Price and Time-Slot Negotiation Protocol for EVs Charging in Highly Congested Distribution Networks

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***Abstract*—This paper presents a multi-issue bargaining mechanism in order to negotiate simultaneously the price and time-slot for electric vehicles (EVs) charging in congested power distribution networks. Alleviating the need for investments in distribution infrastructure to install EV chargers, an aggregator coordinating EVs provides flexibility to the system and reduces congestion. The proposed negotiation algorithm is based on well known Rubinstein alternating offers which is implemented and tested using a simple case scenario between EV and aggregator. Results achieved validates application of proposed negotiation mechanism for EV charging systems. Moreover, the general detailed description of the protocol as well as the implemented utility functions in this paper could expand its viability for more complex applications.**

***Index Terms* – electric vehicles, charging systems, energy trading, transactive energy, congestion management.**

I. INTRODUCTION

Transactive energy has been one of the most widely debated disciplines in the recent years. There is not a single definition of this term. However, Edison Electric Institute [1] proposal is fairly general and integrates in a holistic way all the tendencies present in this very broad concept that is in itself a highly multidisciplinary field of study. Basically, referring to the term transactive energy means grouping a set of economic management techniques that are combined with traditional control techniques which allow an integral management of power systems.

Among the tools provided by this new power system control framework, there is a vast set which is related to trading techniques. Even when electrical markets and trading techniques are widely implemented at transmission level in nearly all developed power systems, the degree of penetration of these techniques in real terminal distribution systems is still marginal due to several reasons listed hereafter; 1) The lack of regulation, or in many cases the existence of a very restrictive one. 2) The size of the data generated by the terminal distribution systems containing from hundreds to million nodes and users. 3) The latency with which we obtain data, that is far from real time in the majority of cases. 4) The heterogeneity of the different devices present in the distribution network and in many cases the impossibility of their remote operation.

The adverse conditions described above may be a delay, but in no way represent a medium-term brake on this new paradigm of electrical systems operation. This system advances in an unstoppable way supported by emerging technologies such as all those related to the internet of things, big data management systems, fast, robust and efficient communications, artificial intelligence, blockchain technology, the development of distributed generation and energy storage systems, electric vehicles, ...among others.

The efforts of the researchers during the last years proposing and implementing new solutions have been tremendous. A huge part of these efforts was invested in investigation related to the peer-to-peer energy trading as a tool to coordinate different agents participating in the terminal distribution network. A good set of examples are provided in [2]. The case presented in [3] proposes a trading system codified using blockchain technology in order to trade with the reactive power injected by PV generators in a microgrid. An open code example of how to implement a simple blockchain-based trading platform can be observed in [4]. In [5], the researchers use a transactive energy approach to coordinate the charging/discharging of the energy storage systems and the electric vehicles in commercial buildings considering some uncertainties for instance, those coming from PV generation. The framework proposed in [6] allows the coordination of a set of residential buildings trading with the energy stored in the PV storage systems. In most of the cases, the authors focus their proposal in solving a specific problem since the coordination of the entire system is too broad a problem to be attacked in a single work. Even the research works that propose a "general framework", like the one presented in [7] for coordinating a distribution system combining optimal power flow with transactive energy trading, assume a large set of simplifications of the real problem.

A common denominator of all research works is the implementation of some kind of market mechanism applied to the flexible loads. The basic differences between the proposals lie in: 1) the agents involved in the market mechanism; 2) the time-horizon in which the market is operated (real-time, day ahead,...); 3) the rules applied to the market; 4) the level of hierarchy of the system (a central agent controls the system or it is controlled in a distributed way).

The work proposed in this paper is mainly focused on the coordination of the EVs in a congested distribution system in which the buildings represent the critical loads and the EVs provide some flexibility. Of course, with such perspective, the work is not new since there are many researchers that propose different techniques to implement this coordination. For instance, the work presented in [8] proposes a framework in which the aggregators run the market where the prosumers participate. The DSO operates the distribution network and an external agent has the role of price coordinator. The idea is to operate the network fulfilling all physical constraints using the price signal among

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the other parameters. In [9], a market mechanism proposes the interaction between the EV aggregators and TSOs. The solution proposed in [10] allows the consumers to create coalitions in a multi-agent environment. These coalitions of prosumers are able to negotiate with each other. Probably, one of the most sophisticated approaches is the one presented in [11], in which the authors use a price signal as indirect control of the EV owners managed by aggregators. As a conclusion, the authors state that the monopolistic profitability of the aggregator must be somehow limited in order to guaranty an adequate competition in the market. Among the above-described research works, we find cases in which the charging schedule is determined by using different market mechanisms. However, in none of them, the trading mechanism consider simultaneously the price and time-slot negotiation. Therefore, this is the contribution of the presented work. This combined price and time-slot negotiation has been employed in the last years to determine the optimal cloud services reservation (see for instance the work presented in [12] that constitutes the conceptual basis of our proposal). However, this is the first time that this multi-issue bargaining technique is being implemented in a transactive energy environment.

The document is structured as follows. In section II, the specific problem in which we applied the proposed negotiation protocol, is stated. Of course, this problem is a simplification of the real case scenario but it is still valid to test the performance of the price and time-slot negotiation protocol presented in section III. In section IV, the description of the utility functions used during the bargaining process are presented. In section V, the performance of the implemented negotiation protocol is analysed and the conclusions are discussed in section VI.

II. Problem Statement

The scenario selected to test the system is a typical urban distribution network. In Fig. 1, a real network is represented in the top left corner. This network is a portion of a real network operated by EDP in Spain containing 30 power transformer stations and around 8500 customers. The details about this network can be found in [13]. As it can be observed, European low voltage networks are operated in small islands fed through power transformers. It must be considered that the elements belonging to a specific island may vary depending on the position of the breakers (BR) in the secondary side of the power transformer. Usually, each island contains several four wires three-phase feeders (F.1, F.2,..) protected by a set of fuses (F_{F1}, F_{F2},...). Each feeder can be monitored by means of an advanced supervisor monitoring equipment (here labeled as M_{F1}, M_{F2},...). Buildings have mostly three-phase connections however, most of the loads and also the end-users inside the buildings (L_1,...,L_6) are single phase unbalancing the total load. Usually each building is protected by a set of three-phase fuses (see for instance F_{L4}) and each individual user also has its own fuse protection (See for instance F_{B1}) and its own advance metering infrastructure (see for instance M_1). As a general data, we could state that the average distance from the power transformer to the connection points is less than 300 meters with around 25 buildings per power stations distributed in around 4 feeders. In many cases, the feeders are highly congested during the peak hours and it is not possible to add more loads, like the ones represented by the EV chargers without deploying new infrastructure or making new investments in the existing one. This situation prevents the DSOs from installing public EV chargers in a massive way. However, according to statistics, the average load during the whole day of the different feeders is less than 10%. That is the reason why flexible loads may help to reduce the congestion and make the system more receptive to embed new loads.

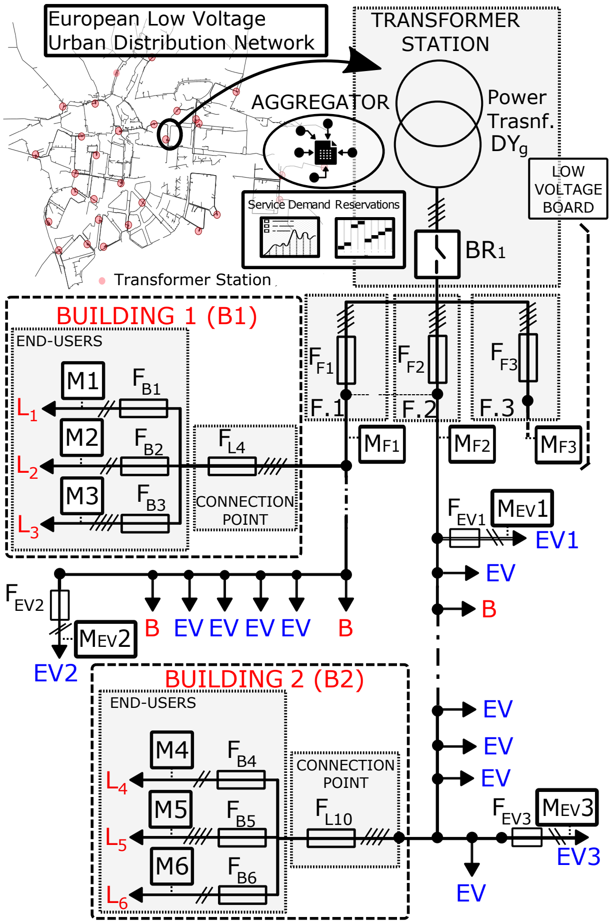

Fig. 1: European low voltage urban distribution network representing the case defined in the problem statement.

In this specific case of study, the existing buildings labeled in red in Fig. 1 represent the critical loads and that should be fed under all circumstances. Electric vehicles (in blue) will represent flexible loads that will negotiate with the aggregator the price and the time-slot in which they are going to receive the requested power. As it is mentioned earlier, this scenario is quite simple yet representing a real problem. The target of the aggregator will be to minimize the non-supplied energy fulfilling all the physical constraints defined by the DSO. To achieve this, the aggregator will use price signals and the proposed multi-issue negotiation technique to determine the price of the energy supplied and the charging period for each of the electric vehicles connected to the system. Even if the ultimate goal of the aggregator is to obtain an economic benefit. This benefit is limited by a pre-set range of variation in price signals and the imperative to minimize as much as possible the energy not supplied to flexible loads. This is a common practice in monopolistic scenarios such as the one we are discussing [11].

III. Alternating Offers Protocol

Each EV owner will have a specific contract in which all the parameters that define its negotiation strategy will be determined. The full set of parameters will be described later in this paper. However in this section, and for the sake of simplicity let us assume that when the vehicle is connected, the aggregator will receive the information from the vehicle that will cross with the one provided by the metering infrastructure and the forecast energy in order to adapt in real time its negotiation strategy. It is far beyond the scope of this paper to define the forecasting techniques or the negotiation strategy of the aggregator and the one defined in the contracts of the EV owners. This work focuses in defining the negotiation protocol but not the negotiation strategy that should be addressed in future works. In addition, in this specific case of study, and due to the limited number of vehicles that can be connected to a feeder and the high speed of the negotiation algorithm (demonstrated later), the negotiation between the EVs and the aggregator will be made in a sequential way using a first in first out strategy (FIFO). The first vehicle connected will be the first starting the negotiation with the aggregator, this will not reduce the generality of the methodology that could be used under other premises for instance parallel negotiations.

The proposed price and time-slot negotiation protocol is based on Rubinstein alternating offers protocol [14], with the whole procedure shown in Algorithm 1. Rubinstein alternating offers is a bargaining model which presents perfect equilibrium solution (see [15]) to a bargaining problem that is to find an agreement upon which the payoff of each agent is no less than the payoff received from the disagreement. This protocol is well recognized and extensively applied to automated negotiations in different fields [7], [12].

In Algorithm 1, the agents are referred as $Agent1$ ($A1$) and $Agent2$ ($A2$). $A1$ and $A2$ represent the EVs and AG. $A1$ will be the one that make the offer and $A2$ the one that evaluate the offer. $A1$ is initialised to be the EV and $A2$ to be the AG but these roles will be switched in the successive rounds. In this specific case and w.l.o.g., EV is selected as the agent that starts the negotiation. Both agents will set their initial preferences and time ranges for each negotiation process. These preferences consists mainly in the initial and reserve prices (IP, RP) and the first and last time slot (FT, LT) selected for this negotiation by each agent. Apart from the previous parameters, there are other parameters that define the negotiation strategy. For instance, agents utility ranges (U_{min}, U_{max}) and (λ) that will be defined in the next paragraphs. EV will query the AG for the set of available time slots (T_a) depending on its required power and its charging time horizon. In order to compute the available time slots, the AG will use real measurements from the critical loads and other EVs, information about already reserved time slots by other EVs and forecast values. If the set of available time-slots is not empty, them both agents fix a deadline (τ) for the negotiation (expressing the number of allowed rounds) and the initialise the first round $(t = 1)$ of the negotiation process.

$A1$ (EV in the first round) will update it expected utility $U^{Ag1}_{exp,t}$. The expected utility in the first round is always the maximum. The agents diminish their expected utility through the successive negotiation rounds according to a concession protocol determined by the next expression. The parameter λ determines the negotiation strategy.

$$U^{t+1}_{exp} = U^{t}_{exp} - U^{t}_{exp} \cdot \left(\frac{t}{\tau}\right)^{\lambda} \tag{1}$$

The EV evaluates the sets of available time-slots if any, and generates an offer containing multiple concurrent proposals of time slots and prices in a so called burst offer generation procedure. These proposals should maximize the EV utility being the target utility the expected utility (U_{exp}). In the first round the expected utility is the maximum one. Each agent can calculate the utility (U) obtained from a set of (P, T) by means of its utility function $U := f(P, T)$ (a deep description of the utility functions is provided in the next section). Inversely, an agent can generate an offer containing a set of (P, T) using the inverse of its utility function $(P, T) := f^{-1}(U)$. It must be remarked that there is no analytical expressions for these inverse functions, in many occasions, the calculations involve complex optimization methods that return approximated results. In short, we could state that f^{-1} functions are used for creating offers while f functions are used of evaluate offers.

Algorithm 1 Multi-Issue Negotiation Mechanism

Input: $(IP, RP, FT, LT, U_{min}, U_{max}, \lambda, \tau)$ for EV and AG.
Output: (P, T) final price and reserved time-slots.

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1:  EV query AG for the avialable time slots $(T_a)$.
2:  AG obtain $(T_a)$ and send to EV.
3:  $t \Leftarrow 0$; Set $Agent1 = EV$ & $Agent2 = AG$.
4:  if $T_a$ is empty then
5:      Process terminated, no agreement.
6:  else
7:      $t \Leftarrow t + 1$ Update negotiation round.
8:      Update $Agent1$ utility $U^{A1}_{exp,t}$
9:      $(P, T) := f^{-1}_{Ag1}(U^{A1}_{exp,t})$ $Agent1$ burst offer generation.
10:     $U^{A2}_{x,t} := f_{A2}(P, T)$ $Agent2$ burst offer evaluation.
11:     if $(t = \tau$ & $U^{A2}_{x,t} < U^{A2}_{min})$ then
12:         Process terminated, no agreement.
13:     else if $(t = \tau$ & $U^{A2}_{x,t} \geq U^{A2}_{min}) \mid U^{A2}_{x,t} \geq U^{A2}_{exp,t+1}$ then
14:         Process terminated, agreement reached.
15:     else
16:         Switch EV and AG in $Agent1$ and $Agent2$ roles.
17:         Goto line 7 to create counter-offer.
18:     end if
19: end if
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Once EV generates the burst offer, it is evaluated by the AG that will select the pair of prize and time-slot (P, T) that maximizes its utility. Let us refer to this utility as (U_x). In order to accept the offer or make a counter offer, the AG check first that the negotiation deadline is not violated, in such case the offer is automatically rejected and the negotiation is terminated. Another condition that will trigger an automatic rejection is that the utility obtained by the AG with the best set of (P, T) is lower than the minimum utility accepted by the AG. In case that the agents are in the last allowed negotiation round $(t = \tau)$, the AG will accept automatically the offer if it provides a utility greater or equal than the minimum. Other condition for accepting the offer provides a utility greater than the utility expected in the next round $(U^{AG}_{x,t} \geq U^{AG}_{exp,t+1})$. Otherwise the AG will make a counter proposal, this means that the AG is expecting a utility in the next round higher than the utility provided by the best proposal in the actual round.

IV. UTILITY FUNCTIONS DESCRIPTION

Proposed negotiation algorithm is based on three main functions: Price, Time-slot and Aggregated utility functions which are used to model the preferences of the EV and AG to implement bilateral negotiation strategies acquired in this paper. These utility functions defines the level of satisfaction of the agents in the form of a number between 0 to 1 (low to high) for any negotiation deal. In this section we will describe the above-referred functions.

A. Price Utility Function

Price utility functions for EVs and AG are described below (see 2 and 3). They are similar, however, as it can be observed EV utility is high at low prices while AG utility functions behaves in an opposite way. An agent always get maximum price utility when the price (P) is equal to its initial price (IP) and minimum price utility (u^p_{min}) when P is equal to its reserve (least preferred) price (RP).

$$U_p^{ev}(P)=\begin{cases} u^p_{min}+(1-u^p_{min})\left|\frac{RP-P}{RP-IP}\right|, & IP\leq P\leq RP \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

$$U_p^{ag}(P)=\begin{cases} u^p_{min}+(1-u^p_{min})\left|\frac{P-RP}{IP-RP}\right|, & RP\leq P\leq IP \\ 0, & \text{otherwise} \end{cases} \tag{3}$$

B. Time-Slot Utility Function

Time is another factor governing the decisions of the EV and AG. Both agents define their preferences of charging time of EV, prior to start a negotiation based on these settings. Time utility functions are applied model of these order of preferences.

1) EV's Time-Slot Utility Function: The EV owner establishes the preferred charging time intervals according to its utility function. These preferences can be predefined or set manually. For instance, the expression (3) represents how the utility vary in a given interval of time (x) being T^x_h and T^x_t the starting time slot and the final time slot of that specific time interval. In that specific time interval, the utility reaches its maximum (U^x_m) between time slots T^x_{mh} and T^x_{mt} and decreases outside this interval according to the cited expression in which the coefficient (α^x_h) determines the rate of variation of the utility outside the maximum interval. The function represented in (4) is an example, but other functions could be proposed. The total utility function during the whole horizon of negotiation $(U^{ev}_t(T))$ can be obtained as an aggregation of the different partial utility functions $(U^{ev}_t(T)^x)$. In case of overlap of two partial utility functions, the total utility is defined as the highest of them. The time utility would be zero for that time region where no partial function is defined. This is just a general example of how to build this function but other methodologies may be applied.

$$U^{ev}_t(T)^x=\begin{cases} u^t_{min} & T\leq T^x_h \text{ or } T\geq T^x_t \\ U^x_m & T^x_{mh}\leq T\leq T^x_{mt} \\ U^x_m\cdot\left\{\frac{T-T^x_h}{T^x_{mh}-T^x_h}\right\}^{\alpha^x_h} & T^x_h<T<T^x_{mh} \\ U^x_m\cdot\left\{\frac{T^x_t-T}{T^x_t-T^x_{mt}}\right\}^{\alpha^x_t} & T^x_{mt}<T<T^x_t \end{cases} \tag{4}$$

2) Aggregator's Time-Slot Utility Function: Prioritising the available time for AG depends on several factors since aggregator has the key responsibility to coordinate with grid services, multiple EVs requests and managing the distributed energy produced by the prosumers within the community. Therefore, aggregator's time-slot preferences are based on the following.

Energy Demand and Grid Infrastructure Availability: AG selects the time range specifying LT_P and FT_P, and then splits the time into time-slots. Each time-slot indexed T is assigned with the priority value $V_D(T)$ depending on the aggregated energy demand forecast of the community, actual consumption, grid availability and other factors. The study of the influence of such factors in the priority curve is far beyond the scope of this paper but in general we could state that for higher expected demand or peak time-slots, AG will assign low priority and vice versa. Fig. 2 represent an example of the priority curve and the power forecast for the critical loads.

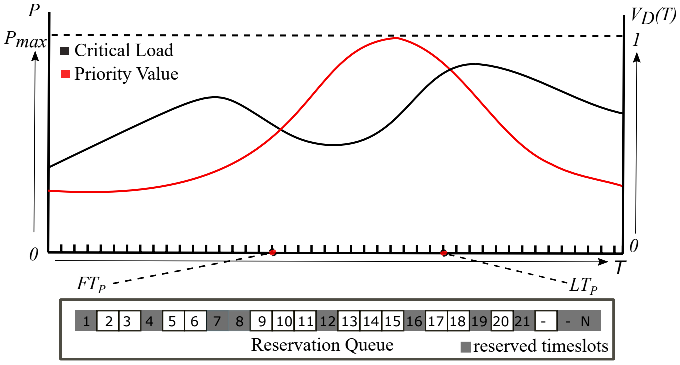

Fig. 2: Prioritised time-slots regarding available power and reservation queue

Time and Energy Devaluation: Since the unused energy would be the loss of revenue for the aggregator therefore it will prefer to reserve the earliest available time-slots.

Request Accommodation: Depending on the EV charging requirements i.e. number of time-slots fulfilling the energy requirement, the request is accommodated to best fit set of the available time-slots. Aggregator prepares the reservation queue for the selected time range which provides information about already reserved time slots and available time-slots. This queue is updated after every successful negotiation when an agreement is confirmed.

Assuming L_J be the requested charging demand by the EV. And L^i_A represents the length of i sets of continuous time-slots available to the aggregator in the reservation queue which fulfills the L_J. Relying on the earlier mentioned three main factors, the available time slots are finally prioritised using (5).

$$V^i=w_D\frac{1}{L_J}\sum_{T=i}^{i+L_j-1}V_D(T)+w_F\frac{LT_P-i}{LT_P-FT_P}+w_B\frac{L_J}{L^i_A} \tag{5}$$

w_D ,w_F and w_B are the weights selected by the aggregator to prioritise i sets of available time-slots satisfying the above mentioned preferences i.e. 1) energy demand and grid infrastructure availability, 2) energy devaluation and 3) request accommodation. Thus, keeping $w_D+w_F+w_B=1$. Based on V^i in equation (5), all indexed i sets of available time slots are prioritised in a way that for highest value of V^i the priority of ith set becomes 1 and for the lowest value of V^i the priority of ith set becomes the last number of the index set. To translate these indices to the time-slots and return the respective priority, a mapping function $f^P_T(T)$ is used. These priorities for the i sets of available time-slots are then transformed to time-slot utility using time utility function in (6).

$$U^{ag}_t(T)=\begin{cases} u^t_{min}+(1-u^t_{min})\left[1-\frac{f^P_T(T)-1}{N^P_{AT}-1}\right], & FT_P\leq T\leq LT_P \\ 0, & \text{otherwise} \end{cases} \tag{6}$$

where u^t_{min} is the minimum utility received by the aggregator for reaching an agreement at its least prioritised time-slot. N^P_{AT} is the total number of available time-slot sets. The utility is zero for all the time-slots which are out of i sets of available time-slots.

Preferences	AG	EV	Preferences	AG	EV
Initial price (IP)	200	10	Price weight (w_P)	0.3	0.3
Reserve price (RP)	10	200	Time-slot weight (w_T)	0.7	0.7
First Time slot (FT)	1	5	Negotiation Strategy (λ)	1	1
Last Time slot (LT)	30	41	Negotiation Deadline(τ)	50	50
Charging Demand (L_J)	3	3	Minimum Utility(u_{min})	0.01	0.01

TABLE I: Preference Settings

C. Total Utility

Both price and time utilities are then adjusted and added up to receive total utility for reaching an agreement after successful negotiation. w_P and w_T are the weights set by the negotiating agents to adjust their respective preferences for price and time utilities, such that $w_P + w_T = 1$. In general, the total utility for a specific agent (EV or AG) can be expressed as:

$$U^{ag}_{total}(P,T) = \begin{cases} 0, \text{ either } U_p(P) = 0 \text{ or } U_t(T) = 0 \\ w_P \cdot U_p(P) + w_T \cdot U_t(T), \text{otherwise} \end{cases} \tag{7}$$

V. NEGOTIATION PROTOCOL PERFORMANCE ANALYSIS

We will present in this section a simple case of study. We will analyze the different negotiation rounds between an AG and an EV. The main parameters of the negotiation round are specified in Table I.

The different negotiation rounds are represented in Table II. EV starts the negotiation trying to maximize its utility, offers its initial price. In the case of the time slots, EV offers the one that provides the maximum utility i.e. $T = 8$ with a time utility of 0.7. According to the weights the total utility of the first offer made by the EV is 0.79. Even when the burst offer mode is activated, in this case there is only one combination that maximises the utility. The EV pass this offer $(P = 10, T = 8)$ to the AG, but this combination produces the minimum utility to the AG (0.01). Despite with the concession that the AG is willing to do in the counter offer, it is expecting to get an utility of 0.98 so the AG decides to make the counter offer $(P = 187.2, T = 7)$ that produces the expected utility 0.98. The process is repeated. In round $(t = 5)$ the EV makes an offer of 0.7 utility. Evidently, in this case the burst mode produces two combinations. Finally the agreement is reached in round 7 with a price of 89.88 and time slot 7 producing a utility of 0.62 for the EV and 0.82 for the AG. Average negotiation time is 30ms per round.

VI. CONCLUSIONS

In this paper a multi-issue negotiation protocol is presented, considering simultaneously price and time-slot during the different negotiation rounds. As previously mentioned, this kind of multi-issue bargaining technique is widely accepted in cloud services reservation environments. However, for the first time, it has been used in a transactive energy environment. This research exploited the similarities of the problem of energy management in a congested distribution network and the use of the limited capacities of cloud services, in order to employ highly effective techniques already implemented in the former case to solve real problems in the latter. A clear limitation of the present work is the simplification of the scenario which is used to test the algorithm (that will be extended in the final paper). However, this does not lessen the generality of the multi-agent framework presented in this paper. Multi-issue negotiation, it is intended to be the cornerstone of an integral terminal distribution network transactive energy-based control system to be developed in future work.

EV	Rounds/Proposals	AG
U_p=1, U_t=0.70. U_{total}=0.79	$\xrightarrow[P=10,T=8]{t=1}$	U_p=0.01, U_t=0.01 U_{total}=0.01, U_{exp}=0.98
U_p=0.076, U_t=0.63 U_{total}=0.46, U_{exp}=0.76	$\xleftarrow[P=187,T=7]{t=2}$	U_p=0.93, U_t=1 U_{total}=0.98
U_p=0.8, U_t=0.70 U_{total}=0.76	$\xrightarrow[P=30,T=8]{t=3}$	U_p=0.11, U_t=0.01 U_{total}=0.04, U_{exp}=0.92
U_p=0.27, U_t=0.63 U_{total}=0.52, U_{exp}=0.70	$\xleftarrow[P=149,T=7]{t=4}$	U_p=0.73, U_t=1 U_{total}=0.92
U_p=[0.86,0.69] U_t=[0.63,0.70] U_{total}=0.70	$\xrightarrow[P=[35,69],T=[7,8]]{t=5}$	U_p=[0.14,0.31] U_t=[1,0.01] U_{total}=[0.74,0.10] U_{exp}=0.83
U_p=0.57, U_t=0.63 U_{total}=0.62, U_{exp}=0.62	$\xleftarrow[P=90,T=7]{t=6}$	U_p=0.43, U_t=1 U_{total}=0.83
U_p=[0.58,0.40] U_t=[0.63,0.70] U_{total}=0.62	$\xrightarrow[P=[89,123],T=[7,8]]{t=7}$	U_p=[0.42,0.60] U_t=[1,0.01] U_{total}=[0.82,0.18] U_{exp}=0.71
U_p=0.58, U_t=0.63 U_{total}=0.62	$\xleftrightarrow[P=89.8,T=7]{RESULT}$	U_p=0.4, U_t=1 U_{total}=0.82

TABLE II: Different negotiation rounds in the case of study

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