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Author(s)	Hill, DJ; Liu, T; Verbic, G
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Smart Grids as Distributed Learning Control

D.J.Hill, *Fellow, IEEE*, T.Liu and G.Verbic, *Senior Member, IEEE*

Abstract—The topic of smart grids has received a lot of attention but from a scientific point of view it is a highly imprecise concept. This paper attempts to describe what could ultimately work as a control process to fulfill the aims usually stated for such grids without throwing away some important principles established by the pioneers in power system control. In modern terms, we need distributed (or multi-agent) learning control which is suggested to work with a certain consensus mechanism which appears to leave room for achieving cyber-physical security, robustness and performance goals.

Index Terms— Distributed control, Networked control systems, Adaptive systems, Smart grids

I. INTRODUCTION

THE topic of smart grids has attracted a lot of attention recently. This paper aims to rephrase the goals and possible implementation of the smart grid agenda in terms of control engineering. The coordination of massive numbers of control devices at different voltage levels gives challenges in uncertainty, scale and control granularity. Two key ideas which can address this are hierarchical distributed control and use of learning.

The term ‘smart grids’ means many things to many people and there is certainly no agreed definition. It is common to hear people say they are working on smart grids anywhere from designing meters or power electronic converters, WiMAX communications to some new look at system dynamics. There is even the debate over whether we should use the term at all. Engineers and academics who have spent years working on advanced control systems for bulk power systems can be a bit put perplexed that the term gets so much ‘hype’ simply because the distribution people have now seen the need for better monitoring and control. These ideas notwithstanding, this paper takes the view that the discipline of ‘smart grids’ has meaning as an area focused on embedded intelligence from a systems approach somewhat ahead of the current state in industry (so maybe ‘smarter grids’), but it remains to more clearly define what we are talking about and what the research goals are, i.e. to put some serious science into the idea. We take the view that this paradigm can apply

anywhere in the whole energy network, but the current

emphasis is on distribution systems, because that is where the development of automation has been least advanced to now. Some ideas towards this aim are presented here. Ultimately, at the core of the smart grid agenda, the goal is to achieve a system which is more adaptive and resilient to changing power supply/demand, failures and attacks. The presentation of a clearer formulation inevitably leads to an agenda of estimation, optimization, learning and control. Thus we can conclude that there should be a very exciting road ahead for collaboration between the power and control areas. Actually, distributed control has strong connections to so-called multi-agent systems, the term used for related ideas in computer and systems sciences and we will use this interchangeably in referring to other work.

The paper is structured as follows. Section II will give a brief overview of the developments influencing power systems. Section III gives a review of power system control. Section IV gives an overview of some recent work in the modern field of distributed control. Section V looks at some research questions that require collaboration between power and control people. Finally, Section VI gives some conclusions. It should be noted that for sake of conceptual flow, brevity and the inevitable influence of our own work, there will be many important aspects of the areas of power systems and distributed control which had to be omitted.

II. MODERN POWER SYSTEMS

It is often said that power systems are currently undergoing a transformation from something that Edison and Tesla would still essentially recognize to something like an energy version of ‘the Internet of things’.

However at this level of anticipation we have major questions about what future grids will look like. In this paper, we will deal with a stage somewhere in between the current state of smart grid development and scenarios where the grid might be dramatically different. Thus we are looking at a situation where larger generators feed into a transmission grid and loads and smaller generators are scattered across sub-transmission and distribution grids.

In Australia at least, it is recognized that there are two main drivers for change [1]. Firstly, there are innovative engineers, often with ICT backgrounds, inside the industry on a journey to make the grid more observable. This has been a journey over decades from SCADA to MPLS to WiMAX networks as progressively lower voltages are covered. The second main driver is external, arising from the emerging energy agenda related to reducing carbon footprints, renewable energy and new loads such as PHEVs. However, we suggest that grids

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D.J.Hill and G.Verbic are with the School of Electrical and Information Engineering, The University of Sydney, NSW 2006, Australia (email: {david.hill, gregor.verbic}@sydney.edu.au)

D.J.Hill is also with National ICT Australia, Australian Technology Park Level 5, 13 Garden Street, Eveleigh NSW 2015, Australia

T.Liu is with the Research School of Engineering, The Australian National University, ACT 0200, Australia (email: tao.liu@anu.edu.au)

with more observability, renewables and PHEVs are not ‘smart’; they are just prepared for it.

Another trend in power systems that arises naturally from extending generation and monitoring to lower voltages is that from a systems point of view, the distinction between transmission and distribution is less distinct. From a control point of view, we now have levels of control granulated to the point where household power control can in principle be harnessed to influence the bulk system. This opens up many possibilities, some requiring care not to cause problems.

III. REVIEW OF POWER SYSTEM CONTROL

Having noted some trends in power systems, there are major implications for future power system control. In this Section, we review traditional control and then look more closely at smart grids.

A. Classical power systems

Depending on the time scale and the operating state, planning and operation of power systems can be classified into the following stages, with distinctively different objectives: planning, balance, stability, performance and recovery. In the *planning* stage, power systems are designed and planned with the future operating conditions in mind to survive most foreseeable disturbances. Control plays a central role in all these stages. Planning must be considered in connection to anticipated controls, which in turn make a particular plan feasible. The other stages relate directly to control systems. The key concerns are frequency, line flows (or phase angles) and voltages. There is a large array of concepts and techniques accumulating the efforts of generations of innovative engineers revered in the power community, but not known to many control theoreticians. To mention one such person related to our topic, Cohn [2] made contributions to the control of interconnected power systems which make large high voltage grids possible. He developed automatic generation control (AGC) of generation outputs in response to load changes to ensure tie-line interchange and frequency are regulated (using PI control). This included the application of distributed frequency-biased net interchange controls. A well-known reference book is by Kundur, another major contributor to power system dynamics and control [3].

In real time, the main objective of power system operation is to keep the system in power *balance*. A nominal balance is provided by generation dispatch mechanisms, usually in a market environment with market clearing using generator and demand bids. The clearing procedure might also include ancillary services, e.g. operating reserves. Overall, balance involves keeping voltages across the system and the frequency within tight limits. This means that the balance between the generation and the demand needs to be in perfect balance at all times. Due to ever present disturbances, several control mechanisms are in place to maintain power system *stability*, i.e. to prevent loss of synchronism and to achieve good post-fault voltage regulation following a large fault.

In normal operating state, *performance* is of major importance, which encompasses both technical and economic performance. Technical performance means keeping frequency and voltage close to nominal while maintaining

reliability standards, i.e. maximizing robustness and minimizing vulnerability, so the system can withstand credible contingencies without significant impact on the participants.

Power system *recovery* might be needed following a complete or partial power system blackout. To avoid blackouts, power system operators need to rely on specifically designed control actions to bring the system back to normal operation following large unanticipated contingencies, when several operational constraints can be violated. These actions are often in direct contradiction with economic performance. For purposes of analyzing power system security and designing appropriate control systems, it is helpful to conceptually classify the system-operating conditions into five states: normal, alert, emergency, in extremis, and restorative. These reflect control approaches following the anticipated operating conditions and contingencies [3].

The complexity of power systems renders centralized control impractical, so the control has been traditionally organized in a multi-level hierarchical manner. The control hierarchy follows the constitution of power systems, i.e. the transmission system, the distribution system, the generators and the loads. The resulting control scheme thus consists of various nested control loops controlling different quantities in the system. Typically, low-level controls are associated with shorter time constants, which ensures virtual decoupling of the various loops. Control is further decoupled relying on distinct underlying physics. For example, at the generator level, voltage and frequency are controlled in separate control loops using voltage and turbine controllers, respectively. There is usually some form of overall plant controller that coordinates the controls of closely linked elements. The plant controllers are in turn supervised by system controllers at the operating centers. AGC was mentioned above. Supervisory voltage control, on the other hand, makes sure that reactive power flows are minimal, which in turn reduces losses in the system. These functions are usually provided by regional control centers, usually called the transmission system operators (TSO), coordinating their respective control areas. Several TSOs might be, but not necessarily, coordinated by a central master controller. The 2006 UCTE blackout, for example, can be largely attributed to lack of central control in Europe at the time [4]. In the absence of a central master controller, the coordination between TSOs is achieved by the exchange of relevant information.

At distribution levels, where voltages are lower and so losses higher, and the network more radial in structure, the control goals are more oriented to efficiency, recovery from outages and voltage control.

Information technology has played an increasingly important role in power system control. It is standard at transmission levels for Supervisory Control and Data Acquisition (SCADA) to provide real-time data every 2 secs, state estimation, optimal power flow, security analysis; there are automatic emergency schemes for shedding load on voltage and frequency – certainly ‘smart’ compared to ideas in development for distribution systems. This is a control paradigm developed decades ago, in the USA following the 1965 blackout, and it is confined to the so-called bulk power system (generation and transmission) with a tendency to treat

problems in angle, voltage and frequency separately. More recent developments which are in the spirit of system-wide control are in Wide Area Monitoring and Control (WAMC) and Special Protection Services (SPS) [5, 6].

Most distribution companies have SCADA these days based on Remote Terminal Units (RTUs) placed at monitoring points to collect local data (usually current, voltage and apparent power) and apply pre-programmed logic type control. Such monitoring and control usually only goes down to zone substation level, i.e. rarely into the LV network. Security control here is typically very basic: phone calls from customers, truck rolls, manual inspections and reclosures.

A key observation is that at all voltage levels, current power systems in normal operation have a large dependence on decentralized control: voltage regulators, PSS, AGC and basic synchronising steps all use just local information. The idea is to rely on local information as much as possible to reduce the communication requirements and enable fast response. The disturbances are thus handled at their origin in order to stop the problems from propagating through the network. Centralised influences occur for balancing dispatch, monitoring via SCADA, manual control, some PSS coordination schemes and some defense schemes for security assessment and recovery. In case of emergencies, centralized control is needed as the interaction between the TSOs might be important so a ‘big picture’ is needed.

The above-mentioned trends challenge these existing control schemes and even more so the associated protection schemes which assume unilateral flows and predictable situations. For small levels of renewables, the generation can be regarded as negative load and the existing systems will cope. But there is surely a tipping point where this can no longer be trusted. It has been variously suggested (but not with any universal message) that this figure could be around 20-30% renewable energy.

B. Smart grids

‘Smart grids’ are generally about better control across all levels, but especially at low voltages. The key point above is that we have been so far able to use decentralised control for normal state, and little automatic control in parts of the LV network. Coordinated control is useful in places. However, there now appears a major leap in opportunity for control. The question becomes what to do with that opportunity to realise benefits but not create other problems.

In Australia, the focus for ‘smart grids’ is on sub-transmission and distribution systems, i.e. 132kV and lower, and this influences what is presented here. The scale of the numbers of devices at distribution level involved requires new solutions for coordination. However, in principle, improvements across all voltage levels appear possible with the smart grid viewpoint.

Presentations of smart grids are normally given in terms of equipment or behaviour. For the latter, we refer to the USA DOE statement [7], including such features as self-healing, operating efficiently and enabling demand response. Such capabilities are being built into the Australian SGSC project [8]. However, as soon as we move to what a smart grid actually is, the discussion is normally about equipment and

particularly measurement of the previously unmeasured. Vendors worldwide, the traditional power ones as well as in communications and computing, are presenting exciting new products with names like Gridrouter with PMUs and transmission type power electronic controllers for low voltages. Here thinking has hardly connected to control engineering, where the emphasis is on concepts like states, knowledge, inference, learning and feedback. Everything has data capable of being distributed on an IP-based network. These network devices will include computers capable of local processing. For example PMUs, previously used sparingly at transmission levels will in the future give detailed phase, voltage etc all over the system. Optical sensors can be scattered far and wide. And of course there are the smart meters. So from a control engineering viewpoint, we get a huge embedded control problem.

One issue that concerns control engineers is latency times. The latency times required vary substantially from one control loop to another. While for VoIP, 200ms might be acceptable, in power system control anything between 1ms to 40ms in Distribution Automation can be needed. Such requirements are of course achievable by a strong traditional communications network but this will not likely be the most efficient way. However, the co-design of observability and control of this complexity is somewhat challenging at this point. The development of the networking appears to be ahead of research in how it will work with the other layers in the overall cyber-physical system. We will refer to this approach as the *communications-based smart grid* (CBSG).

A structural feature that we should recognize for a CBSG is that it consists of interdependent networks (or a network of networks, i.e. layers of power, communications, computing and control (which does align a little with the Internet idea). Otherwise, we can think of microgrids or more general clusters [9] interacting with ICT.

There is another line of thinking which is emerging, i.e. that we should not leave the future so dependent on affording strong communications networks. The higher voltage levels substantially operate with decentralized control as noted above. More modern FACTS devices like SVCs, STATCOMs respond to local measurements while allowing more centralised set-point control. With these devices being now designed for low voltages, along with new devices such as the ‘electric spring’ [10], where a novel mechanism at each load shares supply uncertainty the possibility of dealing with uncertainty and granularity in a highly distributed way remains a possibility. This has the attraction of alignment with previous use of decentralized control.

C. Beyond the hype

Researchers are generally very pleased for the arrival of smart grids, power engineers after a relatively quiet decade or more in power systems research and control engineers since many of the goals motivate their current attention to control over networks – see the next Section IV. But there is a lot of ‘hype’ amongst the excitement and that’s natural for a while.

Taking the word ‘smart’ seriously suggests capabilities like cognitive ability in humans, i.e. memory, association, images, patterns, attention, action, problem solving, which could be

summarised as self-awareness, self-organising and self-recovery for our purposes. In a word, the control terms ‘adaptive’ or ‘learning’ are more meaningful to scientifically capture the essence of what is needed. We will argue that ultimately this capability needs to be ‘distributed’. Networks need to know what is happening elsewhere, what might happen, be able to adapt locally and globally and finally to keep operating when things go wrong.

To make a step towards defining smart grids as a control process, we suggest it is an electricity network with in-built or embedded processes which ensure:

1. Observability of all power flows, voltages, currents, phases and frequency;
2. Inference to translate the data to knowledge (as indicators) about balance, stability, performance and recovery;
3. Distributed granulated decision and control to ensure balancing, stability, performance and recovery;
4. Emergency reconfiguration for recovery.

Multi-level monitoring and diagnosis will build self-awareness. One of the first useful outcomes can be a reliable state estimate [11], [12] which is essential for analytics and control. Distributed learning control responding to uncertainty gives self-organising capability. Reconfigurability to attack problems as they arise in a staged response gives self-recovery (or self-healing).

The process of utilising the data may be impeded by the sheer volume, especially if it is collected in a central data centre [13]. This approach, which follows naturally from the SCADA use of this star topology, even at higher voltages has been questioned especially for recovery (as in SPS schemes).

Analytics which provide prediction, optimisation, enhanced protection are clearly useful. The step to the ability to automatically respond to changes and events within distribution automation requires a large cultural change to allow manual operators to hand-over more to automation. Advanced distributed intelligence and control schemes will certainly enable adaptive tele-protection and learning processes to manage fast response to emergencies.

As illustrations of control projects at the distribution level, we have Active Volt-VAR Control (AVVC) and Fault Detection, Isolation and Restoration (FDIR). These are clearly set-up for advanced distributed control over the new communication networks. Using distributed control to build adaptivity to the changing circumstances needs to deal with the scale of millions of devices. Centralised control (within the CBSG framework) is clearly limited for scaling. On the other hand, it remains to be seen how far a decentralised approach can work. Looking back at classical power system control, recall that for basic operation many controls were decentralized, but for recovery more centralized systems prevailed. This trade-off between centralized vs decentralized is new to LV networks and is complicated by the huge number of devices to be coordinated. The issue of scaling is of course a key one in the field of algorithms in computer science for optimisation, sorting and the like. Here it appears we can derive some useful techniques such as combining optimisation with learning ideas.

In Australia, the SGSC project has projects in AVVC,

FDIR and other so-called grid application areas. A similar state supported project is Korea’s Jeju Island Smart grid Test-bed [14]. In Australia and North America there are many smart-meter projects focused on demand management, electric vehicles and customer applications.

IV. REVIEW OF DISTRIBUTED CONTROL

The field of control has progressed largely by redeveloping an agenda of modeling, estimation, stability analysis and feedback design for progressively more difficult models including large-scale systems, adaptive systems, nonlinear systems and more recently topics very relevant to smart grids such as hybrid systems (allowing switching events), distributed control (which allows local controllers to interact), and networked control (which usually refers to control over a communications network). Here we make a brief review of some recent ideas in distributed control that appear relevant to future power system control.

A. Centralized vs Distributed Control

When the information of the entire system are available for the design purpose, then all subsystems can be lumped together as a single system and typical modern control methods such as linear-quadratic (LQ) optimal control and pole placement for linear control systems can be applied. This method is termed as *centralized control*. One of its key features is that all sensors signals are sent to a single processor to produce the control signals, which results in the fact that every sensor output affects every actuator input.

However, for a large-scale system, both the synthesis and the implementation of a centralized controller are often impossible in practice [15]. Firstly, a large-scale system may have a huge number of states, inputs and outputs, and classical optimal control design algorithms usually cannot handle such a design problem. Secondly, in many systems, subsystems are geographically distributed. Thus, to implement a centralized control scheme, unknown variations of the original interconnection topology of the system are inevitable.

In response to these concerns, *decentralized control* method has been proposed where information transferring between certain groups of sensors or actuators is restricted. This characteristic may reduce the implementation and calculation complexity of the control laws. But the drawbacks are that such controllers may need more ‘intelligence’ to handle uncertainties, and performances of systems with decentralized controllers may be not as good as those of systems with centralized controllers. For more details of decentralized control, please refer to a survey [16], a recent monograph [17] and references therein.

In order to strike a balance between centralized control and decentralized control, i.e. to achieve better performance similar to centralized control as well as to reduce the complexity for the controller design like decentralized control, *distributed control* has been explored, where each controller can receive a restricted subset of sensor signals from other subsystems and the control algorithms are calculated based on all of these available information. From this point of view, decentralized control can be seen as a special case of distributed control [18].

Generally, for a more complicated problem, *hierarchical control* may be preferred because it decomposes the problem into more manageable units, and centralized control, decentralized control and distributed control may be used in different layers according to different control purposes [19].

B. Optimal Design for Distributed Control

For a general linear quadratic Gaussian (LQG) optimal control system with a global cost function, optimization methods have also been developed in the literature to design distributed controllers [20]. The obtained method has linear complexity and the property that adding new agents to an already existing system only changes the calculations in previously existing neighbors. In [21], dynamic price mechanisms were introduced for decomposition and distributed optimization of feedback systems.

Optimal decentralized controllers were constructed by minimizing a closed-loop norm of a feedback system subject to constraints on controller structure in [22]. An algebraic condition – *quadratic invariance* was introduced to identify a class of constraint sets with respect to the system, under which the design controller problem can be solved by convex optimization. This condition was also used to design distributed controllers for a network of control systems connected over a graph in the literature.

Another import topic in this area is Distributed Model Predictive Control (DMPC) which is an extension of the classical MPC for networks or large-scale systems (for details of MPC, please refer [23] and references there in). In [23], this method was used to achieve coordination among agents where the MPC problems were solved with only local information. The cases where the agents can or cannot exchange information when solving their local optimization problems were considered. In [24], the DMPC controllers were designed based on the dual decomposition of the convex optimization problem, and a stopping criterion for the DMPC scheme which was verified by each agent itself and guaranteed closed-loop suboptimality above a pre-specified level of the system was given to reduce the amount of iterations.

C. Control Over Communication Networks

Since network technology becomes cheaper and more reliable than fixed point-to-point connections, more and more control systems have operated over networks, where sensor, actuator, diagnostic, command and coordination signals may all travel over data networks. The estimation and control functions might be distributed across multiple processors, also linked by data networks, which leads to control distributed across multiple computational units, interconnected through packet-based digital communications [25]. These also make the entire system have a hybrid nature [26], and stimulate the research in the relevant field.

Event-triggered based control is one of the recent directions in this field. To reduce the complexity of computation as well as the burden of transmissions without destroying the performance of the system, control signals of such a controller are kept constant until the violation of a condition on the state of the system triggers the re-computation of the control signals

[27]. Issues of packet loss and transmission delays arising in distributed nonlinear networked control systems were studied in [28], where a subsystem broadcasts its state error to its neighbors only when the subsystem's state error exceeds a specified threshold. The maximal allowable number of successive data dropouts (MANSD) and the state-based deadlines for transmission delays were predicted. Under the assumption on the MANSD, different types of stability of the resulting system were obtained for cases whether delays being zero or not.

On the other hand, communication networks usually have finite bandwidth, which makes computational and communication constraints of the information to be transferred become a significant issue in performing control operations. Therefore, control under finite bandwidth communication constraints or digital finite communication bandwidth control as well as some related issues like systems with quantized states and the interplay among data rates, coding structure, communication protocol, and dynamic behavior of the controlled system has received much attention in the past decade. Recently, the authors of [29] studied control system dynamics with finite communication bandwidth control, where multiple agents collaboratively provide inputs to a control system in order to achieve a common objective that no single agent could achieve alone, which is related to both nonlinear optimal control and the information-exchange in the distributed control of nonlinear systems.

D. Consensus, Synchronization and Feedback Networks

Other active areas in control science, which are closely related to distributed control are consensus of multi-agent systems and synchronization of dynamical networks. By combining synchronization of dynamical network and consensus of multi-agent systems where independent agents are controlled over a network [30], i.e., the closed-loop system becomes a kind of time-varying network, the authors presented a framework for so-called feedback networks. For more details for related areas, refer to recent surveys [31, 32] and application to power systems [33].

Special attention has been paid to the optimization of LQG control systems with a large population of identical subsystems or agents. Approximation techniques and numerical methods for computing various suboptimal centralized controllers have been developed in the literature where coupled Riccati equations play a critical role. As discussed above, for systems with a large population, these approaches have the basic limitation of computational complexity. To obtain simplified and efficient control laws, the *Mean Field* concept (well-known in complex networks) was introduced in [34], in which a game theoretic approach was used for the design of decentralized controllers by recasting the centralized cost measure into a set of individual cost functions. Due to fact that in the large population scenario with respect to the cost functions, the impact of all other agents on a given agents exhibits a deterministic feature in its evolution, and therefore was replaced by its approximation. This approximate replacement known as state aggregation or mean field approximation led to a highly decentralized controller for each individual agent.

V. RESEARCH QUESTIONS

Many research questions at the interface of control and power engineering are implicit in the above discussion. In the following some ideas for tying recent developments in distributed control to the issues raised in Section III are briefly presented.

A. Basic Agenda

The above-mentioned challenges ultimately will require a paradigm shift in the way power systems are controlled and operated toward more distributed control. The control schemes will need to accommodate certain self-organizing capabilities. The ability to learn from the interaction with the environment will help the control agents to cope with increasingly uncertain operating conditions.

Modeling must now include the communications networks and optimization will be granulated over all voltage levels. Greater automation is an area where the inclinations of control engineers might meet resistance unless care is used. For example, there are protocols of manual inspection before reclosing after something like a tree falls on a line because of the risks of live feeders. Such features must be built into new solutions.

At the same time, we can question use of millions of devices in any coordinated way. Certainly, there will be control at higher voltages and at loads (demand management), from the centre and customers respectively, but how to structure this – the architecture of smart grid control? How far to granulate? How far down in voltage do we need centralised monitoring and control? Do we need control through meters and will customers allow it?

The question of the extent to which such systems can work if there is limited communication between all the devices reminds us of investigations into how flocking and swarming occurs in nature. Here biology gives ideas for how to handle achieving remarkable goals with large numbers of small actions in the presence of much complexity and limited information exchange. Translated into the power systems area, we are asking how to use a large number of small changes, e.g. heating adjustments to houses, to have a big affect higher up the grid. Such ideas have been suggested for system level control previously [35] and now have potential in the harnessing of new power electronic developments [10].

B. Cyber-physical Model

The requirements for smart grids require communication architectures for fast adaptive coordinated control and protection across the whole grid. Recall we have questions about information architectures, such as how to establish QoS guarantees in the networking. New middleware type information structures have already been suggested, such as GridStat [36]. The models need to accommodate the distributed control ideas of networking, latencies, packet loss for analysis. Such models do not appear to exist.

Thus the smart grid view presented here involves energy and information networks of mixed types all interacting in a cyber-physical feedback network. We can design them to be efficient, effective and secure one by one, but what about as a complete system? There needs to be models developed for

purposes of systems analysis and control design allowing for the interdependence. Some work in the complex networks area [37] and in control theory by the authors [30] deal with this in an abstract way, but this cannot be translated to smart grids without appropriate models. The model will need to be layered and precise all the way down to house level. An interesting step idea is the idea of equipment taxonomy [38].

Behaviour, performance and vulnerability should all be seen as dependent on the system structure (represented by a graph), couplings and device characteristics. This view is firmly established in the field of complex networks [39].

C. Control Architecture

With a diversity of new control devices and sensors which can give data every few milliseconds and layers of networking, there is a wide array of possibilities for control. We now have an end-to-end optimal learning control problem: and potentially an impossible optimisation task. We mentioned two basic approaches, namely CBSG and decentralized (via power electronic control) which can in principle deliver end-to-end adaptive control. These could co-exist. But the structures have to be worked out. Remembering those millions of devices, the issue of how to do this as an architecture question is significant. This question pervades many aspects of smart grids, for reasons of just managing the data, i.e. avoiding data overloads at critical places, but also implements in-time control where and as needed.

The clear research agenda here in the CBSG is to look at P2P structures, analysis of data loss and delays. The event-triggered communications opens up possibilities in limiting communications to minimal, helping cyber-security.

It is certainly not unreasonable to think about how to keep the smart grid simple. This is where issues of the best communications structure and control design interact. The traditional power engineering instinct is to keep as much of the control local. Different control architectures need different communications. In distributed control, the authors' approach to feedback networks [30] suggests using selected P2P strategies.

In the available literature on alternative control techniques applied to power systems, several of the above issues have started to gain significant attention. Multi-agent systems (MAS) approach has been applied to many power engineering problems [41], such as energy management [42], [43] power system restoration [44], load shedding [45], voltage control, [40], [46], [47] black start [48], and state estimation [49]. The main idea behind MAS is to model complex infrastructures, such as electricity networks, as a network of distributed, autonomous, and adaptive intelligent agents that are working together to achieve a global goal. One of the strengths of MAS is that they enable adaptive self-organizing cooperative control, scalability, and plug-and-play functionality, which will likely facilitate their wide-spread adoption.

Work on decentralized control is proceeding on several fronts. In [50], the mean field approach was used to investigate decentralized charging control for large populations of plug-in electric vehicles (PEVs) whose electricity demand has a significant impact on electrical power grid. By considering the charging control for an infinite PEV

population, a collection of local charging control turns out to be a Nash equilibrium. Then under certain conditions, the obtained decentralized control strategy results in that the total demand composed of aggregated PEV charging load and non-PEV demand is constant during charging intervals. There is a need for further study of the capability of such algorithms for other control tasks.

D. Adaption and Learning

Without doing a detailed history, it is safe to say that the idea of making the grid more responsive to situations arising goes back decades. And areas of control engineering such as adaptive control and intelligent control for instance have contributed to such capability [51]. A lot of work has been done on possible use of adaptive algorithms and learning in power systems. One interesting approach is given in the thesis [52]. Here ideas similar to those of learning control have been used to enable rapid response adaption to a succession of system failures

Against the backdrop of this, the main issue in implementing MAS is their ability to learn from the interaction with the environment to adapt from ever changing operation conditions. To this end, distributed model predictive control that has been proposed to tackle energy management [53], AGC [54] and stability controls [55] can be useful. On the learning side, reinforcement learning has been proposed [56] in stability controls and in [45] successfully implemented in MAS framework.

E. Cyber Security

The interaction of purpose and security in deciding architectures arose in the early days of the Internet. Mesh type structures, with uniform connectivity, are more robust to attack than star (or, in general, scale-free structures). In the development of P2P structures for better control for example, a concern is how not to create cyber insecurity. Recently the study of interdependent networks in network science [37] has added insights into how cyber and physical structures might interact to create collapse situations, albeit with very simplified models. Control algorithms to arrest collapse in power networks alone remain interesting for research. The broader scope of cyber-physical security is even more challenging. In a smart grid, there are power, communications, computing and control layers all of which can be entered by an intruder.

We mention this here, because considerations of cyber-security place constraints on what can be done for distributed control.

F. Future Grids and Control

Power systems in the past were designed very conservatively with tried and true components. Now the early stage of smart grids development is overlaying these systems with ubiquitous sensing. We will know better what it is doing. But demand management at the load end and automation overall, will enable us to defer capital expense and replace the power system by something 'more unstable' to get higher performance as occurs in areas like transport. Reliability (measured by indices SADI, SAFI) improvement can be now much more a product of control! Reconfiguration can replace

redundancy of equipment. The reliability paradigm can change to be control-based.

More futuristic possibilities such as *Constrained Carbon Grids* enabled by end-to-end distributed learning control are a fascinating topic for later.

VI. CONCLUSIONS

The emerging subject of smart grids is reviewed with the suggestion that a more ambitious research agenda is needed to give credibility to the use of the term 'smart'. By posing the goals of smart grids as a control problem, it is seen as within the framework of distributed learning control. This gives a promising future for research and development.

There are some overarching themes to keep track of, namely: 1) how to keep the smart grid simple and 2) how to keep it cyber-physical secure while realizing the performance benefits of control? The full development of these ideas will need to involve control engineers with input from the computing, communications and complex networks areas.

VII. ACKNOWLEDGMENT

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IX. BIOGRAPHIES

David Hill (M'76, F'93) currently holds the Ausgrid Chair of Electrical Engineering and an Australian Research Council Professorial Fellowship in the School of Electrical and Information Engineering at the University of Sydney, Australia. He is also a Principal Researcher in National ICT Australia. His general research interests are in networks, power systems, stability analysis and distributed control.

Tao Liu received his BE degree from Northeastern University, Shenyang, China, in 2003 and his PhD from The Australian National University in 2011. His general research interests are in dynamical networks and switched systems.

Gregor Verbie (S'98, M'03, SM'10) received his BSc (1995), MSc (2000) and PhD (2003) degrees in Electrical Engineering from the University of Ljubljana. In 2005, he was a NATO-NSERC Postdoctoral Fellow at the University of Waterloo, ON, Canada. Since 2010 he has been with School of Electrical and Information Engineering, The University of Sydney, Australia. His general research interests are in power-system operation, dynamics and control, electricity markets, and optimization applied to power systems.