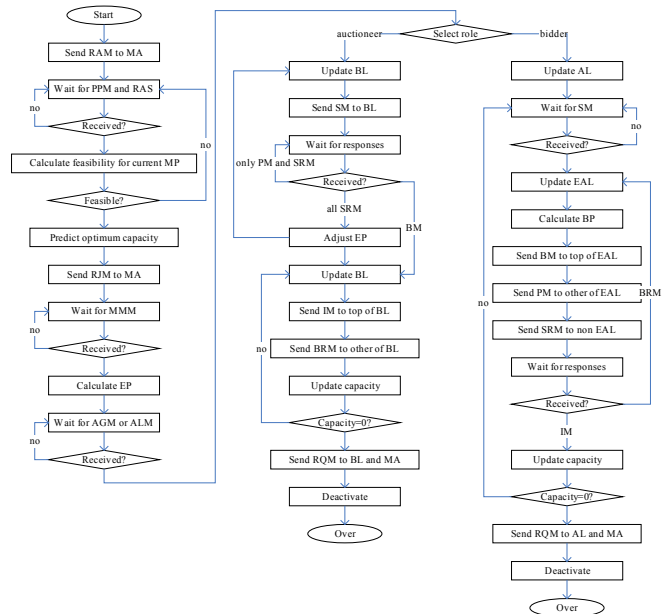


Figure 8. Resource agent behaviors.

Based on Price Publication Messages (PPM) and Market Mode Messages (MMM), each active RA calculates  $P_{Gi\min}$  (the lowest price with which generator  $G_i$  will sell its production) or  $P_{Li\max}$  (the highest price with which load  $L_i$  will buy its consumable). In principal, there should be

$$P_{Gi} \in [P_{Gi\min}, P_{Gi\max}] \quad [P_{OC}, P_{OS}] \quad \text{and} \quad P_{Lj} \in [P_{Lj\min}, P_{Lj\max}] \quad [P_{OC}, P_{OS}].$$

Hereon, the Negotiation Phase (NP) starts. If the energy market is in LR mode, active generators will set their RA to be Auctioneers, and active loads will set theirs to be Bidders. If it is in GR mode, active generators will be bidders, while active loads will be auctioneers. According to AGM or ALM that has been received by each active RA respectively, bidders will create an Auctioneer List (AL) and auctioneers will create a Bidder List (BL).

The NP continues until MA perceives that there is only one active RA on RL. At this moment, all the other RA, which have once taken part in the negotiation, have already made deals with their peers by auctions and successfully quit the energy market. Here comes the Conclusion Phase (CP) of current MP. The MA will send a Capacity Request Message (CRM) to the last RA. When the RA receives CRM, it will return its rest resource with a Capacity Notifying Message (CNM), followed by a RQM. When there is no active RA on RL, MA will issue a Demand Publication Message (DPM) according to CNM and send it together with PRM, initiating the next MP.

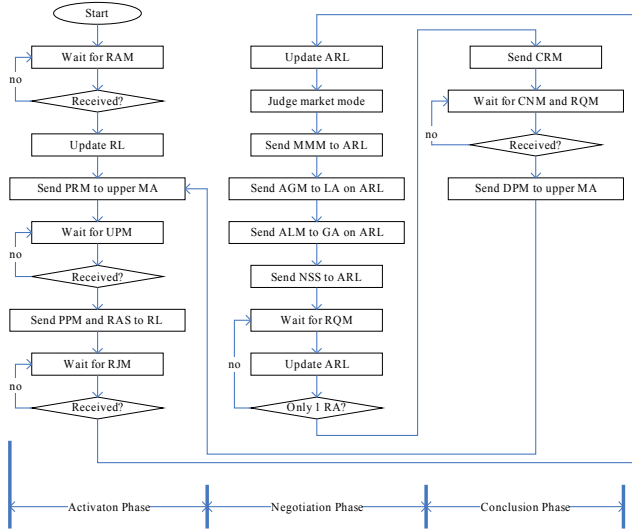


Figure9. Market agent behaviors.

## V. SIMULATION RESULTS

Agents Num.	GA	4	6	8	10	15	20
	LA	4	10	20	40	60	80
Auction Type	FPSB	183	189	199	211	332	480
	Vickrey	186	187	199	210	330	483
	English	151	155	158	162	178	206
	Dutch	147	150	152	155	174	200

A software simulator, which emulates the coordination among agents within a microgrid as introduced above, is programmed in JAVA, in which the parameters are preset as follows:

1.  $P_{OS}$  and  $P_{OC}$  are randomized from  $[0,1000]$ , according to  $P_{OS} > P_{OC}$ ;
2. 4 GA will join when  $P_{OC} < 400$ , 4 LA will join when  $P_{OS} < 600$ , flexibility of other RA are randomized;
3.  $Q_{Gi}$  and  $Q_{Lj}$  are randomized from  $[0,100]$ ;
4. Initial prices of RA are randomized according to  $P_{Gi} \in [P_{Gi\min}, P_{Gi\max}] \quad [P_{OC}, P_{OS}]$ ,  $P_{Lj} \in [P_{Lj\min}, P_{Lj\max}] \quad [P_{OC}, P_{OS}]$ .

It can be easily seen from the simulation results with different market scenarios that for FPSB or Vickrey auction, among every 100 successfully finished MP, the average amount of messages a RA sends and receives is around 480; as to English or Dutch auction, among every 100 successfully finished MP, the average amount of messages a RA sends and receives is about 200. According to amount of data exchange among the MAS, price sealed bids can be more appealing when privacy and security concerns of different market players are emphasized. While, open cry processes will be preferred, if density of communication through local data links is stressed.

## IV. CONCLUSION

Aided with advanced computer science and communication technology, the smart grid will work in a distinct way than the traditional power system. Since the supply and demand matching of devices within a microgrid or between peer microgrids is based on microeconomic principals, a global optimization on energy consumption will appear beyond the ownership of each market player, which can obviously damp the peak demand, hence reduce the construction cost of transmission system. Moreover, with the automated negotiation and coordination enabled by applying MAS, a much shorter market period (such as 1 minute) can be realized on the smart grid, which will allow more RES with less predictable power output to be deployed. The smart grid, combining both the efforts on substitute energy and energy efficiency, will become the core of future energy supply chain in the green growth of low carbon economy, and even the most delicate and effective social management tool that mankind has ever acquired.

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