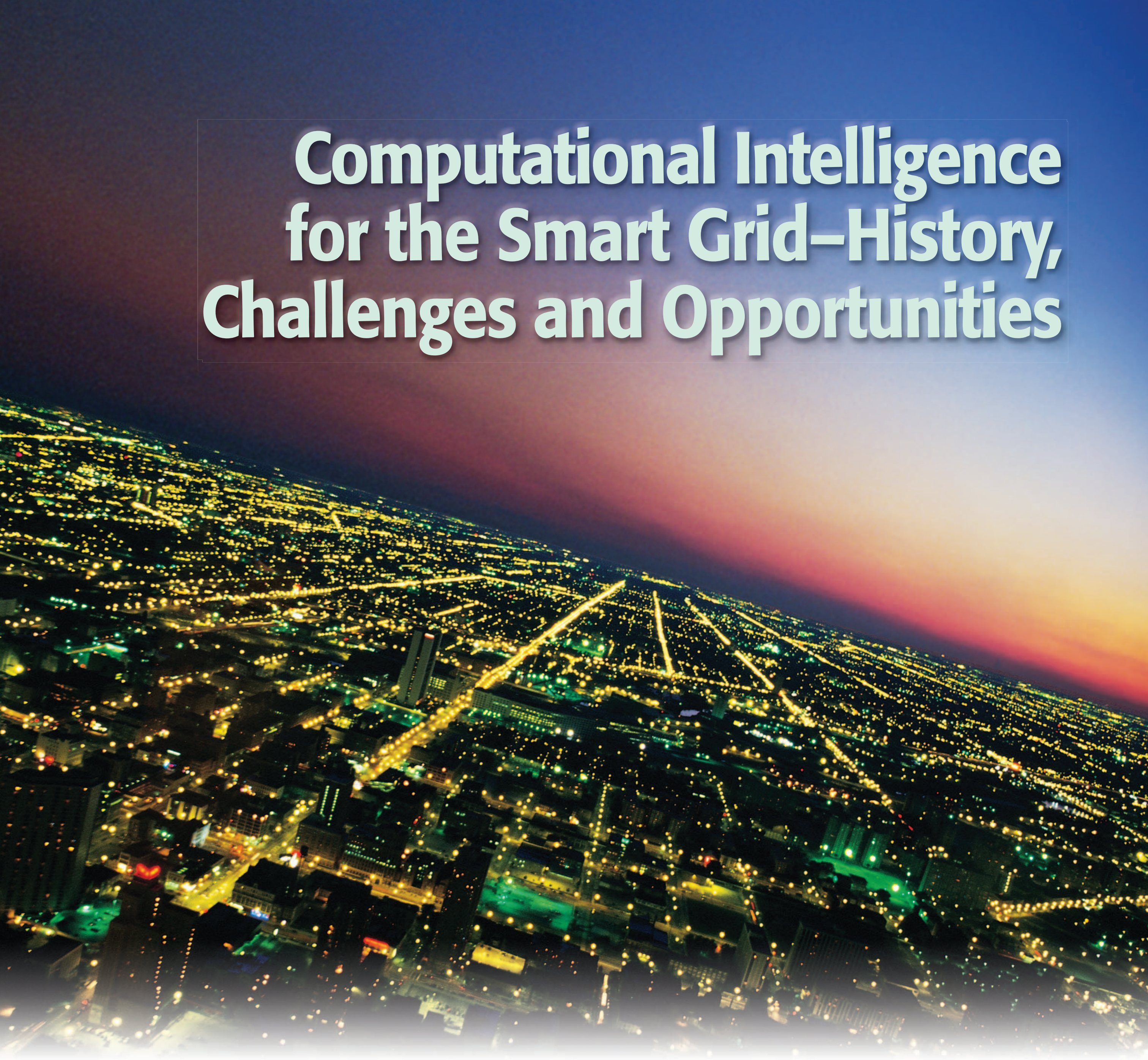
Computational Intelligence for the Smart Grid–History, Challenges and Opportunities



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Abstract–This paper reviews the evolution of four generations of concepts of the "smart grid," the role of computational intelligence in meeting their needs, and key examples of relevant research and tools. The first generation focused on traditional concepts like building more wires, automated meters, workforce development, and reducing blackouts, but it already had many uses for computational intelligence.

The second generation, promulgated by Massoud Amin at EPRI, entailed greater use of global control systems and stability concepts, and coincided with new issues of market design and time of day pricing. New third generation and fourth generation concepts aim for a truly intelligent power grid, addressing new requirements for a sustainable global energy system, making full use of new methods for optimization across time, pluggable electric vehicles, renewable energy, storage, distributed intelligence and new neural networks for handling complexity and stochastic challenges. Important opportunities for society and new fundamental research challenges exist throughout.

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[1] The views herein are those of the author, not representing NSF or any other organization.

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I. Introduction

Computational intelligence faces a wide variety of opportunities to help us meet the global need for a more intelligent electric power grid. To meet these opportunities, we also face some important challenges in upgrading the foundations of our field, and really living up to its full promise. At the same time, talk about the "smart grid" has stimulated many people in all fields – computational intelligence, control theory, and many other fields – to try to get rich quick, without really thinking about where we are trying to get to with the power grid or with intelligent systems in general. Many of us have a special responsibility to understand the larger target, first, before deciding what to propose or what to fund from the huge menu of possibilities. This paper will review the larger needs and strategic situation, introducing specifics in the context of the needs that they serve.

II. Roadmap for the Intelligent Grid–Needs and Opportunities

The fourth generation intelligent grid as illustrated in Figure 1 has an important role to play in the larger urgent task of humanity to achieve a sustainable global energy system [1]. In the long term, we would want all the decisions made in the power grid – from switching of low level relays and generator controls to global decisions made by Regional Transmission Organizations (RTOs), from millisecond-to-millisecond decisions to control unwanted harmonics through to multiyear planning decisions – to be the best possible set of decisions in some sense, with enough sensor inputs to make it possible to compute the best decisions and enough actuators or control authority to get close to the full potential efficiency of the system. In other words, the total collection of algorithms used all across the system should somehow implement a true intelligent optimal control of the system as a whole, with foresight and adaptation and resilience in coping both with random disturbances and systematic threats from terrorists. It should be a true intelligent system.

This vision is *not* the same as the usual concept of multiagent systems, in which each individual component of the system is some kind of intelligent agent. From game theory and economics, we know that systems of multiple optimizing agents will converge, at best, to something called a Nash equilibrium. In the general case, a Nash equilibrium will typically be far inferior to any of the best possible outcomes (Pareto optima), unless there is a special effort to design the larger market system or coordination to achieve some kind of collective optimality. That special effort is one of the key defining elements of the fourth generation vision.

Of course, this vision will not become real overnight. The need for these full capabilities was not fully appreciated until recently. Therefore, I will first review earlier visions of the smart grid, and some tangible near-term needs, which can serve as steppingstones to the real thing.

III. The First Generation Vision

Prior to 1998, the IEEE Power Engineering Society (PES, recently expanded to become the Power and Energy Society) pushed hard for greater national attention to the needs of the power grid. Many engineers argued that the grid is aging rapidly, even as we try to place ever more challenging new demands upon it, such as new nonlinear loads (like computers) which generate harmonics and make it difficult to maintain power quality. They argued that the people needed to maintain that grid are aging even more rapidly – creating a serious workforce crisis, which is more serious now than ever[2]. Bob Thomas of Cornell and of PES argued that we need to revisit the theory of Large-Scale Nonlinear Systems (LSNS), to help us do a better job of minimizing blackouts and cascading outages. In 1986, NSF invited Thomas to come to set up a program in LSNS and in power engineering, starting in 1987, which evolved to become part of the expanded program, EPAS, in existence today.

Many power engineers recognized even then that computational intelligence had a lot to offer in coping with these well-established challenges. For example, Dejan Sobajic of the Electric Power Research Institute (EPRI) recognized the importance of Time-Lagged Recurrent Networks (TLRN) and Backpropagation Through Time (BTT) as a tool for prediction and diagnosis in power systems, and did important substantial work in collaboration with Bernie Widrow. Bob Marks and Mohammed El-Sharkawi from PES helped set up the IEEE Neural Networks Council, and applied neural networks to areas like security assessment. An important annual conference was created, Intelligent Systems Applied to Power (ISAP), which included applications of neural networks, fuzzy logic, evolutionary computing and other methods to power engineering. Mo Yuen-Chow and Kwang Lee developed new, breakthrough systems for real-time diagnostics of electric motors and power systems, using TLRN. Curt Lefebvre, who had earlier developed the NeuroDimensions software package with unique capabilities in handling TLRNs [3] , then used these tools in real-world applications to generator control,

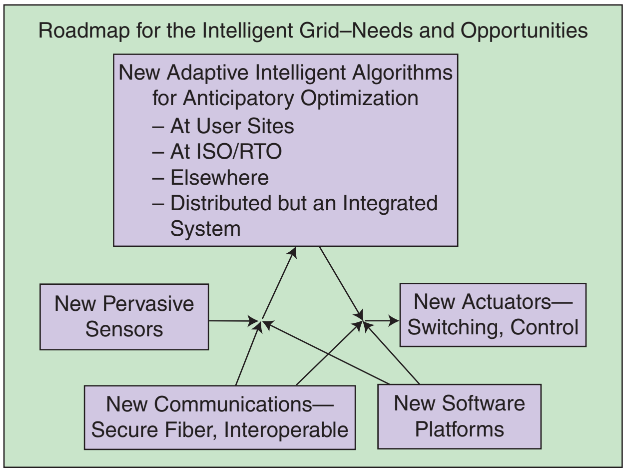

FIGURE 1 Vision of the fourth generation intelligent grid.

New third generation and fourth generation concepts aim for a truly intelligent power grid, addressing new requirements for a sustainable global energy system, making full use of new methods for optimization across time, pluggable electric vehicles, renewable energy, storage, distributed intelligence and new neural networks for handling complexity and stochastic challenges.

which gave him a position as founder and for many years president of a new company, NeuCo. He now estimates that these tools are used in 20% of US coal-fired generators.

At the same time, the power industry itself also recognized many more mundane needs for upgrades – such as the use of automated electricity meters (which did not require human meter readers to go out and measure people's electricity use) and simple sensors and communications to let them know what was actually going on in a complex, diverse grid, with many components dating from before television, let alone the internet.

In essence, the first generation vision of the smart grid is to put lots of money into all of these things – to modernize the grid, to support the kind of research reported at PES and ISAP at a higher level, to build new wires, to install new meters and install some new sensors and communications, to make the existing grid better able to cope with blackouts.

Certainly we need new meters, new wires, new sensors and communications before we can really implement the full fourth generation vision. At the same time, it's important that we not get locked into standards or legacy investments which make it more difficult to move ahead to the fourth generation; for example, overreliance on wireless communications in some parts of the grid may make it actually harder to achieve the security requirements which will become ever more important, as potential adversaries develop access to intelligent systems and the ability to drive by key power installations.

IV. The Second Generation Vision

The next chapter in the story begins, strangely, at a workshop organized by NASA Ames, close to EPRI. A university researcher named Massoud Amin presented an excellent paper on time-lagged recurrent networks[4], which caught the eye of Dejan Sobajic and others at EPRI. They brought Amin to EPRI, where from 1998 to 2001 he pioneered a new effort on smart grids[5], and created what I would view as the second generation vision of the smart grid.

The key element here was essentially an extension of the LSNS idea – an effort to go to the control theory community, to find and develop the best possible methods to achieve stable control of this complex system. Amin also acted as a vigorous spokesman for EPRI in this field. He presented EPRI bar charts showing that total US R&D into the power grid proper, public plus private, was under $20 million per year – a much smaller percentage of revenues than with any other major industry, except trash collection and one other. From then until recently, NSF probably was more than half of the government side of this. For about three years, the Department of Energy has had large additional investments, though the bulk of the funding has done to developments within the scope of the first generation smart grid. After leaving EPRI, he has continued to act as a spokesman for this vision.

Amin also popularized the term "self-healing" in this area.

At the same general time, there was growing interest in the background for a key concept called *time of day pricing*. For a long time, the cost of generating electricity has varied a great deal from hour to hour of the day [6]. Yet customers usually pay the same price for electricity, regardless of the time of day. Economists have long urged us to change this situation, so that prices can reflect costs, and encourage people to buy more of their electricity at times when it is less expensive.

This is called "load shifting." Before 2000, most policy analysts felt that Public Utility Commissions (PUCs) would never allow time-of-day pricing, no matter how much it could add to efficiency and to reducing congestion, but this slowly changed.

Another key development in this period was the acceleration of the "deregulation" of the electric power industry, which many called "reregulation" or "new market rules." Because electric power is a kind of natural monopoly, it is not realistic to talk about "just getting rid of all regulations;" however, major efforts began to try to build as much of a market-based decision system as possible. The key idea was to make the generation of electricity a truly open, competitive market, while creating new Independent Systems Operators (ISOs) and Regional Transmission Organizations (RTOs) to make the higher-level decisions controlling the use of transmission systems, subject to continued regulation by PUCs of transmission companies (transcos) and local distribution companies (discos) which take electricity to "the last mile" to small-scale users. Even now, much of the research and policy thinking on power grids does not properly account for the new central realities of the ISOs and RTOs, described very clearly and mathematically in a series of workshops held in 2010 by the Federal Energy Regulatory Commission [7]. Marija Ilic, who ran electric power at NSF in that period, worked hard to mobilize the PES community to perform R&D to help in these transitions. She also contributed heavily to the more recent workshops at FERC [7], which focused on the most important near-term research challenges related to ISOs and RTOs.

Prior to deregulation, electric utilities were generally allowed to send 1% of their revenues to support research at EPRI, as part of the rate base. Because this was generally lost during deregulation, EPRI went through substantial struggles in later years, especially with regards to its ability to support university-based basic research.

V. The Third Generation Vision

For part of 2001, I was asked to manage the electric power area at NSF, in addition to the long-standing program in computational intelligence, after Marija's return to university.

At that time, the newspapers were full of headlines about California losing many billions of dollars, and many jobs, due to an electric power crisis. The headlines and the high-level decision makers were full of conventional wisdom saying that nothing could be done to reduce the physical cost of electricity to California in less than three years – but I was skeptical. At a recent ISAP conference in Brazil, people in Cepel ("the EPRI of Brazil") had demonstrated new transmission technology which could have saved California many billions, so far as I could tell. Because Brazil does have a kind of European level of higher education, was investing more in grid R&D than the US, and faced major challenges in the electric power area, they had started to deploy technologies for digital control of power flow (Flexible AC Transmission Systems, FACTS, and also magnetic control technology borrowed from Russia) and developed a new technology "SIL" for pumping more electricity safely on existing lines. To help California with its urgent crisis, I contacted EPRI and proposed that we hold a joint workshop in California, inviting the Brazilians, to discussed what could be done on an urgent basis, by importing advanced Brazilian technology to the US.

This led to a fateful meeting in a hotel in Washington between Fritz Kalhammer (a vice-president of EPRI), Massoud Amin, James Momoh (then at Howard but already selected to take over electric power at NSF as a new rotator), myself, and Edris and one other person from EPRI. When I asked Kalhammer to cosponsor the workshop on transmission, he said yes, on one condition. The condition was that we should also cosponsor a workshop on what he viewed as the biggest unmet need for R&D in that industry – the need for global dynamic optimization of the entire power grid as one system. In today's grid, he said, the engineering is all too narrow and stove-piped. People design independent little pieces based on how they would behave in isolation or under some kind of hypothetical model, but there is nothing to guarantee that the pieces all work smoothly together as a larger system. The pieces should be designed to contribute as much as possible to the larger system – as PIECES of the larger system. There should be one large optimization. "I expect you will tell me that this is a pipe dream, and impossible, just like all the other power engineers I have spoken to about this, but this is what we really need more and more for the system as a whole." He was rather surprised at first that Momoh and I agreed so quickly. But in fact – Momoh had spent years developing the world's most advanced Optimal Power Flow (OPF) system, marketed by EPRI, which is probably the most advanced system for that task even today. OPF performs a truly global optimization of the grid already, integrating all kinds of local decisions – but on a SINGLE time-slice, as a kind of static optimization. And I myself had spent many years pioneering the new area of adaptive, approximate dynamic programming (ADP) [8–12], to address the general problem of optimization across multiple time periods, with foresight and learning, in the face of nonlinearity, random disturbance, and complexity, such as what mammal brains must be able to cope with.

So we reached agreement very quickly.

The first workshop, held in October 2001 (one month after 9/11), was an unusual experience. It was chaired by Chen-Ching Liu, well-known in ISAP for his work applying fuzzy logic to power systems. The Brazilians presented extremely impressive detailed plans for how to insert their technology into the Western power grid, which could have stopped the bleeding as soon as six weeks after start of work. The SIL technology would have allowed a quick upgrade of existing power lines between California and the Rockies, allowing underutililized coal plants to sell California low-cost electricity without raising costs or supply in other areas. But high-level political appointees in other agencies of the federal government would not come, because they felt insulted about the whole idea that the US could learn something from Brazil. Speakers for the major ISOs did come, and agreed that the plans from Brazil would be workable immediately – but asserted that the market rules then in place made it impossible for anyone in the US to pay for the upgrades. First, they said, we need the research to change the market rules to empower someone to do the work. EPRI representatives made convincing presentations that the crisis was costing California on the order of $20 billion per year, not really ending "after the crisis." They also quoted major corporations who said they would start outsourcing many, many jobs from Silicon Valley if electricity supply were not fixed up; it wasn't, and they did. The costs to the US economy, and to the funding of California state education, may be substantial to this day.

> **Certainly we need new meters, new wires, new sensors and communications before we can really implement the full fourth generation vision. At the same time, it's important that we not get locked into standards or legacy investments which make it more difficult to move ahead to the fourth generation.**

The second pair of workshops, held back-to-back in April of 2002 in Playa Del Carmen in Mexico (with cosponsorship from Conacyt of Mexico), were far more encouraging. The first workshop focused on global dynamic optimization of the grid, drawing mainly on people active in PES or ISAP. The second workshop focused on algorithms for global dynamic optimization in general, leading to [12]. It was a great warning that some people still asked: "Global dynamic optimization of the grid, and algorithms for global dynamic optimization – what relation could those very different areas possibly have to each other?"

These workshops led to the third generation vision for an intelligent grid, described in the chapters by Momoh and myself in [12]. The key idea was not to simply get rid of the existing OPF methods, but to *augment* OPF by training and adding a value function or critic network. Advanced neural networks would be used to approximate the value function, because of the superior function approximation abilities of traditional multilayer perceptrons (MLP)[13,14] and because we know that neural networks in brain can handle much greater spatial complexity than MLPs [15]. OPF already inputs a measure of present utility as part of the optimization; in dynamic stochastic OPF (DSOPF), it would input the same utility measure plus a value measure representing the future. That neural network critic network could be initialized as something already meaningful to the power grid, such as El-Sharkawi's trained neural network representing the degree of network security. In addition to upgrading OPF, the measures of value, λ, output by OPF would be transmitted as price signals throughout the grid. They would be used to provide a kind of dynamic measure of price, superior to the static measures of locational marginal price in common use today [7].

> **Even now, much of the research and policy thinking on power grids does not properly account for the new central realities of the ISOs and RTOs, described very clearly and mathematically in a series of workshops held in 2010 by the Federal Energy Regulatory Commission [7].**

At the first of these workshops, Venayagamoorthy also presented new empirical laboratory results on the new controller for turbogenerators he had developed with Wunsch and Harley, based on Dual Heuristic Programming (DHP [10]). He showed how it could withstand disturbances three times as large as those which would end up shutting down turbogenerators controlled even by the most capable alternative controllers in use today. This began a collaboration with the "EPRI of Mexico" in Cuernavaca, which may be able to deploy this kind of new technology more easily than the more conservative systems in the US. Note the control of individual turbogenerators requires training a value function of only a dozen variables or so, which can be done relatively easily by online learning or particle swarm optimization or the like with MLPs; more complex systems, like wide-area control [16], require moving up to more powerful neural networks like Object Networks, and returning to more biologically plausible local learning rules like modulated backpropagation.

Though ADP has finally become more popular in mainstream control theory and operations research lately, some of the recent work in control theory has neglected the stochastic case. These applications require returning to the general stochastic case and to model-based approaches (even if the models themselves are a hybrid of neural networks and first principles models) to cope with the complexity of the systems. Of course, the same is required to fully understand similar capabilities in the mammal brain.

At one NSF workshop, a speaker working in classical linear robust control once said: "If all you do is maximize value added or profits, you will lose the reliability of the system. That is hard enough by itself to achieve. You are too optimistic. We prefer that the system should be based on solid theorems proving absolute, unconditional stability. We will not use anything else in the real world." The power company executive who had been funding his work got up and said: "If you have no room for value added, we have no room for you." My reply was perhaps more moderate: "It is you who is overly optimistic. If you think you can offer 100% ironclad guarantees that blackouts will never occur in the power system, you are not really addressing the real world. You are relying too much on imperfect models. With the uncertainties and nonlinearities that we face in the real world, the best that we could do is to minimize the probability of a blackout, or minimize the expected value of the damage due to blackouts. That is an optimization problem, which ADP addresses head-on, as much as we possibly can. I would call this resilient control, as opposed to robust control. But in fact, as economists would tell us, the proper utility function should also include a term to account for value added. There is some value to quality of service or insurance against blackouts, but in order to achieve a Pareto optimum between these concerns and concerns about cost or value added we need to formulate utility functions which account for both of them."

There is a still a role for simple common-sense reliability rules, of course, but the third generation grid would converge to an intelligent balance between the competing goals here. Research in *nonlinear* robust control theory tells us that the most robust controller in the general case is a controller "which solves the Hamilton-Jacobi-Bellman equation;" that is exactly what ADP does, as accurately as we know how to do. There is room for more research to improve our arsenal of general-purpose ADP algorithms, but ADP is exactly that family of methods which exploits adaptation, learning and approximation to "solve the Hamilton-Jacobi Bellman" equation as effectively as possible.

VI. The Fourth Generation Vision

The fourth generation vision has crystallized out from many discussions of global energy needs [1] and real-world markets since 2001. Though I presented an early version of that vision in 2009 [17], this paper itself is perhaps the most complete and reliable statement of that vision to date.

The main objective in the fourth generation grid is to help humanity as much as we can, to overcome energy problems which threaten its very existence.

When I asked Kalhammer to cosponsor the workshop on transmission, he said yes, on one condition. The condition was that we should also cosponsor a workshop on what he viewed as the biggest unmet need for R&D in that industry—the need for global dynamic optimization of the entire power grid as one system.

A. The Vision for Cars and the Grid

The first and most urgent of these problems is the growing dependence on fossil oil, a resource in finite supply which creates severe near-term risks of unmanageable conflict and economic shocks. The technology already exists which would let us become totally independent of the need to use fossil oil[1]: the technology of GEM-fuel flexible plug-in hybrid cars (PHEV). ("GEM" refers to gasoline/ethanol/ methanol – more precisely, the ability to use gasoline, blended (E85) ethanol, blended (M85) methanol, or any combination of the three as a fuel, without requiring the driver to flip any kind of switch when switching between them.)

One key goal of the fourth generation grid is to maximize our ability to use and afford these kinds of GEM-PHEVs, especially in case of a sudden oil shock. Computational intelligence can play a crucial role here, not only at the grid level, but also within the cars themselves – *if* it is used in partnership with other key technologies.

For example, in 2008, Danil Prokhorov of Toyota showed how use of neural network control [18] could improve the mileage of the Prius hybrid by 15% without increasing the cost of the vehicle at all. This is a huge increase, by automotive industry standards. This made heavy use of control by TLRNs, which are also seen as an important core technology in work from Ford, Siemens, and other participants in the IEEE CIS task force on alternative energy. It is very unfortunate that Bernie Widrow's classic example of the truck backer-upper (a TLRN cleverly trained with BTT) has not been so widely used in university courses as it deserves to be.

More recently, there has been a major scare claiming that a scarcity of rare earth materials, required in the permanent magnet motors of hybrid cars, would limit our ability to shift to PHEVs. IEEE has recently coined the more general term "PEV" (pluggable electric vehicles) to include PHEVs, pure electric vehicles (EV) and fuel cell cars which can be plugged in. The scarcity of rare earths would threaten all of these PEVs, and conventional hybrid cars as well. But it turns out that two alternative types of electric motors – induction motors IM and switched reluctance motors SRM – do not require rare earths, and actually allow greater average efficiency across the entire driving cycle, *if* a resilient enough controller can be found for this very challenging nonlinear control problem. (Harley – one of the few really front-line experts in such motors in the US – has reported that SRMs and IMs are about equally good here.) Toyota has recently reported that, thanks to breakthroughs in control, they at least will no longer need the rare earths in the main motor (the traction motor) of their cars. Intelligent nonlinear control can make this more widely available.

Major automobile companies already have control chips able to handle GEM flexibility at fairly low cost – but full use of optimal adaptive methods could allow cars to really optimize performance on the fly as fuel mixes vary, and to use "virtual sensing" [10, chapter 10] to reduce sensor hardware cost. TLRNs and ADP are the two key technologies needed here, in partnership with domain experts. Work by Sarangapani demonstrating efficiency improvements by use of ADP on Otto and diesel engines may be a useful first step towards this goal.

Even more important to PHEVs is the goal of reducing the cost of batteries and power electronics, which ends up requiring longer battery lifetimes and flexibility in getting full use of new types of power electronics. Battery manufacturers have told me that lack of general, flexible battery management systems good enough for use in cars is the main obstacle to companies like GM getting full use of the lowest-cost effective batteries now available – let alone starting the use of new types of batteries. Ordinary ADP and TLRNs should do well enough, with the right data input and variables, for overall control of batteries – but to control individual battery cells better, and handle new switching degrees of freedom within batteries (as explored, for example, by Song Ci [19]), might require use of Object Nets, because of the complexity and network properties of the task. For power electronics, new NSF-funded work by Khaligh and Emadi has demonstrated that new power chips and high-frequency designs (http://hybrid.iit.edu) could halve the cost of power electronics for advanced PHEVs like the Chevrolet Volt, while adding a fast recharge capability able to plug into standard 480 volts AC "level three" recharging as defined in the National Electric Code. This opens up new opportunities for control , and also makes a radical change in what the future grid might look like, since 480 volts AC is much easier for the grid to provide than the fast DC recharge stations now being deployed in the US and Japan.

Many believe that the primary obstacle to greater use of PHEVs occurs at the local level of the power grid [20]. There, too, the technology of high frequency power conversion [21] may play a crucial role. The demonstrations of Khaligh and Emadi basically tell us that we could use the new chip-based technology at the local distribution level as well, but we do not yet know whether costs would be reduced enough to justify a massive replacement of old transformers with new (higher rated) chip-based power converters. The benefit of the new type of converters may depend on our ability to actually exploit the new switching capabilities they require, which requires that they be paired with more intelligent control and a smarter distribution grid. In short, greater intelligence may be a crucial part of the essential transformation here. This new

The results in Germany [24] show that the potential contribution of demand response to load shifting is far greater than traditional field or elasticity studies reveal, because new technologies and automation allow demand to respond more intelligently to price in the future than it can at present.

switchability would also allow better defense against serious near-term threats like massive solar storms [22].

B. The Vision for Renewables and Peak Shaving

The most crucial advantage of DSOPF over traditional OPF and static optimization methods concerns *foresight* – the ability to juggle supply and demand across time, in the face of uncertainty.

The balancing of supply and demand across time is already a major economic issue for power grids[6]. For example, a large part of the cost of transmission systems is the cost of wires designed to handle the rare times of peak load, such as air conditioning at noon in the hottest few days of the summer. Even today, a better balancing across time could lead to substantial savings, and less need to build new wires (or less risk of blackouts with a given level of buildout) [7].

One key feature of the fourth generation grid will be many new ways to do time-shifting of the traditional sources and generators: (1) better demand response – ability of loads to adapt as prices change over the day; (2) better "ramping," ability to change generation levels efficiently, as in the talk by Alstom at the FERC workshops [7]; and (3) more storage in the grid, in part perhaps because of PEVs hooked up to the grid (as in "vehicle to grid" technology, V2G) but also because of greater use of new batteries – both central and distributed – as well as compressed air storage and more pumped hydro. (Note that I do not include hydrogen in this context, even though it is a very efficient way to consume taxpayer dollars, and a wonderful fuel for reusable rocketplanes, which, if done right, would add energy from space to the menu of affordable renewable energy options.) To take full advantage of all these new degrees of freedom, we need to be able to perform better optimization across time. To account for uncertainties and unpredictable events as part of this optimization, there is essentially no alternative to the development of more powerful ADP systems, at all levels of the grid.

Among the key uncertainties, of course, is uncertainty about when the wind will blow, as well as uncertainties about clouds floating over solar farms, rooftop PVs and uncertainties in load.

Very sophisticated optimization methods are already in use at ISOs and RTOs, for all the different traditional time scales used in electric power, from regulation to planning . Thus it is already apparent that better capabilities and use for ADP, on the scale of complexity encountered in power grids, could be of great assistance in what ISOs and RTOs already do. This is already under discussion in the FERC community [7], but new more advanced neural network tools will be essential to making it work on the scale required. Many of the benefits of intelligence come from adding things like anticipation to day-ahead unit commitments, so as to reduce the cost of adaptation when it comes time to do actual dispatch; similar benefits exist with large logistics systems where similar methods may be used [23].

Many US researchers have argued that household demand for electricity can be shifted a few second or minutes, but not enough to make major changes in our ability to use renewable energy sources like wind, which require load shifting from one time of day to another or more. Studies prove that this is true, for more conventional types of load shifting or demand response. However, a combination of simulation studies and field studies in Germany [24] using a new software platform "OGEMA" have demonstrated that massive load-shifting can be achieved in a system which allows intelligent agents to be inserted both at the grid level and at the household level. The true fourth generation grid would insert true intelligent systems (based on ADP) as services at both levels, designed so that the combination of these "services" itself is an implementation of a larger virtual ADP decision-making system including both levels. The results in Germany [24] show that the potential contribution of demand response to load shifting is far greater than traditional field or elasticity studies reveal, because new technologies and automation allow demand to respond more intelligently to price in the future than it can at present.

Of course, the optimization to be performed here would actually be a multicriterion optimization, respecting the right of individual household to specify the parameters of their respective parts of the greater utility function. Even today's OPF systems do this kind of thing implicitly. The development of Pareto optimality theorems and stability results for multiplayer ADP systems is one of the useful potential areas for future research here, probably requiring collaboration of economists and engineers, as with other aspects of market design. This should be a very viable line of research, since Dynamic Stochastic General Equilibrium theory and DSOPF have many common assumptions, and the "lambda" vectors common to all three of them are essentially the same vectors.

Another aspect of this challenge is to expand the intelligent optimization to also include the many new degrees of freedom offered by recent breakthroughs in the technology for controlling flows of electricity in the grid [21, 25-29] as well as the new sensor information resulting from NSF-funded research on phasors [30] and other relevant types of sensors. It has been estimated that effective use of such new technology could cut the cost of transmission lines for renewable energy in half [29]. These kinds of cost reductions, *combined with* other essential breakthroughs and R&D in energy technology (also within the scope of EPAS funding), could make it possible for humanity as a whole to transition to renewable energy without nuclear proliferation risks, and without paying more for electricity than we do today.

Greater use of civilian nuclear fission power in developing nations could result in a massive increase in the availability of sensitive materials and technologies, even to substate actors; the renewable path would be far safer, if we can also make it more affordable.

McElroy and his collaborators [31] have estimated that the onshore wind resources of the US (and other nations) are many times larger than their entire electricity demand, and should cost only 6.7 cents per kwh for generation as such; if we can make deep reductions in the additional costs due to the difficulty of using 80% wind on the power grid, this would already allow us to make a massive transition at an affordable cost. Many of us believe that solar farms, especially with new energy conversion systems for solar thermal power, have the potential to be even more reliable and less expensive. Energy from space, such as space solar power or laser-induced deuterium-deuterium fusion in space, also looks likely to be a low-cost energy source, if necessary work on lower cost reusable access to space could be initiated. These three sources, between them, are very likely to be able to meet all the needs of the earth at an affordable cost, sooner than we expect – if we develop a power grid fully able to use them.

VII. Summary and Conclusions

Enormous investments are now being made to upgrade electric power grids, and to implement the first and second generation visions of the smart grid. This paper has provided a roadmap for reaching a fourth-generation power grid, which would build on those kinds of investments, and would use intelligent system-wide optimization to allow up to 80% of electricity to come from renewable sources and 80% of cars to be pluggable electric vehicles (PEV) without compromising reliability, and at minimum cost to the world economy. It is one of the crucial elements of a global strategy to address urgent issues of sustainability in economic growth and progress which appear to be a matter of life or death for humanity as a whole.

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