Architectures for novel energy infrastructures: Multi-agent based coordination patterns

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***Abstract*— Due to the increased proportion of small renewable energy sources in a distributed setting (DG-RES), active control of small distributed energy producing and consuming systems will play an important role in future electricity grids [1]. These distributed energy resources have production patterns, which are either partially stochastic (e.g. wind, solar cells) or are coupled to the primary user process (e.g. co-generation of heat and electricity). Furthermore, on the demand-side, and increasingly on the electricity storage side, opportunities exist for actively serving stability applications in the grid by real-time supply/demand coordination. In the future, an information and communication layer for grid coordination could serve a portfolio of ICT-applications on timescales running from seconds to hours.**

To get a grip on these (r)evolutionary developments, possibly toppling the electricity grid, in this paper, architecture requirements for future high proportion DG-RES electricity grids are collected from a Power Electronics System point of view as well as from an ICT point of view using an inventory of business models in the power grid that focus on coordination of multiple small-scale DG-RES resources. Modeled from an ICT point-of-view, these give rise to architectures for applications that can successively be implemented in hardware and software as active components in the distribution grid. A number of possible grid control strategy coordination patterns (GCPs), which are defined in a generic, reusable manner, can be seen to emerge. GCPs, connected and intertwined to one another on several layers (physical, commercial) of the grid, together, can provide the framework for coordination in the overall intelligent grid.

Bottom-up approaches of implementing coordination in future active grids appear to be the method of choice to use in implementing the GCPs. Software agents [2], [3] coordinating primary processes using market algorithms, as implemented in the PowerMatcher approach [3]-[4], appear to be very suited for this.

I. INTRODUCTION

Currently, there is a lot of interest in Smartgrids, a paradigm, that encompasses an evolution to a malleable or active power grid, in which electricity producers and consumers at all distribution levels of the electricity network are grid-aware and appliances are more or less grid-friendly and even support retaining particular Quality-of-Service attributes of the grid. These Smartgrids are to be seen as key elements for the incorporation of larger proportions of small-scale distributed and renewable energy resources (DG-RES) and coupling of emergent small scale storage units for energy carriers on the grid. Smartgrids are to be seen as a combination of existing grids with a more or less loosely coupled layer of information and communication systems. Coordination of power generation and consumption on a large number of small scale units, retaining the same level of power quality and reliability, requires basic new approaches different from current top-down thinking in the utility industry. Furthermore, apart from current market driven operation of electricity-grids on a highly aggregated level, more localized market components will have to be added in order to initiate local market incentives. Finally, the coordination efforts should occur transparent to the primary processes of the users with clear benefits to them. In this paper, after presenting a multi-perspective view on these new developments, a number of architectural patterns is described for coordination.

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II. POWER SYSTEM BUSINESS MODEL CONTEXT VIEWS

A. *Entity/process view*

The various entities and processes of power system operation are depicted in Fig. 1. Following the Gane-Sarson [6] approach for information modeling, the rectangles denote entities, the rounded ones refer to processes. Arrows indicate information streams. The vertical axis gives an indication of the hierarchical level in the grid. The electricity producing and consuming entities are devices (loads and generators). It can be seen, that installations on the demand and supply side may play a role in the grid in a number of manners:

- Balance Supply Demand and Manage Transport pertain to balancing, contingency- and transport management on the higher voltage levels. Done by a Transmission/ Independent System Operator (TSO/ISO). In most countries this is done on the basis of the operation of Programmes of Programme Responsible Parties (PRP) on a one day ahead basis. These programmes are checked for line- and transport capacities. This mechanism reflects the current optimization of nationwide supply and demand matching in liberalized countries. In order to minimize the burden of imbalance, PRPs are given incentives to schedule their demand and supply one day ahead as accurately as possible from demand and supply predictions.

- Manage Portfolio. A portfolio is in the hands of a programme responsible party. Generally, consumption profiles of classes of small customers in portfolios are derived from historic data and are stratified based on a particular meteorological day and day type. The same mechanism also holds for reconciliation. Imbalance costs are passed on to customers in flat tariff according to their averaged profile, not on the basis of their actually measured usage of electricity in time. In the same way as for consumption profiles, the production profiles of small customers could be stratified to yield accurate predictions to be used in planning the portfolio. During day-to-day operation, for larger loads, the realizations are monitored in real-time by programme responsible parties to allow for slight strategy changes in the control strategy of the portfolio.
- Coordinate Commercial Cluster. A number of different generators and/or consumers together are managed as a whole virtual power plant (VPP) with certain characteristics and dynamics given by the constituent loads. This entity can be part of a portfolio to be optimized. The operation of a cluster of devices within a commercial VPP-context is not constrained to a certain area. To the operator of a portfolio, the VPP acts as any other plant in the portfolio, possibly even with greater versatility. The load curve of operation of the VPP could have a similar shape as physical counterparts in the portfolio.
- Coordinate Technical Cluster. A cluster of devices is managed to generate a virtual power plant to assist network operation. This is a version of the virtual power plant that is confined to a certain network topology in a geographical area. The ‘plant’ operates in the hands of a network operator and is like a voltage regulator at a feeder or equipment to deliver ancillary services. A technical VPP may be used to mitigate distribution bottlenecks or react to contingencies by acting in a micro-grid configuration in case connected parts of the grid are in an erroneous state.
- Device2Device Optimization. Confined area coordination of supply and demand. In this case one could imagine owner confederation of an apartment complex that manages equipment in individual apartments to keep a contracted profile within limits. Coordinated (synchronous or asynchronous) operation of devices here reduces network losses and avoids investment cost for the high voltage transport infrastructure. Part of the distribution grid acts as a local energy exchange network.
- In-home Energy Management. This business model implies in-home electricity usage strategy management [7]. As an example, the amount of imported electricity is managed in view of external price developments. Steering individual devices to synchronicity between demand, supply and, in the future increasingly, storage, is one of the control objectives.

B. Planning, time and market view

Operation of devices may be part of one or more activities in the grid. Which activity leads to financial gains is strongly dependent upon the tariff structure, the current status of the grid and the flexibility in demand and supply which may be linked to e.g. (micro-)climate conditions. Fig. 2 illustrates possible trading arrangements for exchange of power. Depending upon the predicted future demand and supply, market parties may agree long-term contracts that may be hedged by futures. Typically a strip of power (MW) delivery via a device during a certain period is traded. In order to fine-tune their projected portfolio for the next day, a trader may buy/sell additional power on the day-ahead market. On an intra-day market, a trader may buy and sell to update their portfolio [8]. All transactions have to fit within the high-voltage transport constraints and the geographically defined distribution constraints. Market designs require a number of rules to be obeyed, which generate a number of imperfections and artifacts [9].

C. Revenue stream view

The revenue streams are contained in Fig. 3. A number of these streams are dependent upon the real-time situation of the grid (*italicized*); others are fixed in time. Prosumers are traditional utility customers, that also have small or DG-RES production facilities.

In order to achieve a continuous equilibrium between supply and demand, currently, the energy markets are composed of a combination of long-term bilateral contracts, OTC(Over the counter)-markets, day-ahead agreements, intra-day markets and balancing markets. The current market constellation is known to have some imperfections and, in particular, does not favor embedding renewables. Future market models may lead to real-time pricing at the retail level, thereby italicizing the "retail price", "service fees" and "distribution fees" streams.

D. Prediction view

In order to have a good estimate of consumption and production prediction of specific appliance types plays an important role. In Fig. 4 a prediction view of operation of a nationwide power system is given. For larger installations meteorological and primary process related models are used to predict production and consumption. As for the consumption side, clustering of small producers will generate a statistically improved forecast. Coordination of devices at the local level can no longer be exercised by traditional central control techniques.

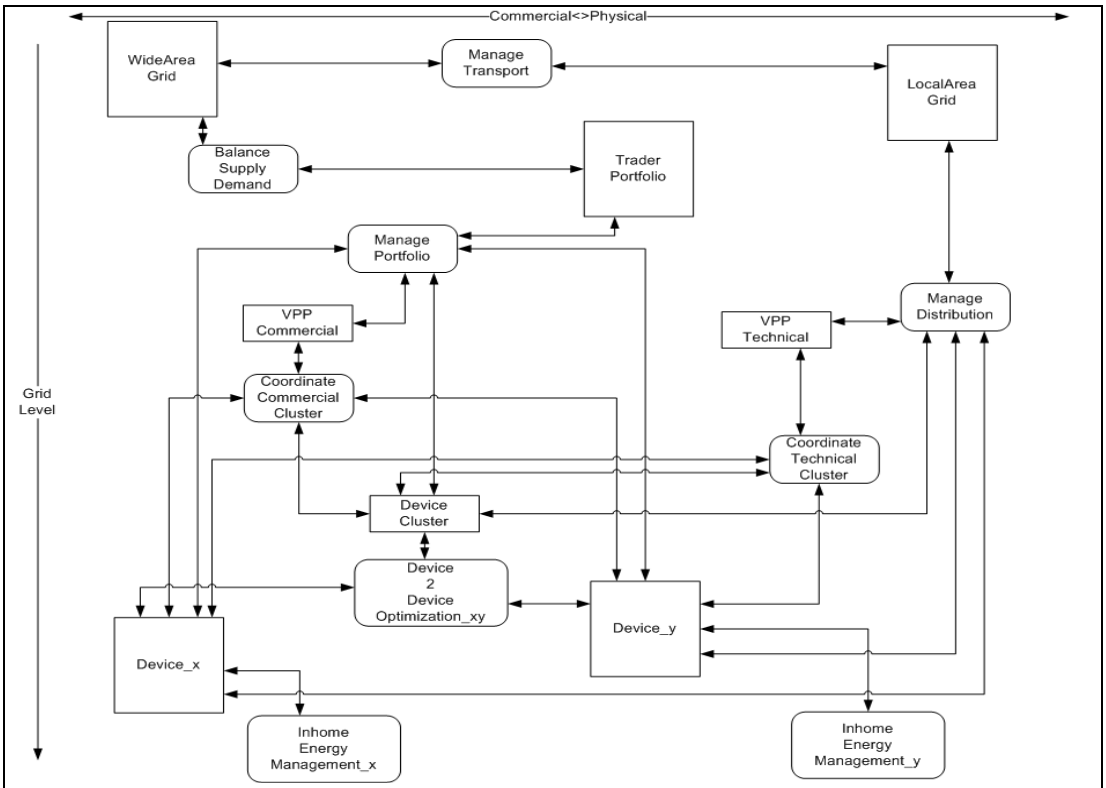

Fig. 1. Processview

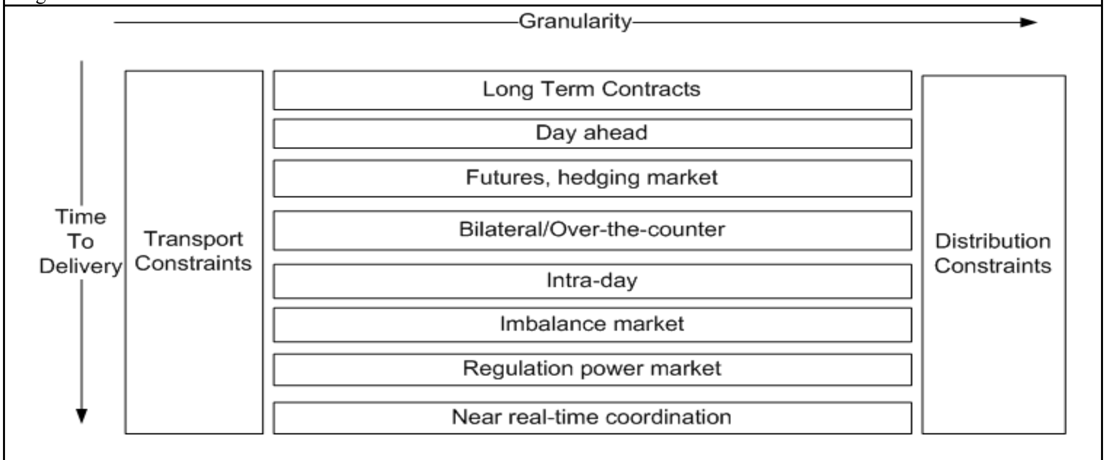

Fig. 2. Market stratification view

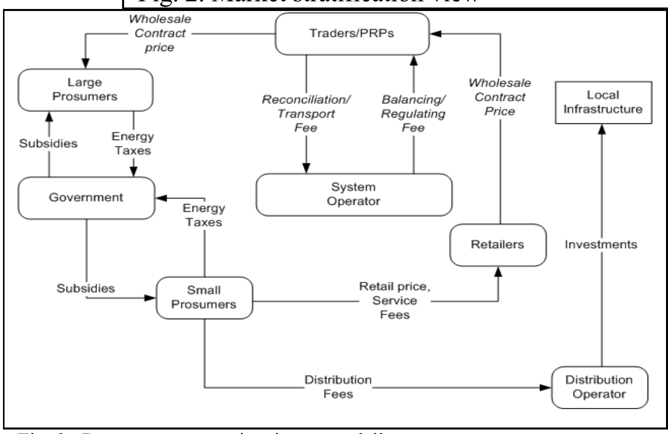

Fig. 3. Revenue streams view in power delivery

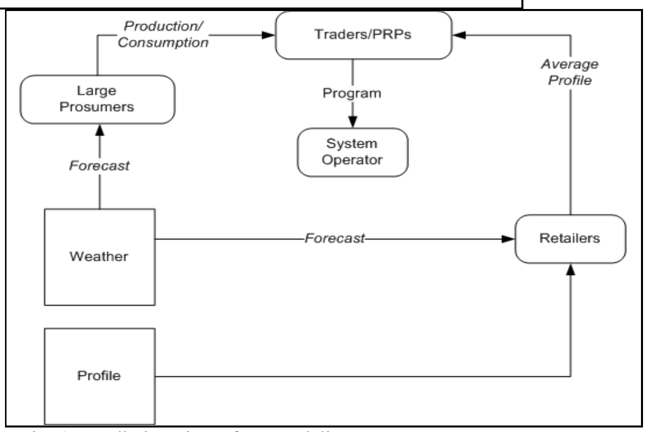

Fig. 4. Prediction view of power delivery

A trend towards decentralized control is visible in current research and applications, and agent-based technology is considered an essential building block [10]. As in ICT architecture modeling, coordination using agents involves mapping the real-world entities upon the coordination strategy. Using micro-economic market theory, there are a number of ways to map the properties of entities:

- By modeling them by their participation degree in discrete types of markets with different timeframes.
- By the bid-timing. Currently market rounds are issued with a certain periodicity. This periodicity may lead to artifacts in the control of devices, based on the allocation from the auctioneer, with higher cycle periods. For instance, a cooling device operated in 15 minute cycles may become too warm.
- By the ultimate control objective. Maximizing commercial gain, avoiding grid congestion or reducing emissions.
- By the bid-structure. E.g. in multi-valued bid curves appliances may not be able to cope very well with a partial allocation and especially generators are energetically inefficient when operated in partial load.
- By the auctioneering mechanism receiving bids and settling transactions.
- By Aggregation level. Representation by an aggregation-representative with common interest and common external data. Individual generation capacity and loads from small customers are not very interesting for a program responsible party; an aggregated load of a certain type of device with the possibility to shift, however, certainly is.
- Locational clustering. Several device types, from their location, may be subject to coupling to other devices purely because they reside in the same apartment and have one meter.

To what type of market to operate on depends upon the price development of specific markets. For instance, in the Netherlands, CHP's in the horticultural sector are operated on a mix of long-term and short-term contracts.

I. CLIENT-SERVER VERSUS PEER-TO-PEER (P2P)

Client-server configurations as well as service oriented architectures are in use for some time now as a means of implementing distributed computing architectures. With upcoming Internet based broad-band connectivity, since a number of years Peer-to-Peer architectures are coming up as an alternative means for distributed processing. A lot of research effort currently is spent to further unveil the potential in simulated and real conditions (e.g. PlanetLab [11]). An overlay network P2P-architecture also provides for a vehicle to more accurately map the real-world of a cluster of suppliers and providers onto an information system than client-server like architectures. The arguments for this are:

- The server-role generates vulnerability and contingency.
- Automatic identification and discovery are basic in P2P; in CS-architectures these are system management determined configuration items.
- Agents and events are natural in P2P and more easily modeled than in C/S.
- Modeling of autonomy and altruism in managing the balance in these kinds of networks resembles modeling utility and cost functions in micro economic markets.

A. Using a P2P architecture for supply-demand coordination

Peer-to-peer architectures are receiving an increasing interest in information architectures. In peer-to-peer architectures control and management functionality is shared between individual peers. Peers are decentralized, have tailored resources and also are autonomous in making decisions. As with respect to auctioning algorithms in the 90s, the combination of using auctioning algorithms in P2P-contexts has received considerable attention during the last decade [12]-[14]. Peers operate in dynamic 'meshes', configurations of entities varying in time, in which tasks are subdivided. P2P network configurations are used today in the case of streaming video applications on the Internet, with minimal usage of resources and bandwidth served by a community of peers. In this respect they mimic the problem of power distribution and capacity constrained management. The interface of a peer-to-peer auction mechanism can be as shown in Fig. 5. Providers interested in delivering a certain kind of service issue a price request to a broker. Depending upon the status of the network, the brokers issue a price offer for service delivery or service consumption. The described concept, PeerMart, also features an accounting scheme. The mechanism is based on call auctions, where prices are shouted and interested parties accept bids on a one-to-one basis.

A bidirectional, asynchronous auction mechanism can be shown to reach a similar allocation price as matching the demand and supply using supply and demand curves [14]. Building in intelligence in the bidding process can be accomplished by dynamically adapting the desired profitability margin for a peer. In the same way as the shape of a bid-curve changes under control of the primary process, the profitability margin of requests for service will be under control of primary process parameters. Distributed Algorithmic Mechanism Design (DAMD) is arisen as a new tool to implement distributed computation using a certain market algorithm, a distributed decision making algorithm and the roles of several actors in a P2P-context. The mechanism is applied for optimizing multicast networks, where cost of a multicast of a peer-to-peer network is optimized by determining the routing scheme.

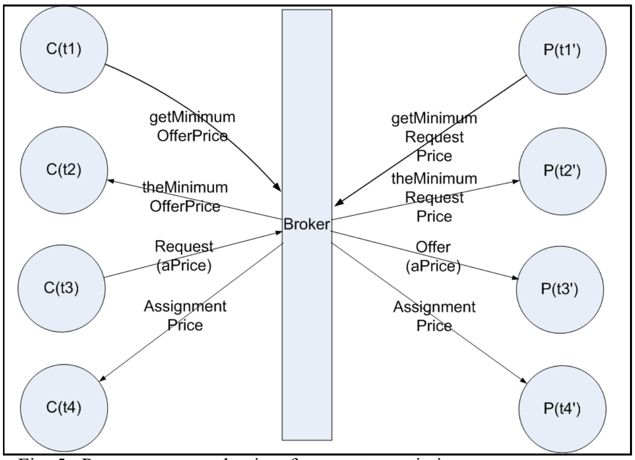

Fig. 5. Peer-to-peer mechanism for agent negotiations

In a simulation of a peer-to-peer network in an energy commodity allocation context the following scheme the PeerMart [13] algorithm was implemented as the bilateral auctioning algorithm. The configuration starts with a large set of devices negotiating for production or consumption of a resource. Each device starts with a random initial primary process status. Requests and offers are issued by the devices dependent upon their characteristics. In the bid/service request there is a call-back for bilateral delivery. The traded amount is a fixed size amount of available capacity.

B. *Event based exchange market mechanisms*

Current power exchange markets have a structured market protocol in which amounts of electricity are traded for market periods at discrete time intervals. Clearing of the market takes place some time before the trading period commences. Examples are existing day ahead markets (hourly periods for one day at a 12 hours notice) and intra-day markets (up to 1 hour ahead). Coordination of devices near real-time requires more direct control, such as the PowerMatcher approach [16], which enables operation near real-time (order of seconds) in periods of 5-15 minutes. Although near-real-time control can be exerted in this way the fixed market periods cause some problems in real-time operation. It is paramount that process events - such as turning on the thermostat - trigger a direct response from a device in order to fulfill user's demand. In the current scheme the market outcome will be disturbed until the next market period arrives. To overcome this effect the event based market concept has been developed and implemented in the PowerMatcher concept.

In an event based market agents can bid, or adjust their bid, at every moment their situation changes and directly receive a new contract after revaluation of the market. Also those agents that are influenced by the market revaluation are informed of their contract changes, as depicted in Fig. 6. These contracts are made for an undetermined period in real-time operation until the next bid is issued.

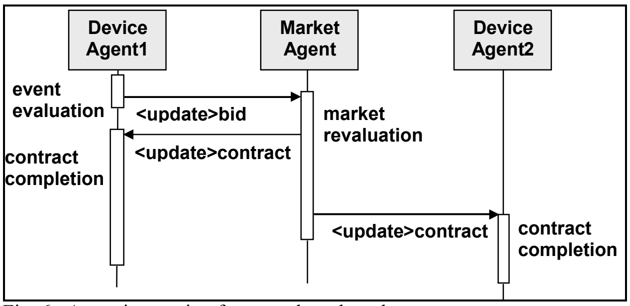

Fig. 6. Agent interaction for event based markets

The event based design increases responsiveness of devices to events from their environment. Also the communication overhead may be reduced, especially for devices at rest (space heating during the night). And not all communication will be focused on fixed moments in time, but will spread out. Event based markets may also give a means to handle ramping up and ramping down effects of devices. During ramping up a device may place new a bid on the market every few minutes, each time with a higher power bid, until maximum power is reached. Although this may lead to communication overhead (several bids are needed for one on/off action of a device), an enhanced bid protocol may be used that takes into account the ramping up/down cycle of a device. Event based markets and periodic markets can be applied in a hybrid way. The periodicity of the latter can be reduced if event based bids are allowed in the market. Also no special mechanism for detection of lost agents is needed since the periodic market will find out. The event based market concept also closely resembles the Napster or Kazaa networks, since only agents will be approached that are involved in a transaction. Thus market agents more and more take the role of broker agents (Fig. 5).

II. AN EXAMPLE OF A COMPOSITE COORDINATION PATTERN

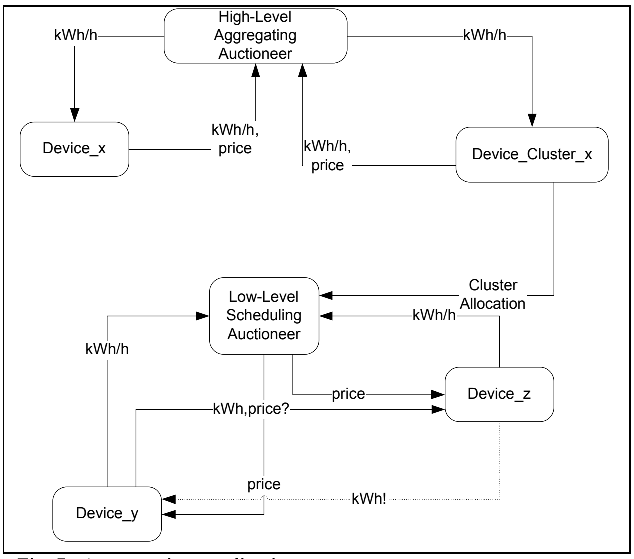

Fig. 7. A composite coordination pattern

For the major part of small loads, prediction of load and generation on an aggregated scale can be done much more accurately than on a localized level. Therefore, aggregated entities facilitate and simplify coordination by reducing data transport for message exchange for monitoring and control. These aggregation advantages might also hold for metering and reconciliation. In Fig. 7 an example of a bottom-up coordination pattern is depicted. On an aggregated level, a high level clustering auctioneer performs collection of realized values in the cluster and the bidding process in futures. In order to perform optimally, the scope and the number of participants should be as large as possible within the optimization context. Once power is allocated to devices, on a low level, this has to be distributed depending upon the primary process status of the individual devices. For sub-allocation a bid-curve allocation approach or a more simplified procedure may be followed [4]. The latter implies emission of a price-vector and monitoring the subsequent realization of power of the devices in the cluster. The latter, auction based, mechanisms are synchronous with a certain period. For more instantaneous loads, simple message exchanges should be possible. As an example a device could emit a request to deliver/buy an amount in a peer-to-peer configuration and other peers interested could possibly answer the request. The PowerMatcher concept, developed by ECN as a market based coordination mechanism for supply and demand of electricity in future grids with large scale distributed generation, applies the above discussed theories. The concept has proven itself in several field tests, of which two tests are described elsewhere [2], [15].

Commercial portfolios in the electricity market can be optimized to accommodate variable output wind energy by utilizing flexible demand like heat pumps as well as distributions system operators may utilize the technology to cope with increased simultaneous generation in residential areas like micro-CHPs.

III. Conclusions

The architecture requirements for future high proportion DG-RES electricity grids have been described from a Power Electronics System point of view, from a market view and from an ICT point of view.

There are four fundamental issues for implementing ICT in power systems: finding the right architecture type for an ICT-application and the coordination algorithm and mechanism, providing scalability, introducing planning of resources in the time domain and experimental verification of the flexibility and timing issues of the communication process within a real-time internal context and synchronous external events (e.g a price-signal). Processes and information streams lead to a number of possible grid control strategy coordination patterns (GCPs), which can be defined in a generic, reusable manner. GCPs, connected to one another on several layers (physical, commercial) of the grid, together might facilitate implementation of composite coordination applications in the overall intelligent electricity grid. Two of the GCPs were actually implemented in two PowerMatcher field tests, which allowed verification of the agent based approach. Future implementation of event-based techniques will allow implementation of even more real-world mappings of grid coordination strategies.

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