Engineering Energy Services of the Future by Means of Dynamic Energy Control Protocols (DECPs)

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Abstract— **In this paper we conjecture that revolutionary advances in future energy services are needed and that these are only possible by means of information technology (IT). To support this claim, we first briefly describe the fundamental needs for changing the ways energy services have been provided, and possible consequences resulting from not adopting qualitatively new paradigms. We next make the case why managing energy services of the future to meet such needs will only be possible when pursuing a systematic deployment of IT-based mechanisms for processing, delivering and consuming energy. We stress open R&D questions to which basic answers are needed in order to rip benefits of IT. Notably, a multi-disciplinary approach to modeling and simulating a cyber-physical system (CPS) comprising the physical energy grids, and its support communications, sensing, and computing cyber layers is essential. Designing regulatory policies for facilitating penetration of IT at the value is also viewed as one of the key R&D challenges. Finally, we introduce our vision of an IT-framework in support of Dynamic Energy Control Protocols (DECPs) and illustrate potential benefits from implementing DECPs.**

I. SALIENT FEATURES OF REQUIREMENTS FOR FUTURE ENERGY SERVICES

Despite the new wave of interest in energy and environment, there is very little recognition of the overall complexity and the R&D challenges related to the evolution of future industry architectures capable of meeting the societal needs. It is, instead, believed that there would be one or two magic technologies to solve the huge problem. In this section we describe this challenge by relating the desired end state to the initial conditions in the industry of today. We suggest that the challenge is so huge that many breakthroughs would be needed. The specific contribution of this paper is the conjecture that, while somewhat ignored, the IT is essential for integrating many novel technologies into the legacy energy systems and for enabling benefits by order of magnitude higher than what is currently perceived possible.

In order to appreciate a true potential benefit from IT-supported energy services, it is important to understand today's industry and planning practices, and to identify major missed opportunities from not deploying IT. While the devil is often in the details, one does not need to be fully familiar with the ways the energy grids operate to understand several conceptual issues. To those more familiar with the telephony system of the past than with the energy systems, it is very helpful to re-think the revolution from the telephony system to today's Internet and other communications multi-media environments to begin and appreciate the potential of paradigm shift in energy systems. This author believes that the analogy is simply striking. The vision for future energy services presented in this paper was re-enforced by one such presentation concerning the revolution from the telephony industry [1].

To start with, one could think of today's (electric) energy systems as the Bell telephony system of the past. The grid is designed in a top-down way with the objectives of distributing electric power to the end users located in the backbone (Extra-High-Voltage (EHV)) grid and, further via distribution (Medium– (MV) and Low -Voltage (LV)) local networks to the small users. Much precision and effort is put into designing and over-designing such very complex grid so that even the worst-case scenario does not affect the consumers. The grid is, however, passive, and the only control is by the large power suppliers and system operators who schedule power generation in anticipation of forecast future system demand. This is done assuming full knowledge about the status of huge number of nonuniform components (relays, breakers, lines, transformers, and much more) dispersed throughout a large geographic network. The only real automated feedback is by the select power plants in response to the EHV grid frequency and voltage deviations from nominal values. As a rule, the energy end-users are by and large assumed to vary at their will. Consequently, the controllability and observability of this large network is rather limited, much the same way as it was in the old telephony system. Despite these poor network characteristics energy services have been quite reliable. This has been mainly due to the over-design of both energy resources and the delivery grid itself. Unfortunately, major pressures and constraints on future energy and environment needs worldwide are not going to be able to serve rapidly growing demand for energy in sustainable ways while effectively wasting unnecessary resources by requiring much resource redundancy. In addition, given the overall temporal and spatial complexity of energy production, delivery and utilization, it has become increasingly obvious that even considerable stand-by reserves do not guarantee unconditional services [2].

Majority of those taking the challenge of sustainable energy and environment have begun exploring many specific, often high-risk R&D avenues in quest for more energy. The efforts range across search for safe nuclear power, cost-effective large-scale solar/photovoltaic power, clean coal, large-scale wind power, through more long-term explorations

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of energy bio-harvesting and the like. While some effort is put into beginning to also make the end-users responsive to system conditions, most of the efforts remain on novel stand-alone distributed renewable energy resources, and much less on the effective utilization of what we already have. These have potential value mainly for convenience, but are unlikely to meet the basic necessary needs of the huge growing demand. Moreover, there are no good R&D tools for prioritizing new solutions according to their value, risks and the associated costs. The efforts are more temporary state and federal subsidies in support of clean technologies, in particular, than systematic approaches to providing an environment in which choice can be made at the price which includes the value at risk when not served.

In short, today's planning and operating practices will require major new energy sources in order to meet the ever-growing future energy demand. Particularly large growth may be for electric energy, given the new trend for electrification of transportation vehicles in order to meet environmental constraints. However, the trend of simply building more is not sustainable in a long run because there is simply not enough new energy to maintain the same per capita energy density consumption as in the past. It is also very difficult to build large-scale new energy delivery infrastructure, particularly given the right-of-ways issues. Even if there were enough, building more would result in higher costs of electric energy services and, notably, unacceptable environmental effects.

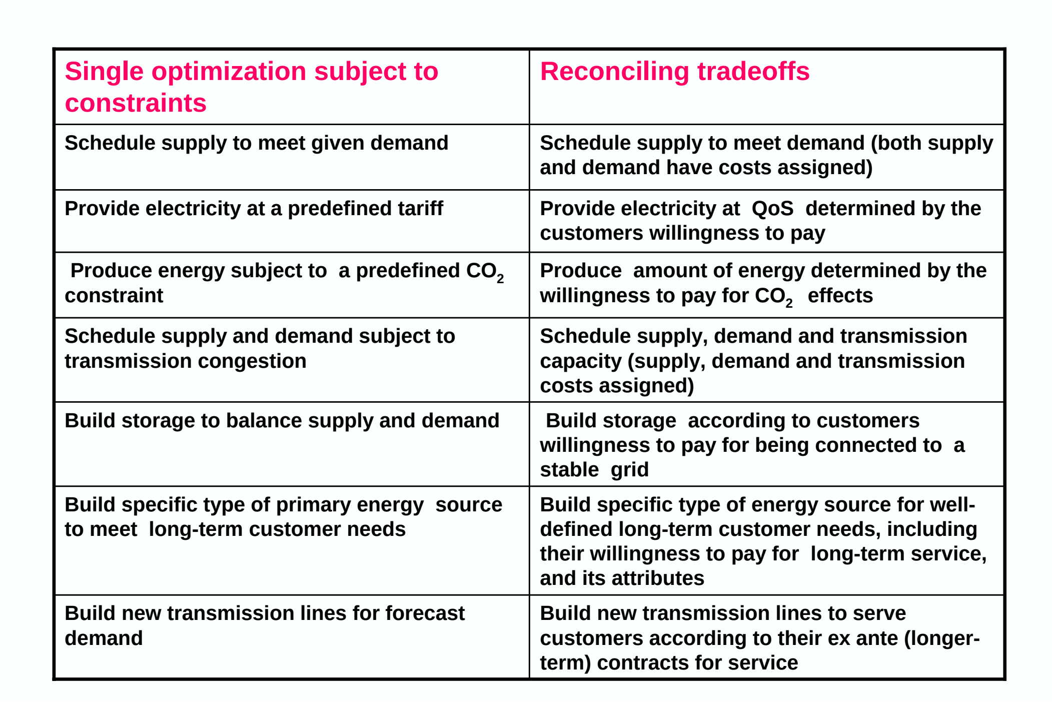
It is becoming increasingly clear that, instead of building more and more, a change of paradigm is essential so that the ”most” is made out of the available resources, and that this be combined with the deployment of carefully evaluated new resources. Making the most out of what is available is multi-dimensional and includes the notions of differentiated Quality of Services (QoS) beyond the socially acceptable levels of service at the differentiated prices.

II. CHANGE OF INDUSTRY PARADIGM: FROM DETERMINISTIC STATIC OPTIMIZATION TO STOCHASTIC DISTRIBUTED ADAPTATION

As the new technologies are being considered, one may consider two qualitatively different approaches to moving forward. First would be to continue according to today's planning and operating industry practices whose general characteristic is performing a single optimization over all resources subject to various constraints. One of the basic constraints is that the supply meets forecast demand. Shown in the left column of table in Figure 1 are several representative examples of how is planning and scheduling done in today's industry. It can be seen that, independent of the type of technology, the decisions are made centrally so that the hard constraint is met (such as supply meeting forecast demand, fixed electricity tariff, transmission line limit). This approach does not allow for much adaptation by those who need the technology. In this approach state regulators do not base their decision of how much greenhouse effect is acceptable, or what the short- and long-term reliable service is worth to the customers in their areas. Instead, utilities are told to deliver certain level of reliability at the pre-agreed upon tariff without taking customer choice explicitly into consideration. Consequently, these financial arrangements are grossly distorted with regard to the monetary risks caused by the amount of reserves needed to manage the uncertainties of equipment status, fuel prices and the actual demand.

Second, a qualitatively different approach would be the one shown in the right column of table in Figure 1. Instead of performing a single optimization, various tradeoffs are defined and evaluated by consumers, suppliers, delivery providers, system operators, providers of new technologies, policy makers. An interactive adaptation necessary for reconciling these tradeoffs is managed when arriving at the solutions acceptable by the decision makers. It can be seen from table in Figure 1 that both candidate technology users and suppliers provide as a result of their own decision making their demand and supply curves for the technology evaluated. The supply and demand curves reflect customers' willingness to pay as well as suppliers' cost functions for deploying the technology of interest. It is important to understand fundamentally different outcomes from these two approaches. In the first approach system demand is forecasted, and resources are scheduled or built for this demand to be met. The cost is a byproduct. In the second approach, the resource scheduled or built takes into consideration customers choice and willingness to pay, a priori. This avoids a situation in which customers are only told after the fact what the cost would be. Similarly, instead of providing services at the predefined, undifferentiated, tariffs to all customers, the second approach enables different Quality of Service (QoS) to those willing to pay more for better service. Similarly, the choice could be given to customers to define their demand for CO_2-free energy supplied to them and the willingness to pay for this choice. Depending on technology attributes, choice could be made for storage technologies in order to ensure uninterrupted service even when the basic resources are intermittent. Finally, and very important, is the choice to value uncertainties. In particular, if some customers wish to ensure certain amount of energy services into distant future, they must provide their information concerning their willingness to pay for this. Only with this information new resources could be built without a high risk that they may not be utilized (stranded assets) and the customers will not be surprised with the additional charges. Given that it is extremely hard, almost impossible, to forecast long-term demand without the explicit information provided by the customers, risks related to these uncertainties must be borne by those who create them and there must be a premium charged to those who are willing to pay for avoiding the risks of not being served.

Most of today's industry and public policy practices fall under the first approach. Consequently, none of current engineering, financial and policy solutions enable genuine reconciliation of tradeoffs at value. However, given that the resources are limited, it is not feasible to simply continue with an approach of unconditional services at the predefined



Single optimization subject to constraints	Reconciling tradeoffs
Schedule supply to meet given demand	Schedule supply to meet demand (both supply and demand have costs assigned)
Provide electricity at a predefined tariff	Provide electricity at QoS determined by the customers willingness to pay
Produce energy subject to a predefined CO_2 constraint	Produce amount of energy determined by the willingness to pay for CO_2 effects
Schedule supply and demand subject to transmission congestion	Schedule supply, demand and transmission capacity (supply, demand and transmission costs assigned)
Build storage to balance supply and demand	Build storage according to customers willingness to pay for being connected to a stable grid
Build specific type of primary energy source to meet long-term customer needs	Build specific type of energy source for well-defined long-term customer needs, including their willingness to pay for long-term service, and its attributes
Build new transmission lines for forecast demand	Build new transmission lines to serve customers according to their ex ante (longer-term) contracts for service

Fig. 1. Single optimization subject to constraints vs. reconciling multi-dimensional tradeoffs

tariffs. This approach has led to various longer-term instabilities seen in unplanned shortages and/or excessive price increases. Moreover, with the newly evolved security threats, it is quite clear that it is impossible to build enough redundant resources to serve consumers during extreme events the same as during normal conditions. Choice must be made concerning what needs to be provided during those events and at which price. This can only be a meaningful choice with the information by the consumers about their willingness to pay for services during such events and how much would they actually need. It is straightforward to imagine significant rationing during the extreme events without severe consequences. Man-created or unplanned failures of major equipment in today's energy grids both lead to the inability to either produce and/or deliver the same energy services as when the equipment status is normal. Today's industry and policy practices do not lend themselves well to preparing for such events differently than for normal conditions. This requires excessive reserve and capacity. Despite these reserves, the overall complexity of operating the system during the unplanned equipment failures still results in hard-to-predict service interruptions.

In this paper we suggest that it is essential to begin to seriously consider a change of the industry and public policy paradigm from the first approach to the second approach. In the remainder of this paper we assess the conceptual challenge of implementing the second approach.

III. THE KEY ROLE OF IT FOR MEETING THE FUTURE REQUIREMENTS

Today's Supervisory Control and Data Acquisition (SCADA) systems in electric power grids and other energy networks, such as gas and oil, are the basic means of on-line equipment management in these systems. In the electric power grids, in particular, they are implemented in the Energy Management Systems (EMS) in charge of individual utilities or power pools.[1] There is no at present on-line communications exchange of well-defined information between the EMSs within the large US interconnection comprising a large number of utilities and pools. This was recognized to be one of the major causes of the August 2003 blackout, for example [2]. Also, within each utility/pool the on-line SCADA is typically implemented at the EHV portion of the grid and with either rudimentary or no SCADA at the MV/LV local distribution network systems close to the customers. Only recently there has been an effort to begin to also provide local networks with SCADA systems.

None of today's software supporting SCADA systems lends itself to the interactive on-line adaptation of various system components. A notable exception are the electric power plants. These are turned on and off based on the longer-term demand forecast, and the outputs of the power plants are adjusted as the demand is forecasted more accurately closer to the real time. Generally, only the total utility (pool) demand is forecasted and its spatial allocation is assumed based on the relative demand peaks. Line power flows, power generation and voltage are measured throughout the EHV portion of each utility(pool) and this information is used to update the equipment status using static state estimators [3]. It is generally impossible to align the state estimator results with those obtained by running power flow analysis. This is caused, among other reasons, by the poor knowledge of power demand at the system buses throughout the large EHV grid, as well as by the wrong equipment status estimates.

[1] Most recently, as part of industry restructuring, some of the control areas are operated by the Independent System Operators (ISOs).

In order to appreciate the importance of more accurate information about demand, we point out that a typical EHV utility (pool) network representation has several thousands of nodes, most of which are loads. Imagine a network in which models are available only for 10% of the total number of nodes, while the others are mixture of forecast data and noise. Moreover, because of the way the total forecast utility demand is allocated to individual nodes, the noise is non-zero mean noise. In addition, the long-term forecast of system demand is very inaccurate which contributes to further wrong representation of long-term nodal demand. Such a network must rely on feedback control to regulate near real-time supply demand imbalances. Resources, typically power plants, participating in so-called automatic generation control (AGC) must be either very fast responding to compensate for imbalances as they occur and/or must be only partially dispatched if they are slower-responding plants. This is a major source of hidden inefficiency, usually not discussed. The estimated cost of AGC is primarily due to sub-optimal dispatch of power plants which use inexpensive fuel (typically slow-responding) and is significant. It should be clear that the worse demand forecast, the higher such hidden inefficiencies are. In addition to this basic supply demand inefficiency, inaccurate representation of demand at a very large number of nodes within a complex network leads to the basic poor situational awareness and robustness of the overall network.

A. The Multi-disciplinary R&D Challenge Underlying IT-Frameworks in Support of Energy Services

In this paper we suggest that a systematic deployment of interactive IT at demand nodes could greatly improve the overall performance of the future energy networks. There are two possibilities here. First, a better model identification of a stochastic load at the major demand nodes is needed. Second, if the demand is to adapt on-line to the changing system conditions, it must have sufficient local IT-based intelligence to sense the conditions, evaluate its own objectives and communicate to the others within the network. This adaptation must be measurable in terms of demand functions for specific service attribute as indicated in table of Figure 1.

Similar IT-supported intelligence is needed in order to implement demand response during the extreme conditions. For example, pre-agreed upon demand functions during such conditions require that the user knows that the conditions are occurring and it responds accordingly by implementing his demand response curve. These conditions evolve fast, and it is essential to automate users' feedback.

In order to make the most out of available resources as conditions vary, it is essential to make the branches of the network also adaptive rather than delivering power without any adaptation. Many other equipment components require IT-supported adaptation and interactions with the rest of the system. One can imagine system protection become more data-intensive and adaptive, as well as fast acting high-gain control of wires and power plants themselves.

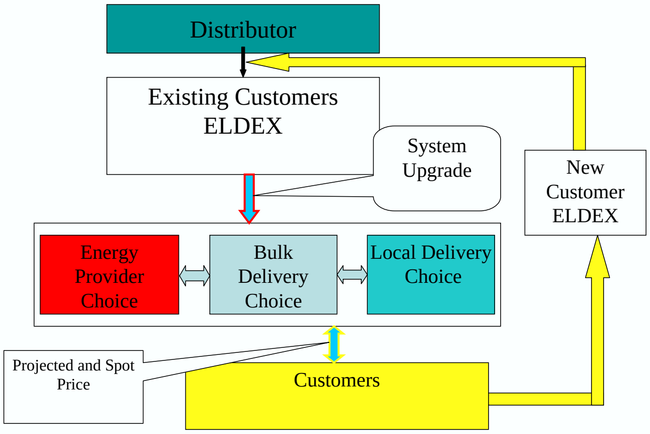


Fig. 2. Distributor: The Key Dynamic Aggregator [8]

This adaptation of various components to changes in system conditions can not be done without understanding what type of data and at which rate must be processed into information essential for adaptation of interest. Broad temporal and spatial and contextual spread makes it a huge challenge. No ordinary ”protocols” can be deployed without taking the physics of the network into consideration.

Finally, an additional need for more timely information processing has come about with the emergence of the electricity markets. The availability of power plants at different times and different locations is generally valued differently. As generation bids are made, these need to be processed interactively between the market clearing and power bidders. For markets to work well, the generation bids must be scheduled with some knowledge of the consumers's demand functions. In [8], the acronym ELDEX was introduced and it stands for Electricity Demand Experiment, which must be carried out to define the customers' demand characteristics, much the way Internet Demand Experiment (INDEX) was carried out some time ago.

IT-based interactions between different industry parties generally take place at various rates and at different spatial coarseness. While it is somewhat understood and accepted that timely information is needed, much R&D is needed to define the type of information which should be exchanged.

Keeping in mind parallels between the revolution of telephony industry and the potential revolution of the (electric) energy industry, the next generation SCADA (IT) for energy systems (the second approach-based) is likely to resemble the paradigms which led to the distributed adaptation in today's Internet. This environment supports naturally the on-line adaptation of the end-users and their iterative interactions with the others. Nevertheless, the presence of the physical energy grid for which the IT needs to be introduced raises the fundamental question concerning the relations between the IT layer and the physical grids for which these are to be designed. Assuring that the performance metrics will be met by the physical grid must somehow be facilitated by the adequate choice of the IT architecture. Recent efforts toward establishing so-called a Common Information Model (CIM) for representing all important objects of an electric power system are not concerned with this very question about what information should be provided and how is it related to the performance of the physical system.We consider this alignment of physical and information network to be the key challenge for next generation energy network systems. Another point of distinction is the need to include economic signals in addition to the technical signals when considering various tradeoffs. This makes the creation of IT for future energy systems a considerable, never before tried challenge.

IV. MODELING AND SIMULATIONS IN SUPPORT OF TODAY'S OPERATING PRACTICES

In this section we contrast the information architectures utilized in the existing SCADA which is intended to support today's operating and planning practices with those we believe that would be critical for future energy systems based on wide-spread adaptation and interactions.

As mentioned earlier, today's SCADA systems in the US electric power grid interconnection are hierarchical and geared to support the current operations and planning industry approach in which the only on-line adaptation is by the power plants. It is also striking that there is no near real-time information exchange between the utilities (control areas) within the interconnection. This information architecture clearly lends itself to the static centralized decision making by each subsystem (control area) on how to adjust the status of power plants by each utility (control area). This is done while forecasting total utility demand, and assuming certain import-export power flow exchanges between the utilities (control areas). All the EMS software of today is based on models which make such assumptions. The software modules range across: (1) unit commitment for turning power plants on and off in order to have enough power to meet the weak-ahead utility demand forecast; (2) economic dispatch to adjust the generation produced by the power plants which are on as the demand is forecast more accurately, on daily or hourly basis; (3) power flow analysis for assessing if the physical variables (line flows, nodal voltages) are within the technically acceptable limits for the power generation and demand patterns obtained running economic dispatch; (4) contingency screening analysis to assess if the system would still be within the technical constraints if any single equipment failure were to take place, and power generation demand profile obtained using (2) and/or (3). System demand forecast is generally done by the centralized software in the EMS center and it does not account for demand characteristics details.

Another basic feature of today's SCADA systems software is that it is not interactive in near real-time. This software does not lend itself to including consumers' willingness to reduce their consumption in response to extreme technical conditions or economic signals. The mathematical models used for the algorithms have models of power plants only. The network nodes where demand is located are simply snapshot forecast load data.

Moreover, today's software in EMS centers is primarily targeted for analysis and not for decision making. The exception to this are the economic dispatch and unit commitment modules which optimize scheduling of real power generated by the power plants. The electric power grid is mainly passive, since the set points for its various controllers are not adjusted in near real-time. Because of this it is not possible to quickly decide on how to adjust settings for controllable line flows, or voltage throughout the system in support of less usual operating conditions.

Also, given that SCADA is primarily implemented at the EHV transmission network portion of the utility grids, the MV/LV local distribution networks are not controlled in real-time. The wire control equipment is pre-programmed for typical demand profile. No interactive adjustments between the EHV (T) transmission networks and MV/LV (D) distribution networks within an utility (control area) are made today.

The consequences of so little on-line adjustment within the complex electric power grid are far reaching. It has been documented that the lack of on-line response other than real power adjustments results in sub-efficient resource utilization during normal conditions as well as in an inability to provide carefully defined services during extreme conditions.

Longer-term planning practices are intended to ensure that there is enough capacity to meet peak demand forecast during the worst-case single (or double) equipment failure. The forecast is usually done at the EMS level and it is invariably wrong, since it is fundamentally impossible to estimate the long-term demand without the long-term ex ante information provided by the consumers themselves. The long-term risk management is entirely static and based on deterministic worst-case condition scenarios. This approach has been known to result in over-design, still subject to hard-to-predict interruptions. The approach is generally the one of risk averse centralized planner.

A. Structural Characteristics of Models Used in Today's SCADA

In order to develop a systematic IT layer in support of physical electric power system operations and planning, it is important to specify:

- Performance objective to be supported by the IT; and
- Adequate mathematical models whose inputs and outputs define the IT required.

Today's SCADA has evolved over time with the need for new applications. At present most of the SCADA functions have a performance objective of estimating equipment conditions and ensuring that the system is viable during steady state (equilibrium) conditions and that the power plants are utilized at as low as possible total generation cost. This is done as demand varies slowly and the state estimators detect some equipment to be out of service. Over time, many numerical techniques have been developed and applied in the control centers, and are routinely used by the system operators. Due to lack of space we omit the detailed description of data processed in today's state estimators, (security-constrained) economic dispatch, unit commitment, power flow analysis, and on-line contingency screening. There is much literature on this, see [4], for example. The numerical complexity of these algorithms has been managed using sparse matrix techniques, as well as so-called localized response property of the power network in steady state. Much effort has gone into exploring this properties in order to run these basic algorithms on-line.

B. Recent Industry Efforts Toward Establishing Sensor Networks, Communications and Control for Monitoring and Controlling System Dynamics

On the other hand, the algorithms for simulating dynamic response of a large power grid to either equipment failure or to the uncertain parameters and/or state perturbations away from steady state equilibria conditions generally do not explore the underlying network structure. This is in part since dynamic simulations are generally done off-line in order to define the worst-case scenarios and operate the system under normal conditions so that if such scenario takes place the instability is avoided. These dynamic simulations are not currently implemented in real time, nor there are on-line measurements (IT) to support such analysis. One of the major roadblocks to faster near real-time transient stability/dynamic small signal simulations and analysis is a lack of structure in dynamic models similar to the structure present in the models used for steady state (equilibrium) EMS applications. This is primarily because typical transient stability models maintain the dynamics of power plants only, while nodes in the network at which demand is connected are eliminated using standard star-delta model reduction [4]. Some of the existing literature recognizes the need for more structure-preserving dynamic models, notably [7]. Nevertheless, it has been very hard to come up with such dynamic load models at the EHV power grid level, and, consequently, demand nodes are routinely eliminated. Independent from the overall paradigm change described in this paper, it has become very clear after the August 2003 US blackout [2] that much more sensing and computing for monitoring system dynamics on-line is necessary. This has led to the follow-up industry efforts, notably the Eastern Interconnection PMU Project (EIPP) [9]. The effort is geared toward deploying so-called Phasor Measurement Units (PMUs) for sensing voltage phase angles of (key) power plants. However, since these devices are still very expensive, they can not be deployed in very large numbers. This raises questions concerning the IT architecture (Wide Area Measurement Systems -WAMS) for communicating on-line these measurements. Also, more recently there have been interesting breakthroughs in designing frequency measurement-based sensor networks and efforts are under way to deploy these. These industry efforts following August 2003 blackout are under way, and some progress is being made toward deploying these technologies. This, in turn, leads to more novel IT-architecture for dynamic monitoring of the complex power grids, such as the Eastern Interconnection in the United States. Again, it is essential to understand the relations of these evolving IT-architecture in light of both performance objectives which it would facilitate and the models to be used. Much more fundamental R&D is needed on this. Our general observation here is that, given the unstructured characteristics of today's transient stability models, it will be very challenging to systematically deploy this new IT-architecture for dynamic monitoring. Determining the best locations for relatively limited number of sensors, and the communication patterns among these sensors and the EMS system so that a provably better system performance is achieved will be a real challenge, both conceptually and numerically.

V. DYNAMIC ENERGY CONTROL PROTOCOLS (DECPS) IN SUPPORT OF FUTURE ENERGY SYSTEMS

As explained at the beginning of this paper, it has become inevitable that future energy systems will have to include much of distributed small-scale power plants (distributed generation-DG-), active response by the consumers, adaptive grid, more responsive policy makers, and other industry entities, electricity markets, system operators, etc. As a matter of fact, even the number and type of entities present within a future energy system will be dynamically varying in response to the overall system situation. Notably, customers are generally going to have a choice in selecting their service providers, and are no longer going to be stranded to their old utility services [13], [6].

While this general paradigm underlies much of the new trends toward ”smart grids”, there is very little understanding of the actual integration processes of these new technologies into the legacy (electric) energy grids. The very dynamics of evolving from today's systems governed by the existing industry practices and model-based SCADA into the new generation IT-supported future energy systems are strongly dependent on the IT in place to facilitate this integration. Viewed this way, we have initial energy system architectures, transitional ones and the end-state architectures as viewed by the proponents of change [13]. As a matter of fact, we believe that it is helpful to view the industry evolution as a constantly evolving process whose dynamics are determined by various technical, economic policy/financial signals. A timely availability of these signals is essential and this is where the IT architecture design begins to play a major role in shaping the energy industry evolution [6]. In particular, presence of a timely IT signal could make all the difference in communicating the value of specific technology to the users. In [8], [10] we have begun to refer to the novel IT-architectures replacing today's SCADA as the Dynamic Energy Control Protocols (DECPs).

We propose in this paper that this essential link between the physical evolution of the future energy systems, on one hand, and the support IT-architecture, on the other, will not be effective without a fundamental conceptualization of the structural characteristics of the new models. Today's models, as described above, simply do not lend themselves to the decentralization, adaptation and interactions, all being salient features of the evolving industry. Just deploying new technologies without equipping them with essential IT-architecture for interacting with the rest of the system by providing the value to the right industry players, at the right location and time, would lead to much waste and

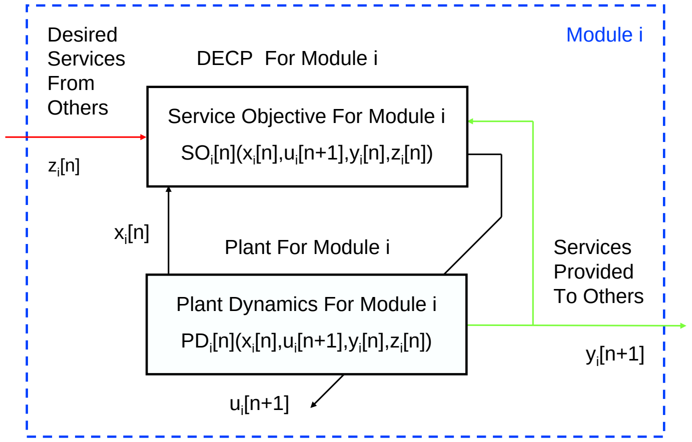


Fig. 3. Basic Modeling of aa Distributed Decision-Driven System Module

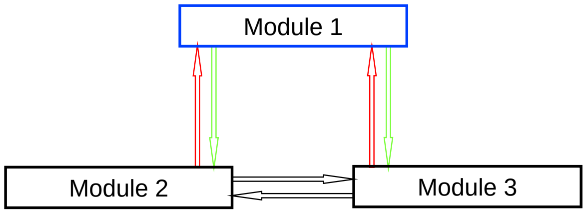


Fig. 4. Decision-Driven Interactions Among System Modules

frustration. Take a drastic example of new wind power: This is an intermittent energy resource with many attractive features (low O&M cost, clean), but the benefits to the energy consumers will not be complete without coordinating this resource with the resources capable of storing energy, notably hydro power, so that the hard-to-control wind power outputs are managed accordingly. Moreover, the value of wind and financial arrangements for this valuation must be done in concert with the others. If this is not done properly, the penetration of large-scale distributed resources will only be a disruptive technology to today's SCADA and, as such, would not be fully utilized. Since the industry is departing from today's centralized SCADA, it is extremely important to conceptualize the effects of the industry changes on the need for qualitatively different models, support algorithms and the related IT-architectures.

In this section we describe the structural features of the new models. To start with, the future energy systems are going to be (and already are) much less stationary than in the past. This points into the direction that, current steady-state, single snapshot models underlying basic applications in today's SCADA will have to be replaced by the models whose inputs are stochastically varying, distributed and often outside of the decision maker and the outputs are interactions with the rest of the energy system, Figure 3.

The decision making is distributed, most typically according to the objective of the decision maker instead of on the system objective. There have been examples of numerous models of such decision makers, ranging from the very simplified ones which assume given conditions in the rest of the system or pose their decision making problem as a statistical optimization problem under very strong assumptions about the environment, such as Gaussian noise, or mean-reverting stochastic processes, or even more sophisticated ones which take higher order statistical characterization of the environment into account when making their own decisions. In our opinion, the most effective are models which view the process of decision making by the multiple agents of similar types under uncertainties [14]. The interactions among these groups of decision makers occur through the physical electric power grid and various policy signals, all facilitated by an interactive IT-architecture sketched in Figure 4. The level of aggregation into modules, and the rules for the information to be exchanged among the modules are open R&D questions ant present. While many local technologies exist for implementing DECPs at each module level (Figure 3), the structure of interaction models is not well defined at present. It is essential to answer the question of IT-architecture capable of facilitating the interactions of these technologies for predictable performance at the value. We assess the fundamentals of the structural characteristics of these evolving models next.

A. Structural Characteristics of the Future Energy System Models

Shown in Figure 4 is a schematics of the future energy networks with many distributed decision makers connected between the network nodes and the ground. Each node has a dynamical characterization, and these local dynamics are subject to interactions with the rest of the system as shown in Figures 3 and 4. The dynamic model of such networks is fundamentally different from those of today. In simple terms, the more active decision makers at the nodes, the more nodes are preserved and the less dense the network is after the star-delta elimination of passive nodes. The actual models of the individual decision makers shown in Figure 3 can be found elsewhere [10], [6]. For purposes of this paper it is important to recognize the co-existence of dynamic models at many nodes within the complex future energy network and the grid imposed equality constraints (Kirchhoff's laws) and the inequality constraints (line flow limits beyond which power cannot be transferred, congestion limits and nodal voltage limits outside which the grid operations are unacceptable). There is much structure in the power flow equations, and this can be explored in the future to establish conditions under which portions of the system can be managed in a distributed way rather than coordinated at each control area level.

Moreover, many sensors and actuators could be placed at the nodes where loads are, in addition to today's SCADA IT-architecture which does not monitor loads nor distributed generation dynamically. Consequently, the overall observability and controllability of the future energy networks could be greatly increased. Completely new questions can be raised concerning the ability to sense and control in a distributed way and to observe and control the interconnected system. Sufficient conditions for this to be done are that the system be fully observable and controllable and that the structure of the system matrix representing the dynamic model is effectively Metzler type matrix [11]. The observability and controllability conditions may be possible to meet in future energy networks with lots of distributed sensors and actuators. As a matter of fact, it will be essential to plan the support IT-architecture (sensors, communications) so that the system as a whole meets these sufficient conditions. Moreover, and very important, is that typical man-made networks are known to be characterized as dynamic systems whose system matrix is a Metzler matrix. In such networks it is possible to establish theoretical bounds within which the system can be controlled and observed in a decentralized way. The weaker interconnections between the nodes, the easier is to meet this condition. For networks with relatively uniform strength of interconnections, this means that the less dense the interconnections the loser couplings between portions of the subsystems which could be managed without additional communications across the subsystems. As a matter of fact the properties are maintained even when any single interconnection within the network is lost, known as the connective stability and connective observability properties [11]. This is critically important for ensuring so-called $(N-1)$ reliability when operating future electric power grids.

These structural properties of future energy grid models form the basis for enabling much more dynamic changes within the system, without having to resort back to the worst-case off-line scenario studies and the inefficient operations during normal conditions in order to avoid dynamic problems when such scenario occurs. The potential savings from avoiding such cumulative inefficiencies are potentially huge. While system-dependent, it is safe to estimate an increase in operational efficiency around 15%, since this is approximately how much reserve is kept to manage the worst-case scenarios today. This is, in turn, potential benefit from deploying right IT-architecture for more adaptive on-line management of available resources. In order to achieve such benefits, much R&D must be done on methods for relating structural properties of the system model and the decomposition/aggregation possible for implementing adaptation for predictable technical performance of the future energy systems.

Particularly challenging are the problems due to saturation of actuators and controllers. In general, when the limits on some controlled loads and/or power plants are reached, the system as a whole may lose the system-wide controllability properties. Similarly if a controller or observer fail, the system-wide properties essential for the distributed adaptation to be effective may be lost. Because of this, it is critical to ensure some redundancy of the IT-architecture and keep some reserve margin when controller happens to reach its limit. Otherwise, typical problems associated with blackouts in today's industry may still occur. Robustness of the model-based IT-architectures must be given particularly serious considerations. One possible approach would be to develop adaptive decomposition and aggregation across the network. This new IT-architecture for ensuring adequate dynamics in future energy networks is a major step forward relative to the very poor knowledge of today's network near real-time system dynamics. If/when this is done carefully, the dynamic behavior of the future energy networks would exhibit reliability properties based on concepts similar to the ones used in Internet today. Reliability is managed in a distributed bottom-up way through active adaptation by both its end users and power plants. An interesting question presents itself concerning the role of learning in such an environment for controlling dynamic response within the energy grid; recently there has been some research indicating that this would be an R&D area worthwhile exploring [12]. Finally, currently asked questions concerning placement of PMUs, Frequency Recorder Units (FRUs), WAMS and the like must be understood in the context of structural properties of the models and supporting IT-architecture designs for predictable performance. This R&D direction is much more promising than in today's SCADAs in which there are simply not enough controllers to ensure robust response in near-real time.

1) The IT-architectures for Implementing Electricity Markets: A very different group of questions arises concerning structure of the models and the related IT architectures for economic decisions, assuming that the new IT-architecture will be capable of ensuring stable response over the broad ranges of conditions. The basic problem is a game-theoretic one, in which different industry participants have separate, often conflicting objectives. The possibilities for novel IT-architectures for supporting economic decisions when offering supply and/or requesting services warrant yet another paper. For purposes of this paper it is important to view the outcomes of both bidding and clearing the bids according to pre-specified criteria as strongly dependent on: (1) how well does (a group of) decision maker(s) model the environment; and (2) the supporting IT-architecture facilitating this decision making. The entire problem of designing IT for predictable and managed performance of the evolving electricity markets must be studied keeping in mind the relations between the models and the IT available to support implementation of such models for desired performance. The ability to implement choice shown in the right column of table in Figure 1 critically hinges on systematic designs of adequate IT architectures. This discussion is omitted from this paper due to lack of space, see [6]. Without describing the details, it should be clear based on the analogy with technical discussion above that without relating the structure of the economic and financial models to the IT-architecture providing key interaction signals, one would experience a real disconnect between the incentives and economic values. The conditions ensuring that the competitive equilibria exist are based on the availability of perfect information. Since this is never the case in real-world systems, many questions concerning the sufficient IT-architecture to support desired economic and financial outcomes of the system as a whole while allowing for distributed, competitive decision making. There is very little research done on this general problem and much R&D will be needed to ensure economic outcomes in the changing energy systems.

VI. CONCLUSIONS

In this paper we have attempted to make the case for systematic deployment of model-based IT-architectures in support of the evolving future energy systems. One of the key observations is that the deployment of many distributed technologies, such as active demand-response and adaptation to the system-wide conditions and distributed renewable generation hold a potential to make future energy systems much more flexible and controllable. However, both their deployment and ultimate benefits will critically depend on replacing today's highly hierarchical SCADA by the interactive IT-architectures of the future. These will comprise many distributed sensors, actuators at the newly deployed distributed physical components (customers,distributed generation, controllable delivery network components) as well as the communications architectures for their interactions in near real time. However, an effective design of these new IT-architectures referred to in this paper as the Dynamic Energy Control Protocols (DECPs) must be based on the fundamental structure of models representing interactions among these components. Most of the hard research concerns identifying these structures and using them for the design of the DECPs. The paper argues that the structures in future energy systems lend themselves more naturally to the distributed decision making and bottom-up interactions among the (groups of) decision makers than in today's networks. While the paper does not fully derive the structures of these new models, the basic rationale for this claim is described. This basic vision is only the beginning of concepts which could be used to develop : (1) novel models; (2) novel software algorithms for distributed sensing and decision making; (3) novel algorithms for grouping of decision makers into near-decomposable portfolios and/or portfolios with common objectives; and, (4) novel models and algorithms for the interactions among the portfolios of decision makers. This must be done with clear objectives to support flexibility and adaptation within future energy systems according to the predictable performance at various industry layers. Such carefully designed model-based DECPs could become the next generation SCADA capable of both near real-time dynamic adaptation for ensuring desired technical response, as well as the slower adaptation for meeting economic and financial objectives in a distributed way within acceptable system-wide performance objectives. Moreover, DECPs would be basic to ensuring reliable and secure energy services even under extreme conditions.

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