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Fuzzy-Based Adaptive Pricing Rules for a Typical Microgrid Energy Management System

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***Abstract*—This paper details the implementation of adaptive pricing rules for a typical autonomous microgrid that aims at generating competitive prices based on monitoring the microgrid's operation conditions. The proposed pricing mechanism aims at maximising the profit from selling electricity to the utility grid, and also maximising the amount of sold electricity throughout the microgrid's lifetime. Therefore, the generated prices are developed based on predicting the demand and evaluating the local generation cost and local generation availability of the installed renewable energy sources. A decision tree based linear programming and fuzzy system are developed to generate competitive prices that maximise the chance of participation in the markets and achieve satisfactory profit. To simulate the behaviour of the markets, we have implemented a Multi-Agent System (MAS) to represent the performance of two competitive sellers and one buyer under the uniform and the discriminatory pricing rules. As a case study, our proposed pricing rules are tested on the power grid of the Joondalup campus of Edith Cowan University in Western Australia. Simulation studies for 30-minutes operation intervals for the developed virtual energy market pool and adaptive microgird pricing strategies have recorded beneficiary sale prices with a reasonable number of electricity trade participations.**

NOMENCLATURE

$Dmnd$	**Electricity Demand**
ETP	**Electricity Trade Participation**
$FLAPR$	**Fuzzy Logic Based Adaptive Pricing Rules**
$FLRdyFrSLElec$	**Fuzzy Logic Based Ready for Sale Electricity**
$FLSL_P$	**Fuzzy Logic Based Sale Price**
G_G	**Gas Generation**
G_P	**Gas Generation Price**
LG_P	**Local Generation Price**
$MoAn$	**Maintenace and Operating Annual Fixed Cost**
MoV	**Maintenace and Operating Variable Cost**
NPR	**Normal Pricing Rules**
Ph_G	**Photovoltaics Generation**
$RdyFrSLElec$	**Ready for Sale Electricity**
RFS	**Ready for Sale Energy**
SL_P	**Sale Price**
$SLDElec$	**Sold Electricity**
S_P	**Storage Devices Generation Price**
S_G	**Storage Devices Generation**
TV	**Trade Value**
Up	**Utility Generation Price**
U_G	**Utility Generation**
G	**Variable Gas Price**
W_G	**Wind Turbines Generation**

I. INTRODUCTION

The smart utilisation for the electricity prices deregulation yields performing a sufficient energy management for typical autonomous power systems. It is also essential to increase its operation reliability and reduce its overall cost of generation. The current Australian energy markets are operating based on the rules that have been developed by Australian Energy Market Commission based on pricing rules applied depending on the place and the size of energy trade. In the eastern states, the Australian Energy Market Operator [3] is the pool that hosts the generated bids from the retailers based on a vertical demand auction mechanism and a uniform pricing rule. Whereas in the state of Western Australia, Synergy [16] is the largest energy retailer, and it is mainly responsible for providing services to the biggest metropolitan areas in Western Australia. Generally, the electricity auctions are divided into vertical and horizontal auctions. In horizontal auctions, the daily demand for a particular demand zone is partitioned by its durations, which considers a distinct lot for each time frame. Whereas in case of the vertical auction, the daily demand is divided into hourly demand lots, where each hour demand lot contains the full demand of that particular demand zone. In both types of auctions, the prices are generated based on two pricing rules: 1) the uniform rules, which allow the auction winners to pay the highest accepted bidding price, 2) the discriminatory pricing rule, which allows the winners to pay their own proposed bids. In Australia, the demand is bundled vertically and the bids are generated based on the uniform pricing rule. Obtaining the information about the electricity markets will help in formulating the pricing rules for the deregulated markets, which will eventually play a substantial part in providing reliable and economic electricity generation for the decentralised energy systems. Engineers and researchers have investigated this issue with different approaches. Developing energy management system that relies on the spot electricity market in its optimum decisions has been proposed in [13]. A market-based mechanism to allow single microgrid operator to control the behaviour of the internal loads has been proposed in [11], [12]. Various marketing strategies for microgrid power market such as spot marketing and pricing that can be applied to predict and ensure its economic viability have been discussed in [15]. [6] has proposed fuzzy logic and integer programming solver to introduce a new price formulation based unit commitment of electric power generators under a deregulated electricity market. By considering the dynamic electricity change and monitoring the effective factors on changing the prices, different approaches can be utilised to build smart integration for the local generation units with the utility grid. A price-based open-loop control signal to facilitate significantly increasing distributed energy resources penetration in the power system by coordinating their participation in electricity markets while also maintaining the local system energy balance has been discussed in [5]. In addition, having the right method to generate competitive bids in a competitive market environment can increase the range of electricity trade for the managed power system. [10] has proposed an electricity market oriented tool that creates bidding strategies in a competitive market environment by combining fuzzy logic and deterministic approaches, and [4] has proposed pricing analyser and generator to generate competitve bids in competitive electricity markets. A novel fuzzy modelling approach to generate strategic biddings to handle uncertainty in market parameters such as load demand, generator bid, power dispatch, price, cost, revenue and profit has been detailed in [17].

In this paper, we are going to detail a new pricing method and verify the results with a targeted case study. Therefore, section II of this paper shows the principles of MAS technology and their proposed operation mechanism. Section IV shows the proposed management system architecture with its expected operation scenarios. Section V details the pricing equations formulation and the fuzzy rules design. Sections III details the methods of generating the case study simulation data. Finally, sections VI and VII will discuss the results and give a final conclusion about this work with future recommended extensions.

II. Multi Agent System Technology

In computer science dictionary, the term Agent refers to a software component that operates autonomously and behaves with predefined behaviours. Agents generally carry several characteristics such being addressable, autonomous, adaptive, social, mobile, communicative and accessible. These characteristics yields the agents to be interactive small parts of a larger software component called “Multi-Agent System ” (MAS) to perform more complicated tasks with common- or multi-objective goals. Agents’ operation mechanism may depend on the information exchanged with external sources, or even with other agents within the same agents’ framework. Several operation standards for the agent development have been introduced by the research communities in this field. The Foundation for Intelligent Physical Agents (FIPA) [1], which is one of the IEEE standard committees, is found to be very active in this firm. What make the Agents unique are their social characteristics, whereas predefined settings that suit the type and the size of the exchanged messages can also be defined by developing a communication vocabulary called "$Ontology$". The ontologies are used to perform coding and decoding for the complex exchanged messages among the proposed agents. In addition, social behaviours can be defined to suit the operation mechanism of the proposed MAS. In our research field, this technology has been widely utilised in developing distributed energy management systems. MAS has been used to perform a microgrid power management in [9], [8]. MAS has also been utilised to simulate the electricity markets auctions in order to run a distributed agents based control for managing the generation resources economically in [14].

In this work, we will use MAS to perform the electricity trade mechanism. Hence the proposed mechanism considers the competitiveness in selling electricity in a spot market pool. The proposed negotiation mechanism is developed to generate Call For Proposals (CFP) messages, which are sent to all participant sellers that are registered with the pool under a common predefined service. In this work we have created "$ElectricityTrade$" service, where each pool participant must be registered under this service to receive the right messages in the right time. When CFP are received, the sellers will reply with either an $acceptance$ or a $rejection$. Depending on the situation at each seller, in case of acceptance, the proposal should include informative details about the proposed offer. Figure 1 the proposed negotiation software sequence. Based on our conservative simulation assumptions, we are expecting at least one of the participants to receive the $rejection$ under the discriminatory pricing rules. Therefore, the software sequence is designed to serve the sellers have the ability to regenerate more competitive prices in the next CFP round. At this stage, CFP generation has not been discussed in this work, and will be discussed in future works.

III. Case Study

To simulate our proposed system, we found it impractical to obtain realistic historical operation data for an electricity market that does not exist yet. Therefore we aimed at generating our semi-realistic operation data based on realistic historical operation data for a typical microgrid including: the weather conditions, generation cost and electricity demand in the studied microgrid. In our investigation, we target a medium size enterprise microgrid as a case study to identify our strategic pricing decisions. The power grid of Edith Cowan University in Joondalup Campus in Western Australia is selected as a case study for simulating the operation scenarios. The first step in our evaluation is identifying the demand patterns in the case study, then evaluating the possibilities of integrating the onsite installed distributed generators. Based on our planning considerations, we could install up to 3964 units of our nominated solar panel product based on their estimated required size of 1318 x 994 x 46 mm, which takes about 5193.2 m^2 from the available on-roof spaces in the campus. For wind turbines, the nominated generation unit size is 4 m rotor diameter. Based on the available onsite installation space, we could utilise 300 m^2 for each wind turbine, to perform the best generation efficiency [7], allowing 56 wind turbines to be installed in this project. The utilised onsite installation

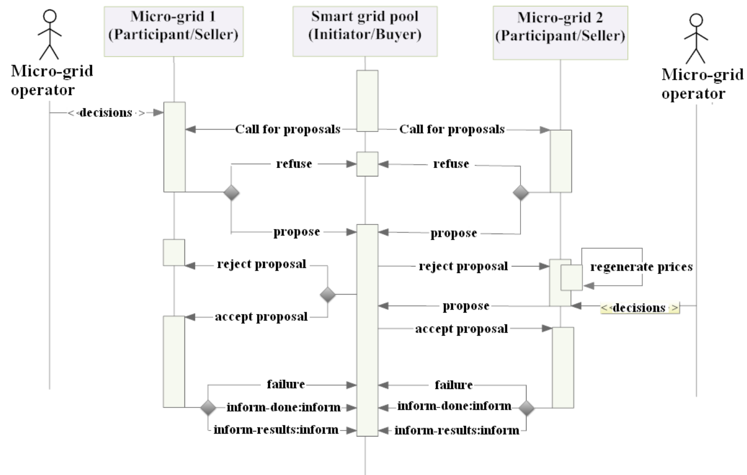

Figure 1. Proposed electronic negotiation software sequence

space in the case study takes about 21,193 m^2 of the campus land space. Identifying that the maximum demand at ECU approaches 3 MW, it is also proposed to install 7 Gas gen-sets, each with 0.5MW dispatch capacity, to safely supply the electricity based on 7 demand lots. In case of storage devices, we have estimated that we could install units to cover 0.35 MW of the total required generation capacity.

The other major pricing problem is evaluating the local generation price based combining the availability of renewable resources and the variable gas generation price. In case of the gas price in Western Australia, we could access [16] to estimate the gas generation price. To utilise the collected data into the local generation price analyses, we would firstly convert the units of gas supply into Nm^3/hr to follow the gen-sets fuel consumption standard units:

$$1Nm^3/h = 0.031736Gj \tag{1}$$

For our proposed size of gen sets, we expect 500kWh of generation capacity. Therefore, it is expect to have 137.6 Nm^3/h of Natural Gas, where the final generation cost is evaluated as following:

$$G_p = G + MoV + MoAn \tag{2}$$

where the cost is evaluated in $/kWh. In case of the utility variable price, we also found it impractical to collect realistic dynamic energy price changes in Western Australia. Therefore, we utilise to the current utility price, but multiply it with the current dynamic National Electricity Market (NEM) price in the eastern Australian states, which is provided by AEMO. In case of the installed renewable sources generation availability, we looked at the historical trends of the weather conditions for 30 minutes operation interval including the average wind speed and direction, average solar irradiation and clouds availability. From the average evaluated trends and the predefined settings for a randomly generated wind speed and solar irradiation data, we could establish our semi-realistic simulation data in this work. In case of the studied microgrid demand estimation, we used a 30-minutes interval demand prediction model, which has been developed from the realistic historical operation data for the case study.. Table I illustrates the identified generation capacity limits for the managed resources in the studied microgrid.

Table I
THE IDENTIFIED GENERATION CAPACITY FOR THE MANAGED RESOURCES IN THE MANAGED MICROGRID

Source	Capacity
G_P	0-$Dmnd$
Ph_G	0-310
W_G	0-250
S_G	0-350
U_G	0-$Dmnd$

IV. POSSIBLE SCENARIOS AND RULE BASE SYSTEM

At this stage we introduce the decision rule base for the economic concerns, where the environmental concerns are added in future extended works of this work. Having storage devices among the dispatch units will increase the complicate the rules of the system due to the uncertainty charging charging/discharging price and time. We start by classifying the demand into three different levels: 0) less than the available renewable energy sources generation, 1) more than the renewable energy sources generation and less than the renewable energy sources together with the storage devices generation, 2) more than the renewable energy sources together with the storage devices generation. Hence these classified operation scenarios are subject to other cost conditions: gas, storage devices and utility generation cost. Including these dynamic price changes would add complexity to the rules. In all cases, the first sub-classification consideration is the result of comparing the local gas gen-sets cost with the external utility generation cost. The second consideration is the result of comparing the storage devices cost with the local onsite gas gen-sets generation cost. The results of these comparisons draw the pricing limits and nominate the optimal generation sources to maximise the benefits and cut the generation cost for the managed microgrid. Figure 2 shows the decisions tree

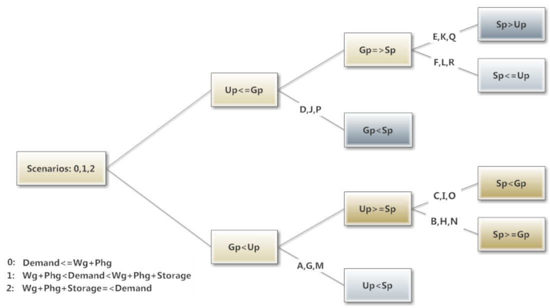

Figure 2. The decisions tree for the classified demand levels as compared with renewable energy sources and storage devices generation capacity scenarios

Table IV
ELECTRICITY PRICES ADAPTATION FUZZY RULE BASE SYSTEM

$SLp\backslash RdyFrSLElec$	S	M	L
S	S	S	M
M	S	M	L
L	M	L	L

for the possible expected operating scenarios in the managed microgrid.

To relate the numbers with the letters in Figure 2, Table II details the possible expected operation cost scenarios. Each of the scenarios is named and referred in the derived operation equations in the next section to make suitable decisions.

V. Decisions and Export Pricing Equations Formulation

A. Pricing Equations

Based on the classified operation scenarios, we built our proposed pricing rules. The rules are proposed to perform a compromised profit with competitive export prices. Based on the implemented rule base for the operation scenarios, we formulate different price equations at each operation scenario. Table III illustrates the formulated equations that evaluate the possible amount of exported energy in every operation scenario, attached with their formulated pricing equations.

The made decisions are sent as proposed offers to the utility energy market pool for further energy trade decisions as illustrated in Figure 1.

B. Adaptive Pricing Rules Fuzzy System

In order to perform the adaptive pricing rules, we relate the amount of Ready For Sale Electricity ($RdyFrSLElec$) to the instantly generated sale price to generate competitive prices. A fuzzy system has been developed to represent this relationship through the illustrated rules in Table IV.

To introduce the nominated fuzzy inputs, we normalise the first input sale price (SLp) by relating it to the utility price(U_P):

$$FLSLp = \frac{(U_P - SLp)}{U_P} \tag{3}$$

and the second input $RdyFrSLElec$ to the amount of full generation capacity (3000 kWh):

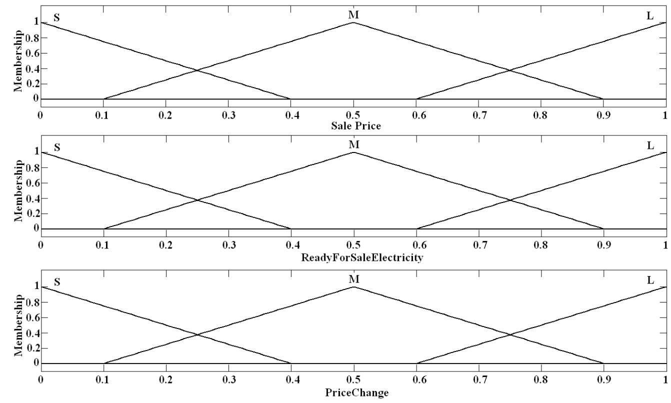

Figure 3. Adaptive pricing rules fuzzy membership functions

$$FLRdyFrSLElec = \frac{(3000 - RdyFrSLElec)}{3000} \tag{4}$$

The proposed simple membership functions that represent the normalised input values are illustrated in Figure 3.

VI. Results

Based on the microgrids' operation scenarios, we have established a range of operation results for each of the participating generation units throughout the year. For simplicity, we would only present a typical one week of load profile, which would give an informative figure of the attitude of the case study. For the price decisions, we established compromised pricing rules that perform beneficial electricity export depending on the number of the accepted electricity trade proposals between the microgrid and the utility grid. To evaluate the robustness of these rules, we have evaluated the number of Call For Proposals (CFP) in the simulated period of time. Then, we have also verified the pricing rules against the expected operation scenarios in the managed microgrid. Since the rules are dependent on the difference between the local generation price and the offered external utility buying price, we found our pricing decisions within this range. Figure 4 illustrates the range of generated sale prices in a one week simulation time.

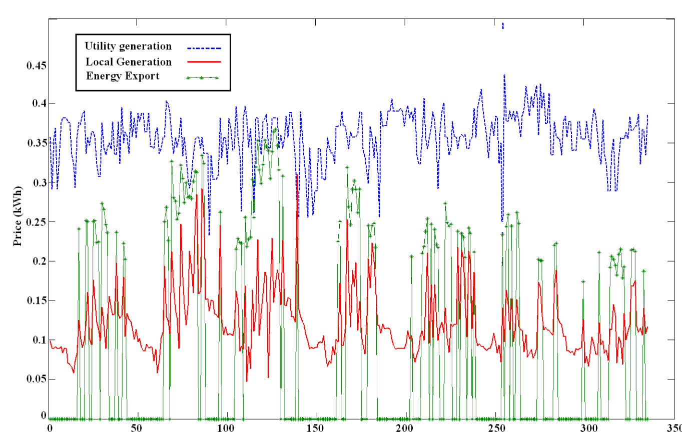

Figure 4. Price decisions profile for a typical one week operation scenarios

Table II
POSSIBLE EXPECTED OPERATION COST SCENARIOS; WITH REGARDS TO THE LEVEL OF EXPECTED DEMAND THE MANAGED MICROGRID

Price scenarios\\$Dmnd$(0,1,2)	(0) $Ph_G + W_G \geqslant Dmnd$	(1) $Ph_G + W_G < Dmnd < Ph_G + W_G + S_G$	(2) $Dmnd \geqslant Ph_G + W_G + S_G$
$G_P < U_P < S_P$	A	G	M
$G_P < S_P < U_P$	B	H	N
$S_P < G_P < U_P$	C	I	O
$U_P < G_P < S_P$	D	J	P
$U_P < S_P < G_P$	E	K	Q
$S_P < U_P < G_P$	F	L	R

Table III
FORMULATED EQUATIONS ABOUT DECIDING THE AMOUNT OF EXPORTED ENERGY WITH ITS PRICE DECISIONS

\\Decision Scenario	LG_P	$RdyFrSLElec$	SLp
A	0	$G_G + Ph_G + W_G - Dmnd$	$(\frac{(U_P - G_P) * G_G}{2 * RFS})$
B	0	$G_G + S_G + Ph_G + W_G - Dmnd$	$U_P - \frac{(U_P - \frac{((G_P + (S_P - G_P) * (S_G) * (G_G + S_G)}{G_G * RFS})}{2}$
C	0	$G_G + S_G + Ph_G + W_G - Dmnd$	$U_P - \frac{(U_P - \frac{((S_P + (G_P - SP) * (S_G) * (G_G + S_G)}{G_G * RFS})}{2}$
D	0	$Ph_G + W_G - Dmnd$	$S_P - (\frac{G_P * (S_P - G_P)}{S_P + G_P}) - 0.02$ if $(Pr >= U_P)$ then $U_P * 0.98$
E	0	$Ph_G + W_G - Dmnd$	$S_P + (\frac{G_P * (G_P - S_P)}{S_P + G_P}) - 0.02$ if $(Pr >= U_P)$ then$U_P * 0.98$
F	0	$S_G + Ph_G + W_G - Dmnd$	$S_G + (\frac{(U_P - S_P) * S_G}{2 * RFS})$
G	$G_P * (\frac{G_{SG}}{Dmnd})$	$G_G - G_{SG}$	$U_G - (\frac{(U_P - G_P)}{2})$
H	$G_P * \frac{G_{SG}}{G_G + Ph_G + W_G}$	$G_G - G_{SG} + S_G$	$U_P - \frac{(U_P - \frac{((G_P + (G_P - S_P) * (S_G) * (Dmnd - (Ph_G + W_G + S_G))}{G_G * RFS * (G_G - G_{SG})})}{2}$
I	$\frac{S_P * S_G}{Dmnd}$	$S_G + Ph_G + W_G - Dmnd + G_G$	$U_P - (\frac{U_P G_G + S_P S_P - G_P G_G - G_G S_P}{2 * G_G})$
J	$\frac{U_P * U_G}{Dmnd}$	0	-
K	$\frac{U_P * U_G}{Dmnd}$	0	-
L	$S_P * (\frac{Dmnd - (Ph_G + W_G)}{Dmnd})$	$S_G + Ph_G + W_G - Dmnd$	$U_P - \frac{U_P - S_P}{2}$
M	$G_P * (\frac{Dmnd - (Ph_G + W_G)}{Dmnd})$	$G_G - G_{SG}$	$U_P - \frac{U_P - G_P}{2}$
N	$G_P * \frac{G_{SG}}{Dmnd}$	$G_G - G_{SG} - S_G$	$U_P - (\frac{2U_P + S_P - G_P}{4})$
O	$G_P - (\frac{S_G(G_P - S_P)}{Dmnd})$	$G_G - G_{SG}$	$U_P - (\frac{U_P - G_P}{2})$
P	$U_P * (\frac{U_G}{Dmnd})$	0	-
Q	$U_P * (\frac{U_G}{Dmnd})$	0	-
R	$U_P * (\frac{Dmnd - (Ph_G + W_G)}{Dmnd})$	0	-

Table V
ELECTRICITY TRADE PROFILE WITH TWO TYPES OF PRICING RULES

Results\\Pricing type	Discriminatory rule		Uniform rule	
	NPR	$FLAPR$	NPR	$FLAPR$
ETP	13	107	96	107
$SLDElec$	19252	180552	160282	180552
TV \$/kWh	5351	44674	43963	44674

In the next stage, we have simulated the implemented MAS as an energy management system that performs the electronic negotiation and represents the managed microgrid as a competitive seller in the electricity spot market pool. Afterwards, a random function has been utilised, with a predefined settings to reflect the nature of the electricity trade with CFP signals. Eventually, based on the nature of the CFP attitude, we found our pricing agent offering a range amounts at different times with different prices. We have also verified the operation of the fuzzy based adaptive pricing rules with the normal pricing rules. The results showed that the fuzzy based pricing rules have generated more competitive prices, which have eventually recorded a higher number of trade participations with the utility than the normal pricing rules during the same simulation period.

In the simulation, we used two sellers. The first seller generates offers based on the normal pricing rules, while the second seller generates offers based on the fuzzy system adaptive pricing rules. Java Agent DEvelopement Framework (JADE) [2] has been used to simulate the proposed agents system with our developed pricing rules code. Figure 5 illustrates a JADE based simulated trade negotiation. It also includes best offered prices sellers selection process by the utility (buyer).

From the recorded results, we found that the proposed fuzzy based pricing rules could increase the number of the trade participations in a month of operation time, which would eventually increase the amount of sold electricity from the microgrid to the utility. Table V shows the performance comparison between the normal pricing rules and the fuzzy system based adaptive pricing rules, each are tested under the discriminatory and the uniform pricing rules.

The results also showed that the fuzzy based pricing rules have reduced the sale price with average of 18.78 %, but however, they have increased the number of trade participations by

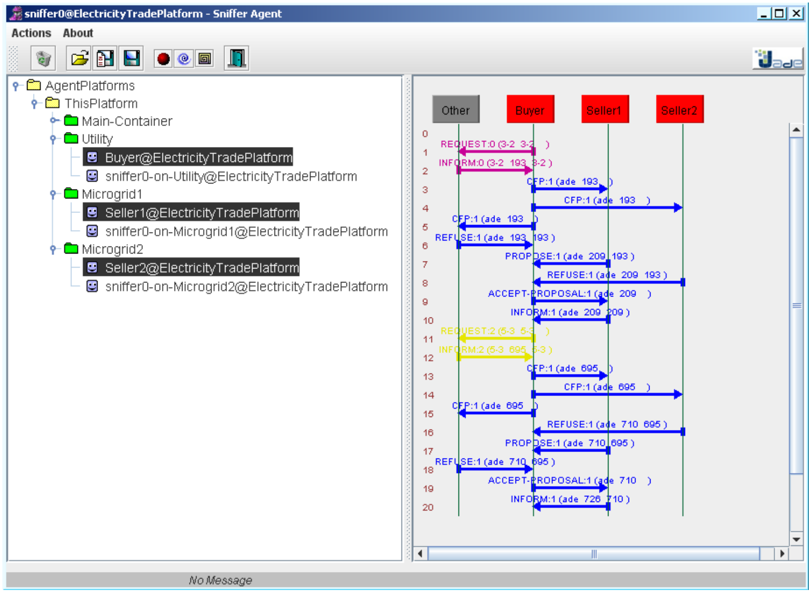

Figure 5. Smart electricity trade process using multi-agent technology

11.4%, and have also increased the amount of sold electricity by 12.6 % under the Uniform Pricing Rules. In case of the Discriminatory Pricing Rules, the fuzzy based adaptive pricing rules have recorded the number of trade participations, accept there were 13 trade participations where the normal pricing rules were the winners in selling the electricity to the grid.

VII. Conclusion

In this paper we have formulated smart pricing equations that aim at generating competitive sale prices for selling the electricity from the local distributed generators within a typical microgrid to the utility grid. The algorithms have been formulated using a derived decision tree based linear programming and fuzzy system to adapt these decisions to the microgrid's sale price and the availability of ready for sale electricity. The formulated equations have been simulated using MAS due to their ability to resemble the intelligent behaviours of the electronic negotiation between the microgrid management system and the utility spot market pool. Based on the semi-realistic operation data in the simulated period of operation, a set of pricing decision figures have been identified. The results have proved that the fuzzy based pricing rules are generating more competitive prices than the normal pricing rules and attracting more interests from the market pool buyer. In this work, we have targeted the economic concerns, where the environmental concerns can be added in further extensions of this work.

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