DEZENT: Autonomous Real-Time Management of Unpredictable Power Needs and Supply

Horst F. Wedde, Sebastian Lehnhoff, Edmund Handschin, Olav Krause

Technical Report #810

Autonomous Real-Time Management of Unpredictable Power Needs and Supply [1]

H. F. Wedde, S. Lehnhoff
School of Computer Science

E. Handschin, O. Krause
College of Electrical Engineering

University of Dortmund
44221 Dortmund / Germany

Abstract

During the past few years a world-wide trend towards renewable and ecologically clean forms of energy has been steadily growing. Private investments are encouraged and heavily subsidized in most of the European countries, through tax deductions, and even more through a very favorable refund program for feeding electric power from renewable sources into the public network. Wind or solar power production is typically decentralized, and, to a large extent, consumers are also producers and vice versa. In our DEZENT project (Decentralized Management of Electric Power Distribution) we have developed a novel distributed algorithm for autonomous agents who directly, on behalf of producers and consumers, negotiate quantities and prices. Within 10 to 50 msec the available supply and current needs are accommodated such that at most a negligible number of users is left unsatisfied after the first period. Also, in our multi-agent based system no malicious user or a coalition thereof may take an illegal advantage of the distribution of information and control such as arising from the simultaneity of producer and consumer roles. In this paper we refine our original algorithm in such a way that extreme "market" strategies like excessive *or* lazy bargaining *are effectively excluded. While not really restricting the user autonomy this makes the participants self-supportive in nearly every respect. At any rate, consumer prices can be expected to be much lower than under conventional distribution and management structures.*

Keywords: real-time applications, safety-critical, real-time systems, embedded systems, distributed systems, multi-agent systems, electronic negotiations, electric power distribution and management

1. Introduction

Rising market prices for energy are the obvious signs of a shortage in fossil fuel. To maintain an efficient and reliable supply of energy throughout the next decades under these circumstances, renewable energies have to be utilized and integrated into the current electric infrastructures. Meanwhile private investments are encouraged and heavily subsidized in most of the European countries, through tax deductions, and even more through a very favorable refund program for feeding electric power from renewable sources into the public network.

Such sources are based on solar or wind power, on renewable fuel like linseed oil, or on hydrogen technology. They are used for electric power generation in typically highly distributed small or mid-size facilities. The sources are inexhaustible, and when coupling electric and heat energy (e.g. in block heat and power plants) the technical efficiency is well over 90%.

Renewable energy production. Traditionally, electric power production and distribution are handled in a centralized manner. While serving millions of households at a time even for unpredictable needs of individual households the overall consumption can be predicted over a year with an accuracy of 3 - 5%. This allows for quite a stable planning of capacities, long-term purchases of fuel (coal, oil, nuclear), and for fixed (and high) prices.

On the other hand, the lack of timely prediction about local or regional consumption peaks requires a very conservative planning of reserve capacities. Also, due to technical constraints in large power plants (like long start-up and shut-down times with extensive maintenance and decreased life times) the generators would run continuously, thereby creating a considerable reserve capacity that may never be used, a built-in waste of energy. In addition, market-based phenomena like after the deregulation in California may result in artificial shortages. Finally power failures in globally managed systems are hard to manage as e.g. recently proven through the catastrophic black-outs in the Eastern US and Canada or, lately, the crashing of hundreds of huge power line pylons resulting from heavy icy rain in Germany. Obviously the centralized solution is not only costly (due to a high overhead and huge reserve capacity), but also highly inflexible and hard to scale. Despite the fast technological progress in utilizing renewable energy one of the major chal-

[1]This work is partially supported by Deutsche Forschungsgemeinschaft (DFG), under contracts WE 2816/4-1 and HA 937/32-1.

lenges in this development is the coordination and management of a very large number of such decentralized systems combined into a power grid. A centralized control concept is much more complex than in case of the traditional large power plant network, thus amplifying the problems mentioned above. Given the enormous costs for achieving (a limited) fault tolerance in the traditional set-up it is, on the other hand, an intriguing idea to *take advantage of the widely scattered facilities as a basis for efficient fault control:* Failures would have a limited impact on the whole system, and under decentralized control a flexible fault management would be robust, under lesser costs. (Every energy producer is a potential back-up facility.) Besides, raw materials come for free, or there are at most minor transportation costs.

In this paper we describe an extended decentralized negotiation concept for distributing electric energy among widely scattered participants (producers and consumers).

Previous and related work. As a result of the recent power black-out in the US and Canada an extensive discussion has started on how to avoid such accidents. In [WMB05] various concepts are presented for separating different supervisory control functions in energy management, for the purpose of a more flexible reaction to upcoming or unforeseen shortages and other extreme situations. The authors in [IAC+05] advertise establishing complex algorithms for guiding large systems out of chaotic situations. These efforts are complemented in survey articles like [MRS+05] and [GB+05]. The common ground for such initiatives is still a global control concept which in itself is highly inflexible, thus failures can hardly be avoided, and they spread easily in uncontrolled ways. Instead, our completely decentralized approach adapts naturally to unpredictable situations including power failures: In the distributed landscape of production facilities breakdowns have typically a local origin, and our power management handles them *in the same mode* as for normal functioning.

In a first decentralized attempt [WH+04] we followed a 2-stage approach geared at negotiation cycles of 10 min duration. For this purpose we developed a prognostic algorithm (SPA) for estimating the highly varying production/ consumption levels for small groups with a very high accuracy.

In the next step we have been able to develop negotiation algorithms that operate in the 10 ms range [WH+06]. During these very short intervals, however, production and consumption can be considered constant (details below), so the agents do not need any prognosis for the negotiation interval.

Extensive research about multi-agent systems has been lately pursued in various application domains [AH+01, DF+01, GrK99], including electric power management [CC+01]. All approaches are based on centralized control, with the disadvantages already discussed. In particular, prices in [CC+01] are negotiated within a central auction system, thus they are open to malicious "market" interventions. Security against malicious users in previous work has been discussed as a function of a centralized security management whereas in [WH+06] we have proven that our decentralized solution is robust against such malicious attacks, and against a representative range of related ones.

Our DEZENT algorithm is, to the best of our knowledge, the first completely decentralized solution for these problems. It has been developed as a key effort of the DEZENT project between the School of Computer Science and the Faculty of Electrical Engineering at the University of Dortmund, in well-funded mid-term research for making the utilization of renewable energy a both ecologically and economically very attractive, even a superior alternative.

We have been demonstrating in a realistic numerical study in [WH+06] that our distributed solution is considerably less costly for the users than a conventional management can deliver, even under the assumption that an extremely small percentage of users might be left to accessing a centralized reserve capacity. In this paper we refine our algorithm by introducing a second step, with the result that the reserve capacity is needed at most under catastrophic circumstances. This opens the door for a truly decentralized production and control system where small regions (e.g. suburbs or even subdivisions) care for their energy needs under a high amount of autonomy.

Organization of the paper. In 2.1, we define the power management and distribution model which is the basis for the distributed negotiation algorithm. The base functions of the latter are defined and explained in 2.2. In section 3 we report on experimental observations of a few phenomena which might cause producers or consumers to be left without sufficient contracts (and thus to depend on a (central) reserve capacity): We define *excessive* and *lazy bargaining*. In 3.1 we refine the base algorithm by excluding excessive bargaining, and in 3.2 we add a second negotiation phase to the algorithm in which the victims of lazy bargaining will be satisfied. We prove the correctness of our construction and give experimental results. In the concluding section we discuss our findings and briefly outline our future work in the ongoing DEZENT project.

2. Distributed Agent Negotiations in DEZENT

2.1 The Model

2.1.1 General assumptions

A. In the sequel we will assume that the needs in an area of modest size (town, suburb, subdivision) can be completely covered through renewable energy. (This has already been realized in quite a number of towns in Southern Germany, through solar panels and windcraft generators alone.) Excess energy would be available beyond the area, left-over needs in a subdivision would be satisfied through excess energy from other subdivisions from the area.

B. Different from conventional market models renewable electric energy comes for free (sun or wind power), or at minor transportation costs. We will assume that fuel-based facilities would be used as back-up facilities, either for single households (placed in the basement) or in a smaller suburb. The resulting prices to make up for fuel, amortization and maintenance are much lower than the current "market" level, according to formulas available from the IWR [IWR05].

C. Typically consumers are also producers, and vice versa. While a complete autonomy would be too costly, or unpractical for technical reasons, the users should have a chance to negotiate prices according to their current needs and supply situation on a peer-to-peer basis.

D. Negotiation processes on behalf of *actors* (human or technical) will be carried out through distributed software agents since they will take place well below the level of actor perception or reaction.

E. As common in Electrical Engineering, electric energy will be partitioned into arbitrary portions, according to needs and supply. Since the actor latency (e.g. a switch action) will be not less than 0.5 sec until the requested action is in effect we will assume that during this interval the need and supply situation is constant. All energy is available in the whole network.

F. The underlying electric grid structure is free of failures.

This opens the door for participants acting under their own responsibility yet poses particular novel challenges on an *appropriate handling of* ***unpredictable*** *consumer requests and producer offers*, under *fine-grained time-critical and stringent fault tolerance constraints.*

2.1.2 Agent negotiation structure. In DEZENT distributed agent negotiations take place on multiple levels within subdivisions of the total agent population. Within these subdivisions (balancing groups) negotiations are carried out through *balancing group managers (BGMs).* While monitoring bids and offers, BGMs will arrange for contracts on power quantities on the basis of "close" matches of bids and offers (see fig. 1).

Negotiations will start independently for the groups on the lowest level (each e.g. corresponding to a small subdivision). If a balance cannot be found for all processes in a group the negotiation scope will be extended to the other groups on the same level, or higher up, under the control of the next-higher BGM. The purpose is to accommodate the unsatisfied processes. Only in the worst case will the back-up services be utilized (2.1.1.B).

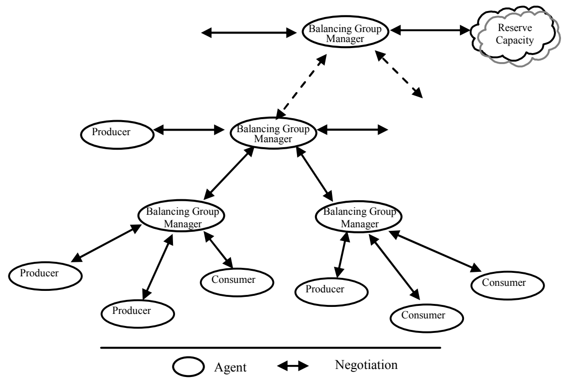

Figure 1: Negotiation Topology

Since an actor may be a producer and a consumer at the same time negotiations are initialized as follows: The customer agent, after having computed the difference *current_needs – current_production* acts as a producer agent if the difference is negative, as a consumer agent if the difference is positive, and it does nothing if the difference is zero.

During each negotiation period consumers issue bids for energy quantities they need, producers offer rates to sell such quantities. Since we assume the need and supply situation not to change during the period under discussion the price for a quantity will not depend on its size, in other words: According to the spirit of the approach ***there are no long-term negotiations or discounts.*** As costs for producers arise just for amortization and maintenance a *limited negotiation range* is deemed appropriate. Within the given range consumers will tend to issue bids on the low side, producers will try to offer power for relatively high rates, each group according to their interests. As the negotiations proceed and unless a deal has been closed producer/ consumer rates are lowered, or raised, respectively, from step to step, in order to be finished before a negotiation cycle is finished. The urge is motivated by the fact that for the next cycle the yet unsatisfied processes would face a narrower negotiation range thus both sides are put to a disadvantage.

2.2 The Base Negotiation Algorithm

I. Negotiation period. As just explained there are producer/ consumer agents and balancing group agents. The latter conduct negotiations between producers and consumers on various levels (see fig. 2). On each level negotiations are performed in cycles of 10 steps each. *For the purpose of simplic-*

ity we assume that in the model presented, based on synchronized clocks, negotiations in each cycle under a BGM start at the same time, and the duration of a step is 1 ms . After reaching the highest level (level 3 in fig. 2) negotiations will be finished since the remainder needs and power quantities will be handled by the main reserve facility. No new customers will be admitted during this period. We call this a ***negotiation period.*** Customers who have been satisfied during the negotiation period do no longer participate (see fig. 3). As a consequence, *a producer cannot act as a consumer during a negotiation period, and vice versa.*

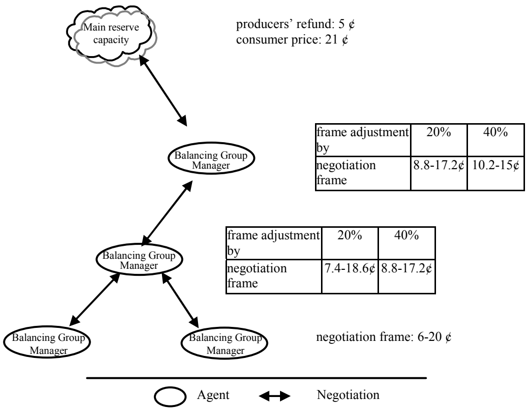

Figure 2: Exemplary Negotiation Frames and Adjustment

II. Price frames and adjustments. Negotiations on each level are held within fixed price frames. Frames on the same level have identical sizes. Customers that are unsatisfied after a cycle of one level will continue negotiations on the next higher level, however, the negotiation frames are shrunk by a fixed shrinking value ***Sr*** for all levels (20% and 40%, respectively, for two variants in fig. 2), lowering or raising the upper and lower limits, respectively, by half of the percentage. We do not only finalize on matching pairs of bids and offers but also consider bids and offers for contracting that are *similar* as specified by preset limits for their differences. *Similar bids and offers lead to a contract price which is the arithmetic mean value between bid and offer*.

Let a current frame at a negotiation level k be denoted by $[A_k, B_k]$; k = 0,1,2,.. For a producer/ consumer the minimum offer/ maximum bid will be A_k/ B_k , respectively. The opening bid bid_0 has to be chosen from $[A_k, ½(B_k + A_k)]$, the opening offer $offer_0$ is taken from $[½(B_k + A_k), B_k]$.

Each agent also specifies a device-specific urgency urg_0 and strategy parameters s_{1C} and t_{1P}. They characterize the gradient of the bidding and offer curves, respectively. When after step n; n ∈ [0,9] the unsatisfied agents adjust their bids/offers this will be done according to:

$$bid_C(n) = -\frac{1}{e^{\frac{urg_0 \cdot n}{s_{1C}} + s_{2C}}} + B_k , \qquad (1)$$

$$offer_P(n) = \frac{1}{e^{\frac{urg_0 \cdot n}{t_{1P}} + t_{2P}}} + A_k , \qquad (2)$$

The s_{2C} and t_{2P} are determined by the opening bid ($bid_C(0) = bid_0$) or offer ($offer_P(0) = offer_0$), respectively.

$$s_{2C} = -\log(B_k - bid_0) , \qquad (3)$$

$$t_{2P} = -\log(offer_0 - A_k) , \qquad (4)$$

Bidding and offering curves, after starting from their opening values, asymptotically approach B_k and A_k, respectively, with increasing *n*.

III. Contracting. At the end of each step unsatisfied consumers are identified and sorted by the BGM for current level k, according to their current bids. Then the consumers are processed top-down starting with the highest bidding consumer. Offers similar to the bid of the first consumer are identified and sorted by price. Offers are processed top-down as well.

For closing a contract between the first-listed consumer and the first-listed producer the needs of the consumer will be fulfilled as far as possible, within the following constraint: ***Only up to X Wh[2] will be granted to the consumer at a time.*** *(This prevents any consumer to purchase a very high amount of energy thus leaving other consumers out in the cold!)* After purchasing X Wh from one or more producers the current consumer's negotiation is interrupted, and the algorithm proceeds with the next-listed consumer. After processing the last-listed consumer, the algorithm starts again with first interrupted consumer (from the top of the list), allowing it to continue its negotiation for up to another X Wh. Going through the customer procedure again it proceeds until no match can be found in the current step any more. The algorithm stops and proceeds with the next step (and the afore mentioned bid/offer adjustments). (This approach is quite similar to the *Round_Robin* mechanism found in process-scheduling to maximize CPU-utilization and to prevent starvation of late or low-priority processes).

When a contract between a similar bid and offer has been closed *(on a maximum of X Wh!)* we distinguish the following cases for handling the total quantities:

1. The needed quantity is only a fraction of the offered size. The offer of the producer is adjusted to the difference of the need and the current size of the offer, the highest bidder is de-

[2] Watt-hour

leted. The algorithm proceeds with the next consumer.

2. The offered quantity matches the needed one exactly. Producer and consumer are deleted, and the algorithm proceeds with the next consumer.

3. The needed quantity is not completely covered by the offer. The need of the bidder is adjusted to the difference of his current need and the given offer size, the producer is deleted, and the algorithm proceeds to identify the next similar producer.

4. If the need of the consumer is not yet satisfied but no similar offers are identified or left, the algorithm proceeds with the next consumer.

Fig. 3 illustrates the progression of the negotiation algorithm under a BGM during one cycle. In this example there are 6 consumers (ascending curves) and 5 producers (descending curves) participating. Encircled bid/offer pairs (of similar values) and numbers correspond to the order in which contracts are closed. According to the first three cases of the afore mentioned algorithm, on contracting either the consumer curve ends (contract 2) due to needed quantities smaller than offers, or the producer curve ends (contracts 3, 4) due to offers smaller than needed quantities. Finally both curves end since needed and offered quantities quantities match exactly (contracts 1, 5, 6). In this example two consumers remain unsatisfied by the end of the tenth step. They start with the lowest possible bid and do not adapt fast. Conversely, the curves that are contracted at 1 start rather high (consumer) or low (Producer), respectively and they adapt their values very fast.

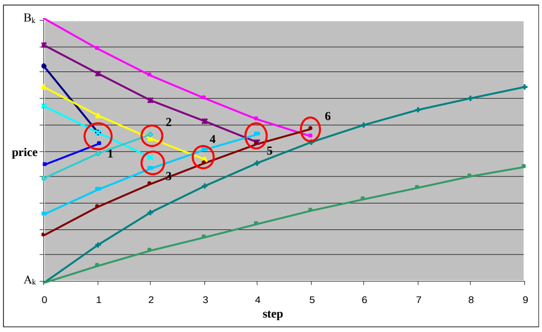

Figure 3: Contracting for Energy Quantities

The algorithm proceeds from level k to level (k+1) if unsatisfied users are left on level k. The BGM on level (k+1) starts with collecting all these users. Then BGM checks for each opening offer or bid from level k whether or not it fits into [$\frac{1}{2}(B_{k+1} + A_{k+1}), B_{k+1}$] or [$A_{k+1}, \frac{1}{2}(B_{k+1} + A_{k+1})$], respectively.

If the check is positive the values remain unchanged for level (k+1). Otherwise the value would be outside of [A_{k+1}, B_{k+1}], and the opening bid/ offer will be adjusted to A_{k+1}/ B_{k+1} , respectively (in this case s_{2C} / t_{2P} have to be recalculated according to (3) and (4)).

3. The Refined Algorithm

3.1 Excessive Bargaining

While discussing security threats in [WH+06] we identified a characteristic form of undesirable chaotic behavior arising from unintentional or naïve approaches as well as from malicious strategies. The bidding and offering curves reflect the customers' urgency resulting from several factors: An unexpectedly high need for (additional) energy or high production may cause an urge for finding enough negotiation partners early enough, i.e. to avoid being eventually referred to the main reserve facility with a major portion of production or consumption needs, respectively (see fig.2). In an extreme marketing strategy a very steep dive from $offer_P(0)$ over the n steps may be designed, or a very strong raise of subsequent consumer bids from $bid_C(0)$. The problem is that even within the short time frame of a step, producer and consumer curves may intersect in such a way that at the end of this step (when bids and offers will be compared for settling negotiations) the values of 2 such curves may not be similar any more – *in the extreme case there would be no similar match between any two bids and offers*. Due to the exponential shape of bid and offer curves *there would be no chance ever in the remainder of the cycle to catch a contract after one of the next steps*. We call this phenomenon ***excessive bargaining.*** Since contracting depends substantially on the preset similarity frames our policy idea is as follows:

(*) *If a producer and a consumer curve intersect within a step then their difference at the time of negotiation should be within the similarity range. In this context* $\mathbf{sim}_{CYC}$ *denotes the similarity throughout cycle CYC. If there is no confusion about the cycle we will write* ***sim*** *instead of* $\mathbf{sim}_{CYC}$ for short.

This requirement is meant to not only avoid the failure of contracting within a complete cycle but rather make sure that contract partners could be identified as soon as possible. This is in the best interests of the processes involved:

- Within a cycle the prices get worse as the steps progress, let alone that contracting may be impossible for reasons as explained above.

- Between cycles the number of competitors may potentially grow from level to level but actually there is the general expectation that a rather small population will be left on each level which leaves a strongly decreasing chance for finding contracting partners. (The design of the algorithm has particular features for this purpose, such as the shrinking negotiation frame sizes.)

For a given cycle *CYC* we formally present the requirement in **(∗)** by:

$$\forall_{C,P}\forall_{n}: \quad offer_P(n) - bid_C(n) > sim$$
$$\wedge \; offer_P(n+1) - bid_C(n+1) \leq 0 \qquad (5)$$
$$\Rightarrow \quad bid_C(n+1) - offer_P(n+1) \leq sim$$

Please note that (5) includes the assumption that at the beginning of step *n* no contract could be finalized between *P* and *C*. In line with the arguments collected under the bullets we will provide producers as well as consumers with reasonable guidelines for choosing the appropriate steepness of their negotiation curve, i.e. determine s_1 and t_1, respectively. As the first observation we state the

3.1.1 Lemma: Any two P or C curves will intersect at most once in a cycle.

Proof of lemma 3.1.1: This is an immediate consequence of the asymptotic behavior of the descending / ascending exponential curves as they approach A_k / B_k respectively.

Due to the exponential shape of the offer/bidding curves and their asymptotical approach towards A_k and B_k, respectively, the absolute gradients of both curves decrease rapidly throughout the cycle (see fig. 4).

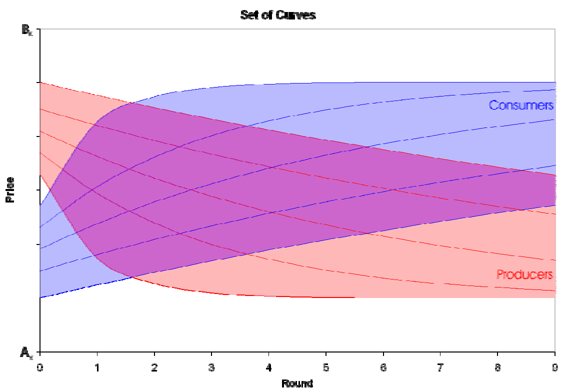

Figure 4: Set of Curves

The lengths of both distances $offer_P(n) - bid_C(n)$ (before intersecting) and $bid_C(n+1) - offer_P(n+1)$ (after intersecting) correlate directly with the angle of the intersection. Thus, as absolute gradients decrease, so are the chances for two offer/bidding curves to participate in excessive bargaining.
Both, the bidding curve's dive and the offer curve's raise are characterized by strategy parameters s_1,t_1, respectively (see section 2.2). The lower the parameter values, the higher are the absolute gradients of the curves.
By preventing the steepest offer and bidding curves from intersecting excessively after the first step (where both curves have their maximum absolute gradients) it is apparent that this constraint applies for all other and less steep offer/bidding curves throughout the cycle as well.

The idea of our approach is to find a lower bound *l* in such a way that for all offer/bidding curves with $l \leq s_1,t_1$ excessive bargaining is not possible throughout the cycle.

We will now state the

Theorem 3.1.2: Let, for the k^{th} cycle CYC_k, negotiation functions for a consumer *C* and producer *P* be given through bid_C and $offer_P$, respectively. Equally let *sim* denote the similarity for CYC_k (see (*)), A_k and B_k the borders of the negotiation frame for CYC_k. Let s_{iC}, t_{iP}; i = 1,2 be the strategic parameters for *C* and *P*, respectively, for the corresponding negotiation period. We assume $0<sim<B_k-A_k$. The the following holds: If

$$s_{1C}, t_{1P} \geq \frac{urg_0}{\log\left(\frac{(A_k-B_k)-sim}{(A_k-B_k)+sim}\right)} \qquad (6)$$

then there cannot be excessive bargaining. In other words: requirement (5) is satisfied.

Remark 3.1.3: It suffices to assume $0<sim<B_k-A_k$, since $sim=0$ is extremely disadvantageous for negotiations, and $sim= B_k-A_k$ results in settling the cycle negotiations in the first step, independent of the individual negotiation strategies chosen. In case of $sim=0$ there occurs either immediate contracting ($offer_P(n+1) = bid_C(n+1)$), or there will be no match for the curves during CYC_k, according to the lemma above.

Proof of theorem 3.1.2: Since

I. We have

$$0 \leq bid_C(n+1) - offer_P(n+1) =$$

$$\overset{(1),(2)}{=} -\frac{1}{e^{\frac{urg_0(n+1)}{s_{1C}}+s_{2C}}} - \frac{1}{e^{\frac{urg_0(n+1)}{t_{1P}}+t_{2P}}} + B_k - A_k =$$

$$\overset{(3),(4)}{=} -\frac{1}{e^{\frac{urg_0(n+1)}{s_{1C}}-\log(B_k-bid_0)}} - \frac{1}{e^{\frac{urg_0(n+1)}{t_{1P}}-\log(offer_0-A_k)}} + B_k - A_k =$$

$$= -\frac{B_k - bid_0}{e^{\frac{urg_0(n+1)}{s_{1C}}}} - \frac{offer_0 - A_k}{e^{\frac{urg_0(n+1)}{t_{1P}}}} + B_k - A_k$$

With the formulas (1), (2), (3) and (4) we eliminate bid_0 and $offer_0$ and get the following expression

$$\frac{\left(bid_C(n) - B_k\right)\cdot e^{\frac{urg_0\cdot n}{s_{1C}}}}{e^{\frac{urg_0(n+1)}{s_{1C}}}} - \frac{\left(offer_P(n) - A_k\right)\cdot e^{\frac{urg_0\cdot n}{t_{1P}}}}{e^{\frac{urg_0(n+1)}{t_{1P}}}} + B_k - A_k =$$

$$= \frac{bid_C(n) - B_k}{e^{\frac{urg_0}{s_{1C}}}} - \frac{offer_P(n) - A_k}{e^{\frac{urg_0}{t_{1P}}}} + B_k - A_k$$

II. In order to prove that this expression is bounded by *sim*, or:

$$D := \frac{bid_C(n) - B_k}{e^{\frac{urg_0}{s_{1C}}}} - \frac{offer_P(n) - A_k}{e^{\frac{urg_0}{t_{1P}}}} \leq (A_k - B_k) + sim \qquad \textbf{(\#)}$$

we replace s_{1C} and t_{1P} by their common lower bound yielding

$$D \le \frac{bid_C(n) - B_k}{e^{\log\left(\frac{(A_k-B_k)-sim}{(A_k-B_k)+sim}\right)}} + \frac{A_k - offer_P(n)}{e^{\log\left(\frac{(A_k-B_k)-sim}{(A_k-B_k)+sim}\right)}} =$$

$$= \frac{bid_C(n) - offer_P(n) + A_k - B_k}{e^{\log\left(\frac{(A_k-B_k)-sim}{(A_k-B_k)+sim}\right)}} =$$

$$= \frac{bid_C(n) - offer_P(n) + A_k - B_k}{\frac{(A_k-B_k)-sim}{(A_k-B_k)+sim}} =: E$$

Since $offer_P(n) - bid_C(n) > sim$ or $bid_C(n) - offer_P(n) < -\text{sim}$

$$\Rightarrow D \le E < \frac{(A_k - B_k) - sim}{\frac{(A_k-B_k)-sim}{(A_k-B_k)+sim}} = (A_k - B_k) + sim \le 0$$

This proves **(#)**, and thus the theorem.

3.1.4 Corollary: With no excessive bargaining possible, whenever a bidding curve and an offer curve intersect within a step, at least one curve discontinues at the end of this step.

Sr = 10%, *sim* = 2 ¢, s_1, $t_1 \in [1,20]$, urg_0=1

Unsatisfied agents	out of 10000 agents	out of 15000 agents
Cycle 1: 6-20 ¢	110	136
Cycle 2: 6.7-19.3 ¢	12	28
Cycle 3: 7.4-18.6 ¢	11	26

Table 1: Excessive Bargaining

Sr = 10%, *sim* = 2 ¢, s_1, $t_1 \in [3.5,20]$, urg_0=1

Unsatisfied agents	out of 10000 agents	out of 15000 agents
Cycle 1: 6-20 ¢	36	45
Cycle 2: 6.7-19.3 ¢	11	26
Cycle 3: 7.4-18.6 ¢	11	26

Table 2: Excessive Bargaining Widely Excluded

Of course, since (6) is only a sufficient condition it is conceivable that e.g. producer agents with a very steep curve intersect, at some point of the unlimited negotiation process, with the very flat curve of a thrifty consumer agent such that still condition (5) is violated. However, in order to learn about the impact of the regulation through (6) we did extensive simulation, with parameters varying over a wide range. We compared the negotiation processes over the 3 cycles: with no limitation on the steepness of the curves, and after the regulation according to (6). A representative and realistic setting is depicted in Tables 1 and 2. We see 3 very clear tendencies:

- There is a remarkable improvement regarding the number of unsatisfied agents after the first cycle: Instead of 110 (136) in Table 1 we find 36 (45), for agent populations of 10000 (15000).
- There is still some success while proceeding through the next 2 cycles in Table 1 whereas no further progress is made in the third cycle in Table 2. Thus this cycle could be skipped cutting the negotiation time down, in contrast to Table 1.
- Although the number of unsatisfied agents is very small after the third cycle these would still be left to accessing the reserve capacity, at very high expenses (in reality much more than in fig. 2). This impression is confirmed throughout the simulation study.

3.2 Lazy Bargaining

As seen from the s_1, t_1 values in Table 2, the restriction on the parameter choice is rather modest so as to leave a *maximal autonomy* to the use agents.

3.2.1 Observation. The left-over consumer agents are unsatisfied since negotiation curves were designed *too flat:* Once a producer and a consumer have intersected one of them drops out of the negotiation (3.1.4 and fig. 3). Thus if, at the end of the third cycle, a consumer process is still left active it had no chance to meet one of the active producer processes. But due to 2.1.1.A there should also producer processes still be left that were able to provide for the energy needed.

Negotiation strategies with "too flat" curves are classified as *lazy bargaining*. We will correct such strategies – which are lazy only relative to the requirement (6) - in a fourth cycle (see fig. 1). We will raise the steepness of such curves just to make sure that the consumers will be satisfied. We will not shrink negotiation frames any further.

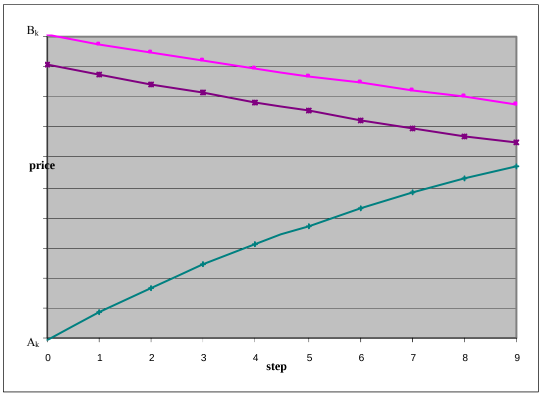

Figure 5: Lazy Bargaining

Some agents might already have partially satisfied their demands in subsequent cycles and thus posses a curve with an appropriate steepness. To maintain an overall fairness, such participants (e.g. the consumer in figure 5) should not suffer from unfair negotiation partners by forcing them to form even steeper curves. Thus the strategic parameters will be adjusted individually.

The idea is to divide this new cycle into three intervals, and to enforce contracting within the inner interval. For the cycle of 10 steps n; n ∊ [0,9] we distinguish the following intervals:

1. *fast contracting* (n ∊ [0,2])
2. *medium speed contracting* (n ∊ [3,6])
3. *late contracting* (n ∊ [7,9])

Insertion of an agent into these intervals is based on step *f* of the first cycle in this period where the first (partial) contract was closed. If an agent did not find any compatible negotiation partners throughout the whole first cycle, *f* is set to 9. Agents that are classified as *fast contractors* may embark on strategies resulting in smoother negotiation curves. Thus the strategy parameters of *fast contractors* are raised. *Late contractors* are treated in the opposite way. Strategy parameters of *late contractors* are lowered.

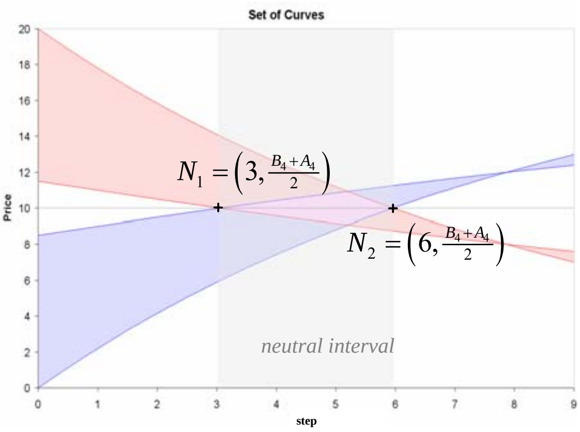

Figure 6: Inner Interval

Negotiation curves will become adjusted to intersect with $\overline{N_1 N_2}$ (see figure 6). Since the coordinates of N_1 and N_2 are well known, the adjusted strategy parameters must be within the following intervals:

$s_{1C} \in [\underline{s}_C, \overline{s}_C]$ and $t_{1P} \in [\underline{t}_P, \overline{t}_P]$ with

$$\underline{s}_C = \frac{3 \cdot urg_0}{\log\left(\frac{2}{B_4-A_4}\right) - s_{2C}} \quad \text{and} \quad \overline{s}_C = \frac{6 \cdot urg_0}{\log\left(\frac{2}{B_4-A_4}\right) - s_{2C}}$$

$$\underline{t}_P = \frac{3 \cdot urg_0}{\log\left(\frac{2}{B_4-A_4}\right) - t_{2P}} \quad \text{and} \quad \overline{t}_P = \frac{6 \cdot urg_0}{\log\left(\frac{2}{B_4-A_4}\right) - t_{2P}}$$

To guarantee a certain amount of fairness, flat negotiation curves should be adjusted more strongly than steep ones (thus also avoiding unfair *financial* consequences). For this purpose we choose s_{1C}/t_{1P} out of the intervals $[\underline{s}_C, \overline{s}_C]$ and $[\underline{t}_P, \overline{t}_P]$, according to the last bid/offer $bid_C(9)/offer_P(9)$:

$$\begin{aligned} s_{1C} &= (\overline{s}_C - \underline{s}_C)\frac{bid_C(9)-A_4}{B_4-A_4} + \underline{s}_C \\ &= \underline{s}_C\left(\frac{bid_C(9)-A_4}{B_4-A_4} + 1\right) \end{aligned} \qquad (7)$$

$$\begin{aligned} t_{1P} &= (\overline{t}_P - \underline{t}_P)\left(1 - \frac{offer_P(9)-A_4}{B_4-A_4}\right) + \underline{t}_P \\ &= \underline{t}_P\left(2 - \frac{offer_P(9)-A_4}{B_4-A_4}\right) \end{aligned} \qquad (8)$$

Additionally we set the *similarity* within the 4th cycle to:

$$sim := 0.15 \cdot (B_4 - A_4) \qquad (9)$$

We will now state the

3.2.2 Theorem: No consumers are left unsatisfied after the 4th cycle.

For the proof we need the following

3.2.3 Lemma: Excessive bargaining is not possible in the 4th negotiation cycle.

Proof of lemma 3.2.3: $s_{1C} \in [\underline{s}_C, \overline{s}_C]$ and $t_{1P} \in [\underline{t}_P, \overline{t}_P]$ both have to satisfy (6) (for cycle $k = 4$) to eliminate excessive bargaining in the 4th cycle. We prove that:

$$\underline{s}_C, \underline{t}_P \geq \frac{urg_0}{\log\left(\frac{(B_4-A_4)+sim}{(B_4-A_4)-sim}\right)}$$

$$\Rightarrow D_{\underline{s}_C} := \frac{\log\left(\frac{2}{B_4-A_4}\right) + \log\left(B_4 - bid_0\right)}{3 \cdot urg_0} - \frac{\log\left(\frac{(B_4-A_4)+sim}{(B_4-A_4)-sim}\right)}{urg_0} \leq 0$$

$$\wedge D_{\underline{t}_P} := \frac{\log\left(\frac{2}{B_4-A_4}\right) + \log\left(offer_0 - A_4\right)}{3 \cdot urg_0} - \frac{\log\left(\frac{(B_4-A_4)+sim}{(B_4-A_4)-sim}\right)}{urg_0} \leq 0$$

We set $offer_0$ up to its maximum B_4 and bid_0 to its minimum A_4, yielding a common upper bound for $D_{\underline{s}_C}$ and $D_{\underline{t}_P}$. We have:

$$\begin{aligned} D_{\underline{s}_C}, D_{\underline{t}_P} &\leq \frac{\log\left(\frac{2}{B_4-A_4}\right) + \log\left(B_4 - A_4\right)}{3 \cdot urg_0} - \frac{\log\left(\frac{(B_4-A_4)+sim}{(B_4-A_4)-sim}\right)}{urg_0} \leq \\ &\leq \frac{\log(2)}{3 \cdot urg_0} - \frac{\log\left(\frac{(B_4-A_4)+sim}{(B_4-A_4)-sim}\right)}{urg_0} \leq \frac{\log(2) - 3\log\left(\frac{(B_4-A_4)+sim}{(B_4-A_4)-sim}\right)}{3 \cdot urg_0} \leq \\ &\leq \log(2) - 3\log\left(\frac{(B_4-A_4)+sim}{(B_4-A_4)-sim}\right) := E \end{aligned}$$

$E \leq 0$ for *sim* with $\frac{(B_4-A_4)+sim}{(B_4-A_4)-sim} \geq \sqrt[3]{2}$. Taking the value for *sim* from (9) we get:

$$\frac{(B_4-A_4)+sim}{(B_4-A_4)-sim} \overset{(9)}{\geq} \frac{(B_4-A_4)+(0.15 \cdot (B_4-A_4))}{(B_4-A_4)-(0.15 \cdot (B_4-A_4))} \geq \frac{1+0.15}{1-0.15} \geq \sqrt[3]{2}$$

This proves that s_{1C} and t_{1P} satisfy (6) and no excessive bargaining is possible within the 4th cycle.

Proof of 3.2.2: We prove that every bidding curve intersects with every available offer curve within the inner interval $n \in [3,6]$. For this purpose, we ensure that every bidding and every offer curve intersect with $\overline{N_1N_2}$ (see figure 6). In formal terms:

$$\forall_{C,P}\ \forall_{n}: \quad offer_P(3) - bid_C(3) \geq 0 \\ \wedge\ offer_P(6) - bid_C(6) \leq 0 \tag{10}$$

I. We have

$$offer_P(3) - bid_C(3) = \frac{1}{e^{\frac{3urg_0}{t_{1P}}+t_{2P}}} + \frac{1}{e^{\frac{3urg_0}{s_{1C}}+s_{2C}}} + A_4 - B_4 =$$

$$\overset{(3),(4)}{=} \frac{1}{e^{\frac{3urg_0}{t_{1P}}-\log(offer_0-A_4)}} + \frac{1}{e^{\frac{3urg_0}{s_{1C}}-\log(B_4-bid_0)}} + A_4 - B_4 =$$

$$= \frac{offer_0 - A_4}{e^{\frac{3urg_0}{t_{1P}}}} + \frac{B_4 - bid_0}{e^{\frac{3urg_0}{s_{1C}}}} + A_4 - B_4 =: F$$

We replace s_{1C} and t_{1P} by their common lower bounds $\underline{s_C}$ and $\underline{t_P}$ respectively, yielding

$$F \geq \frac{offer_0 - A_4}{e^{\frac{3\cdot urg_0}{\left(\frac{3\cdot urg_0}{\log\left(\frac{2}{B_4-A_4}\right)-t_{2P}}\right)}}} + \frac{B_4 - bid_0}{e^{\frac{3\cdot urg_0}{\left(\frac{3\cdot urg_0}{\log\left(\frac{2}{B_4-A_4}\right)-s_{2C}}\right)}}} + A_4 - B_4 =$$

$$\overset{(3),(4)}{=} \frac{offer_0 - A_4}{e^{\log\left(\frac{2}{B_4-A_4}\right)+\log(offer_0-A_4)}} + \frac{B_4 - bid_0}{e^{\log\left(\frac{2}{B_4-A_4}\right)+\log(B_4-bid_0)}} + A_4 - B_4 =$$

$$= \frac{offer_0 - A_4}{\left(\frac{2}{B_4-A_4}\right)(offer_0 - A_4)} + \frac{B_4 - bid_0}{\left(\frac{2}{B_4-A_4}\right)(B_4 - bid_0)} + A_4 - B_4$$

$$= 0$$

$$\Rightarrow F = offer_P(3) - bid_C(3) \geq 0$$

II. We have

$$offer_P(6) - bid_C(6) = \frac{1}{e^{\frac{6urg_0}{t_{1P}}+t_{2P}}} + \frac{1}{e^{\frac{6urg_0}{s_{1C}}+s_{2C}}} + A_4 - B_4 =$$

$$\overset{(3),(4)}{=} \frac{1}{e^{\frac{6urg_0}{t_{1P}}-\log(offer_0-A_4)}} + \frac{1}{e^{\frac{6urg_0}{s_{1C}}-\log(B_4-bid_0)}} + A_4 - B_4 =$$

$$= \frac{offer_0 - A_4}{e^{\frac{6urg_0}{t_{1P}}}} + \frac{B_4 - bid_0}{e^{\frac{6urg_0}{s_{1C}}}} + A_4 - B_4 =: G$$

We replace s_{1C} and t_{1P} by their common upper bounds $\overline{s_C}$ and $\overline{t_P}$ respectively, yielding

$$G \leq \frac{offer_0 - A_4}{e^{\frac{6\cdot urg_0}{\left(\frac{6\cdot urg_0}{\log\left(\frac{2}{B_4-A_4}\right)-t_{2P}}\right)}}} + \frac{B_4 - bid_0}{e^{\frac{6\cdot urg_0}{\left(\frac{6\cdot urg_0}{\log\left(\frac{2}{B_4-A_4}\right)-s_{2C}}\right)}}} + A_4 - B_4 =$$

$$\overset{(3),(4)}{=} \frac{offer_0 - A_4}{e^{\log\left(\frac{2}{B_4-A_4}\right)+\log(offer_0-A_4)}} + \frac{B_4 - bid_0}{e^{\log\left(\frac{2}{B_4-A_4}\right)+\log(B_4-bid_0)}} + A_4 - B_4 =$$

$$= \frac{offer_0 - A_4}{\left(\frac{2}{B_4-A_4}\right)(offer_0 - A_4)} + \frac{B_4 - bid_0}{\left(\frac{2}{B_4-A_4}\right)(B_4 - bid_0)} + A_4 - B_4$$

$$= 0$$

$$\Rightarrow G = offer_P(6) - bid_C(6) \leq 0$$

With $F \geq 0$ and $G \leq 0$ inequation (10) is proven.

According to lemma 3.2.3 there is no excessive bargaining possible in the 4th cycle. We have proven that every offer curve intersects with every bidding curve within steps 3-6. Due to (5) every pair of offer and bidding curves is contracted by the next step at the latest. Thus every pair of offer and bidding curves, that intersects within steps 3-5 is contracted within steps 4-6 at the latest. A pair of offer and bidding curves, that intersect exactly in step 6 and have not been contracted yet, will do so after step 6 (at the beginning of step 7).

Model assumption 2.1.1.A states that the total needs can be covered through renewable sources. Thus during every step *n* there is at least one producer or a group of producers with enough energy left to cover the needs of any remaining unsatisfied consumer. If a consumer would be left unsatisfied by the end of the 4th cycle, there would be at least one producer or a group of producers left to cover the needs of the unsatisfied consumer. Since both curves intersect within steps 3-6, the consumer and producer have been contracted. Due to corollary 3.1.4 at least the consumer curve discontinues. Thus, no consumers are left unsatisfied after the 4th cycle.

□

Unsatisfied producers do not violate our model assumption and sell their surplus energy to the local reserve capacity.

4. Conclusion

The concept of *excessive bargaining* originated from our security studies in [WH+06]. It realizes restrictions for negotiating agents that *respect their autonomy to a maximal extent*. Avoiding *lazy bargaining* through a (costwise) fair regulation (in 3.2) is at the same time smooth enough to still allow for requirement (6) to hold, a considerable conformity of measures.

We have defined a novel distributed real-time negotiation procedure for agents taking care of producers and consumers of renewable energy. While being a key instrument for developing an adaptive distributed control system for the well-funded research project DEZENT it is an unprecedented truly distributed algorithm for multi-agent systems for the purpose. It had become clear (see [WH+06]) that such energy systems will turn out to be more economical for individual consumers than the traditional centralized architectures. A major incentive for our approach came from the fact that renewable energy is mostly for free (or at least for minor transportation costs), inexhaustible, and has no ecologically negative impact. This allows both for narrow negotiation ranges and a specific real-time concept. Different from market models in any related scientific discipline we do not need to utilize long-term negotiations or discount rates.

The security against reasonable attacks has been thoroughly discussed in [WH+06].

For the DEZENT algorithm we restricted ourselves to time-synchronized negotiations on all levels just in order to reduce the descriptional complexity, for the sake of conceptional clarity. For the same reason we did not include a feature for customers to drop out from negotiations once preset price expectations would not be met. Adding such features would not change any property demonstrated here.

Obviously the flexibility and scalability of our distributed solution are very high. As long as the balance group managers (BGMs) are operational the control system is completely fault tolerant to failures of energy providers while directing customers smoothly to relying on neighboring sources or, in the extreme, to a main reserve capacity. More generally the system is reacting with a very high robustness to unexpected events. If the BGMs would be supported through RAID architectures this functionality could be guaranteed, thus blackout or artificial shortage phenomena like discussed in section 1 could kept to the case of *catastrophic* failures. While the BGM architecture like in Fig. 1, 2 depends on the structure both of the power grid and of the population the DEZENT system adapts very flexibly to any change. As an example, even the number of BGM levels (thus of the bargaining cycles) might well exceed 3.

A purely technical argumentation may hide the fact that in the envisioned novel energy systems the users themselves, as producers or consumers, individually or as small groups, exert a remarkable amount of control, hence also of *responsibility*. Given that in our current studies most of the distributed negotiations involve just small numbers of users (i.e. the contracting is mostly done on lower levels) one could expect a novel cooperative attitude among them. This is even more so since the users do not really know how the contracting happens. (They do not have to know since they can from the beginning rely on the absence of malicious behavior or, at least, of any success thereof.)

Recent progress in electric technology led to the idea of including novel forms of fuel cells into the design of decentralized wind and sun-based energy production. This motivated much of our work. In the near future we should assume that the main reserve capacity (traditional large power plants) would be replaced through more regional, or even local, block heating and power plants that could serve as back-up facilities for small to large suburbs.- Right now we are finalizing agreements with towns in Southern Germany for realistic field studies.

References

[AH+01] P. Anthony, W. Hall, V. Dang, and N. Jennings: „Autonomous agents for participating in multiple online auctions". In *Proc. of the 17. Int'l Joint Conference on Artificial Intelligence (IJCAI'01) Workshop on E-Business and the Intelligent Web*, Seattle WA, USA, July 2001.

[CC+01] J. Contreras, O. Candiles, J. I. de la Fuente, T. Gómez: „Auction Design in Day-Ahead Electricity Markets". In *IEEE Transaction on Power Systems*, 3 (16), August 2001.

[DF+01] L. C. DiPippo, V. Fay-Wolfe, L. Nair, E. Hodys, O. Uvarov: „A Real-Time Multi-Agent System Architecture for E-Commerce Applications". Proceedings of the *Fifth International Symposium on Autonomous Decentralized Systems*, pp. 357-364, March 2001.

[GB+05] F.D. Galiana, F. Bouffard, J.M. Arroyo, J.F. Restrepo: „Scheduling and Pricing of Coupled Energy and Primary, Secondary, and Tertiary Reserves". *Proceedings of the IEEE*, vol. 93, issue 11, pp. 1970-1983, Nov. 2005

[GrK99] A. Greenwald, J. O. Kephart: „Shopbots and Pricebots". In *Proc. of the 16. Int'l Joint Conference on Artificial Intelligence (IJCAI '99)*, Stockholm, July 31-August 6, 1999.

[IAC+05] M.D. Ilic, E.H. Allen, J.W. Chapman, C.A. King, J.H. Lang, E. Litvinov: „Preventing Future Blackouts by Means of Enhanced Electric Power Systems Control: From Complexity to Order". *Proceedings of the IEEE*, vol. 93, issue 11, pp. 1920-1941, Nov. 2005

[IWR05] International Economic Platform for Renewable Energies official homepage. URL: http://www.iwr.de

[MRS+05] Y.-V. Makarov, V.I. Reshetov, V.A. Stroev, N.I. Voropai: „Blackout Prevention in the United States, Europe, and Russia". *Proceedings of the IEEE*, vol. 93, issue 11, pp. 1942-1955, Nov. 2005

[WH+04] H. F. Wedde, F. Th. Breuer, W. Freund, E. Handschin, D. König, H. Neumann: „Decentralized Real-Time Management of Largely Unpredictable Power Needs and Supply". *Proc. of the 28th IFAC/IFIP Workshop on Real-Time Programming (WRTP2004)*, Istanbul, Turkey, Sept. 2004.

[WH+06] H. F. Wedde, S. Lehnhoff, E. Handschin, D. König, O. Krause: "Real-Time Multi-Agent Support for Decentralized Management of Electric Power"; *Proc. of the ECRTS'2006, July 5-7, 2006. Dresden/Germany; IEEE Computer Society Press*

[WMB05] F.F. Wu, K. Moslehi, and A. Bose: „Power System Control Centers: Past, Present, and Future". *Proceedings of the IEEE*, vol. 93, issue 11, pp. 1890-

1908, Nov. 2005