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Multi-agent Coordination in Market Environment for Future Electricity Infrastructure based on Microgrids

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***Abstract*—Although the financial crisis shrinks oil price, human as an entire race still face the future of a hot, flat and crowded world [1]. Therefore, a critical transformation from our traditional energy consumption manner of fossil fuel combustion must be made. After years of endeavor in research and experiment, a number of Renewable Energy Sources (RES) has already become technically available as alternatives. A pivotal task still needed to be carried out is adapting the existing electricity infrastructure, which is still a very efficient energy delivery facility, to incorporate emerging RES openly and equally. For the purpose of wide adoption of RES, which results in the evolution to next generation infrastructure for electricity, impellers should contain economic and political measures, rather than only technology. In this paper, we introduced the architecture of future electricity infrastructure based on microgrids for high RES penetration. Moreover, we brief the mechanisms of a prevailing electricity market, for economical incentives of RES accommodation. Most important of all, the multi-agent model of the proposed system and its coordination mechanism within the market environment is elaborated.**

Keywords—multi-agent, electricity market, infrastructure, microgrid, renewable energy, demand response

I. INTRODUCTION

In the near future, a substantial amount of electricity will be fed into the power grid 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 [2], 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. In this case, the traditional paradigm of centralized control used in current electricity infrastructure will reach the limits of scalability and complexity.

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 coordination mechanisms for the low-end of the grid hierarchy must be based on economic principles as well.

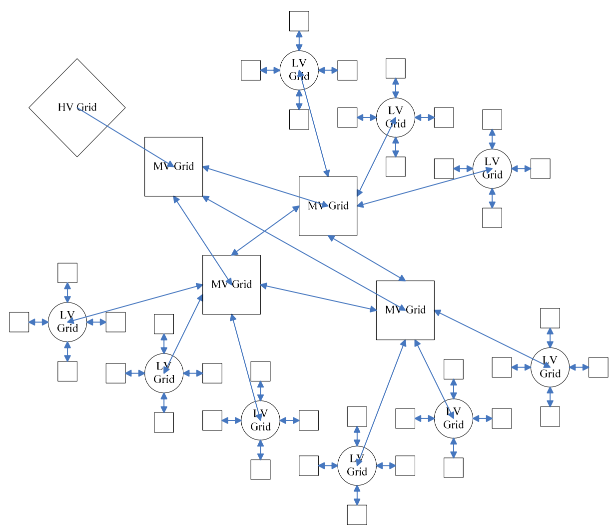

Figure 1. Future electricity infrastructure based on microgrids.

II. ELECTRICITY MARKET STRUCTURE AND MECHANISM

In this section, the pivotal components and mechanisms of a prevailing electricity market in 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 takes 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.

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

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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.

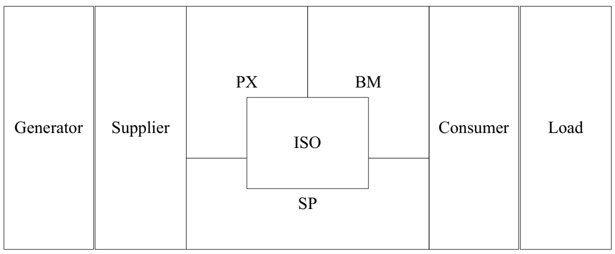

Figure 2. Electricity market structure.

The day-ahead and within-day balancing schedules are as follows [3].

A. ISO Day-Ahead Balancing Process:

1) By 09:00, publishes the day-ahead demand forecast.

2) By 11:00, receives the Initial Physical Notifications (IPN).

3) Calculates the available national plant margin or shortfall.

4) Verifies system security with demand predictions, IPN, and planned transmission outage.

5) By 12:00, issues the total system plant margin data to the market for the day ahead.

6) Forecast constraint costs based on the estimated Final Physical Notifications (FPN), bid (offer) prices and volumes.

7) If necessary, calls the most economic balancing service contracts to ensure system security.

8) During the following 11 hours, receives updates of Physical Notifications (PN).

9) By 16:00, publishes the revised national plant margin and zonal margin.

B. ISO Within-Day Balancing Process:

1) Publish averaged demand forecasts every half hour for a defined period until gate closure.

2) As participants become aware of changes to their physical position, they will advise the ISO.

3) At defined times, the zonal and national margins will be reassessed and provided to the market.

4) Undertake security analysis and reassess the requirements of balancing services contracts.

5) At gate closure, PN will become FPN and ISO will have received bids (offers) with prices and volumes from the participants in BM.

6) During BM, ISO will balance the system, with regard to technical constraints, dynamic operating characteristics of supply and demand balancing services, and uncertainty in demand.

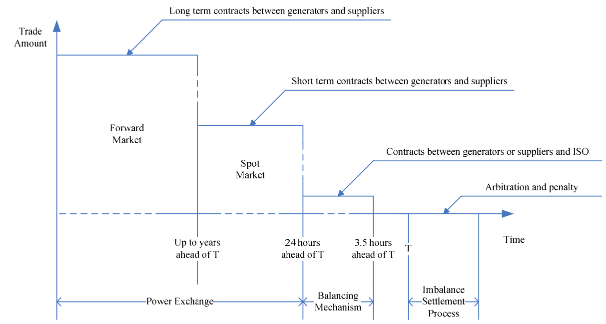

Figure 3. Electricity market mechanism.

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 [4]. This is a trading environment in which the big players enjoy special advantages: they have the deep pockets to pay the entry and on-going costs of participating in it and 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.

Here comes the critical issue of how to facilitate RES penetration 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 uniform of overall future market and regional spot market can be realized by transferring SBP (SSP) 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 indispensible 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 current prevailing electricity market. A multi-agent system carrying out the required functionality is elaborated in the following part.

III. Model of Future Electricity Infrastructure

Our work addressed in this part is to construct a coordinating system based on multi-agent technology with microeconomics principles for the future power grid mentioned above to match the electric power supply and demand both within the microgrids and among them, which will fulfill the primary control requirement for the electricity infrastructure to operate steadily. There are two main tasks:

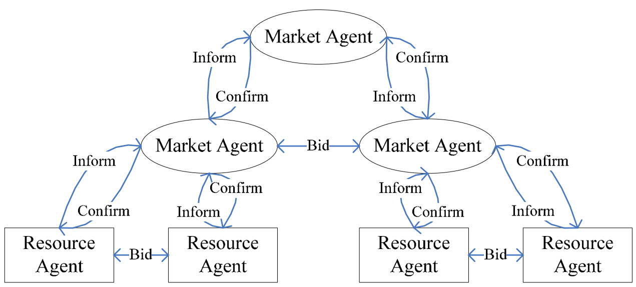

Figure 4. Future electricity infrastructure modeled as MAS.

The first one is to design resource agents that can bid in delegate of each generating, consuming and storage device within a microgrid. These resource agents can have the same general structure of simple reactive agent, but equipped with different bidding strategies according to the various properties of the devices they serve. With this method, the behaviors of devices in the microgrid can be economically optimized according to their flexibility on energy supply or demand over time.

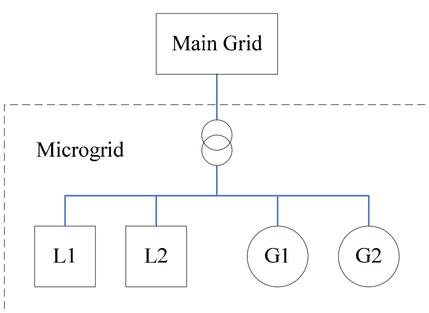

Figure 5. Simplified circuit model of a microgrid.

The second one is to design market agents that supervises the microgrid, detecting whether there are resource agents being added into or removed from the underneath microgrid, initiating market period for all the resource agents, and confirming deals between biding rounds. In case of a microgrid which is rich of electricity consumers, a node of virtual load will appear on the level of market agents in the meshed mid-voltage grid. Correspondingly, a node of virtual generator will appear, if the underlying microgrid is rich of suppliers. The market agent should also generalize and issue demand function for virtual load (or supply function for virtual generator in form of negative demand) to outside suppliers of the microgrid it covers, which can be either feeders from high-voltage transmission system or peer microgrids behaving as VPP. In addition, the market does not need to differentiate bids from underlying market agents or resource agents, which will allow more flexibility for the MAS to be deployed on real-life complex grid architectures.

In such a hierarchically distributed environment, 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.

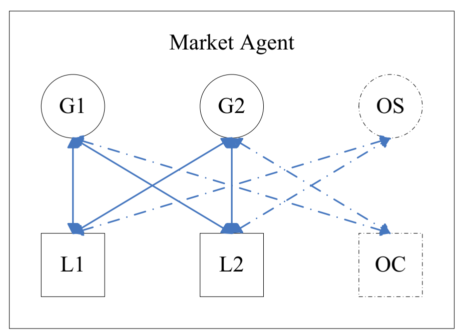

Figure 6. Market model of a microgrid.

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 (as shown in Figure. 5). 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).

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 biding round, which results in a static environment [5]. These facts are the fundamental basis for the coordination system based on MAS to be built.

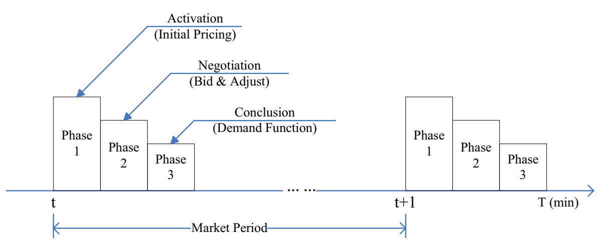

Figure 7. Market procedure of a microgrid.

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 [6]: 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.

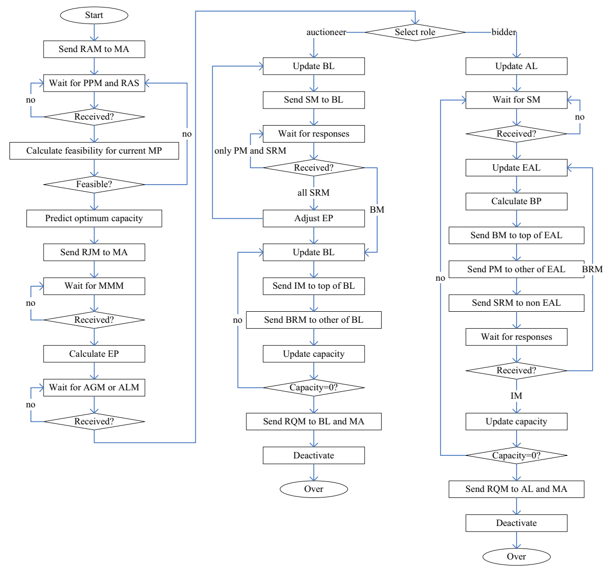

Figure 8. Resource agent behaviors.

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 $P_{Lj\max}$ (the highest price with which load L_j will buy its consumable). In principal, there should be $P_{Gi} \in [P_{Gi\min}, P_{Gi\max}] \subseteq [P_{OC}, P_{OS}]$ and $P_{Lj} \in [P_{Lj\min}, P_{Lj\max}] \subseteq [P_{OC}, P_{OS}]$. 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).

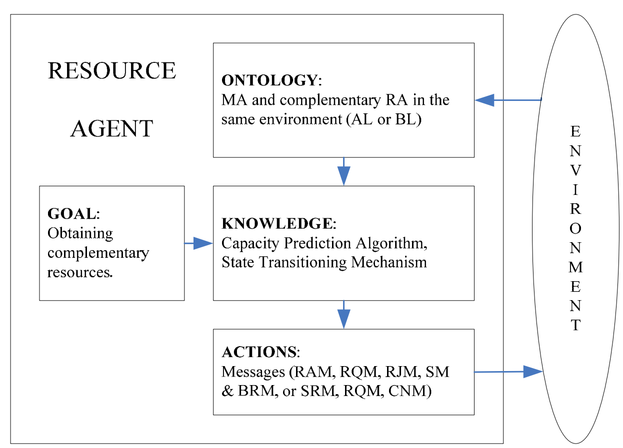

Figure 9. Resource agent architecture.

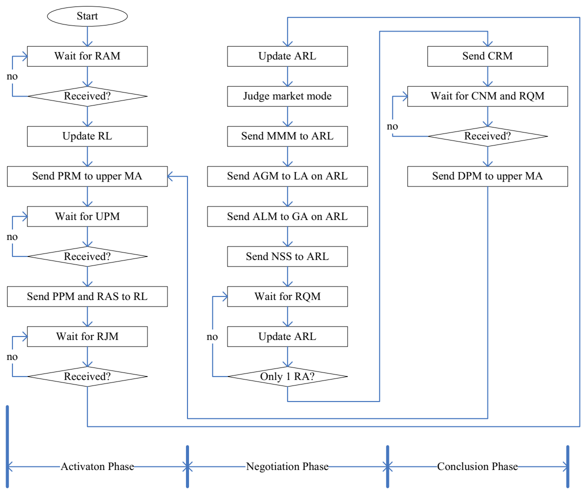

Figure 10. Market agent behaviors.

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.

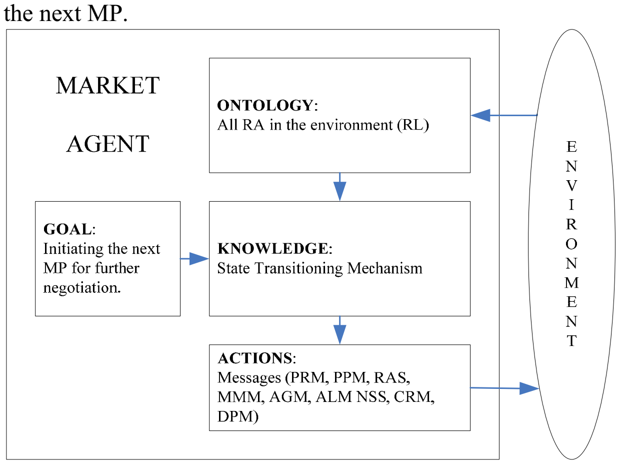

Figure 11. Market agent architecture.

V. Priliminary Restults

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. 8 generators and 8 loads within 1 microgrid;
2. P_{OS} and P_{OC} are randomized from [0,1000], according to $P_{OS} > P_{OC}$;
3. 4 GA will join when $P_{OC} \geq 400$, 4 LA will join when $P_{OS} \leq 600$, flexibility of other RA are randomized;
4. Q_{Gi} and Q_{Lj} are randomized from [0,100];
5. Initial prices of RA are randomized according to $P_{Gi} \in [P_{Gi\min}, P_{Gi\max}] \subseteq [P_{OC}, P_{OS}]$, $P_{Lj} \in [P_{Lj\min}, P_{Lj\max}] \subseteq [P_{OC}, P_{OS}]$.

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 180; as to English or Dutch auction, among every 100 successfully finished MP, the average amount of messages a RA sends and receives is around 150. According to the similar amount of data exchange among the MAS, price sealed bids can be more appealing to our application on coordination of microgrids, for the privacy and security concerns of communication between different market players.

VI. Conclusion

Aided with advanced computer science and communication technology, the future electricity infrastructure based on microgrids with MAS coordination will work in a distinct way than the traditional power system. Due to the independence of each microgrid to the main grid, which is derived from its ability of intentional islanding in case of disruptions either inside or outside the microgrid, the future power system will be much more reliable than its predecessor. 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 future electricity infrastructure, which will allow more RES with less predictable power output to be deployed.

Acknowledgment

Our work is related to that of two main groups of researchers that apply MAS to power engineering. Energy research Center of the Netherlands (ECN) devised the PowerMatcher [7], a market-based control concept for supply and demand matching in electricity networks, which is able to reduce imbalance costs in commercial portfolios. National Technical University of Athens (NTUA) studies the operation of a multiagent system for the control of a Microgrid, which optimizes energy exchange between the production units of the microgrid and the local loads, as well as the main grid [8]. While the former one puts emphasis on the structure of MAS for power system and the software architecture of different agents, the latter one attaches great importance to the market operation of the microgrid and bidding mechanism of resource agents. Our work presented in this paper aims at incorporating the interests of both previous studies, as well as constructing a distributed open software platform for the future electricity

infrastructure, enabling the involvement of other delegate MAS with operation goals of power quality and protection.

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