The Role of Intelligent Systems in delivering the Smart Grid

E. M. Davidson, V. M. Catterson, and S. D. J. McArthur
Institute for Energy and Environment, University of Strathclyde,
Glasgow, United Kingdom.
Email: edavidson@eee.strath.ac.uk, v.m.catterson@strath.ac.uk, s.mcarthur@eee.strath.ac.uk

***Abstract*—The development of "smart" or "intelligent" energy networks has been proposed by both EPRI's IntelliGrid initiative and the European SmartGrids Technology Platform as a key step in meeting our future energy needs. A central challenge in delivering the energy networks of the future is the judicious selection and development of an appropriate set of technologies and techniques which will form "a toolbox of proven technical solutions".**

This paper considers functionality required to deliver key parts of the Smart Grid vision of future energy networks. The role of intelligent systems in providing these networks with the requisite decision-making functionality is discussed. In addition to that functionality, the paper considers the role of intelligent systems, in particular multi-agent systems, in providing flexible and extensible architectures for deploying intelligence within the Smart Grid. Beyond exploiting intelligent systems as architectural elements of the Smart Grid, with the purpose of meeting a set of engineering requirements, the role of intelligent systems as a tool for understanding what those requirements are in the first instance, is also briefly discussed.

I. Introduction

The continued increase in energy use in tandem with environmental concerns is driving interest in "smart" or "intelligent" capabilities of energy networks. Both EPRI's IntelliGrid initiative [1] and the European SmartGrids Technology Platform [2] envisage "smart" functionality as the key to meeting our future energy needs.

The scope of that "smart" functionality is wide. The characteristics of the "Smart Grid" set out in [3] and thus areas of application range from smart metering, demand-side management, integration of distributed generation, energy storage and renewable resources, to back office systems which exploit data from an upgraded, potentially more observable, energy network.

A key question is how "smart" functionality will be achieved. It is likely that an integrated suite of complementary tools, techniques, and standards, co-operating to meet the technological requirements of future networks, will have to be developed.

The selection of technologies appropriate for this purpose must center on proven solutions that can handle the complexities of real network situations. While novel techniques and approaches may be required to implement the functionality required, the practical issues of noisy data, computational complexity, robustness, and upgradability must be strongly considered before deployment becomes a reality.

The capabilities required by the proposed future networks can be divided into two separate but related parts. The first is the decision-making functionality that evaluates network state and proposes actions to meet certain objectives. This includes high level strategic objectives such as maximizing DG access, through to lower level technical objectives such as not exceeding thermal constraints. Each utility, and each topographical region will have differing priorities and objectives, meaning that the particular requirements on decision-making functionality will change with the situation.

The second part of the intelligent grid vision is the platform for delivering this distributed and varying decision-making functionality. Based on requirements such as plug-and-play capability, local autonomy, and self-managing and self-healing operation, this platform is itself a challenging system to design and build.

This paper considers the role that intelligent systems techniques may play in meeting the challenges posed by these requirements. Section II discusses the need for decision-making functionality, and how this may be addressed. Section III considers the requirements on a smart grid delivery platform, both from the perspectives of distributed and robust deployment, and self-monitoring and self-managing capabilities. Section IV examines the role of intelligent system approaches with respect to more conventional or traditional analytical approaches. Finally, Section V discusses the potential role of intelligent systems in the life cycle management of "Smart Grids", i.e. tools to help planners and policy-makers decide what the engineering requirements of the "Smart Grid" are.

II. Intelligent Systems for Providing Control Decision-Making Functionality

Intelligent systems techniques may have a role to play in providing a "Smart Grid" with "intelligent" network management and control functionality. By "intelligent" here, we mean control and management functionality with the properties associated with intelligent systems: flexibility; graceful degradation in the face of measurement and communication errors and plant failure; and, potentially, the ability to learn and improve performance over time. While not all intelligent systems display all of these properties, different techniques can display them to varying degrees. By way of a set of examples, we will use a project called AuRA-NMS (Autonomous Regional Active Network Management System).

AuRA-NMS was a three and a half year research and development programme that involved seven UK universities, two distribution network operators and a major manufacturer and it had the aim of developing and demonstrating a "smart" active network management system. AuRA-NMS was driven by the DNOs' need to increase DG access to networks while avoiding or deferring the cost of network reinforcement. In addition to cost implications, ANM can also help connect generation more quickly given the time-scales often associated with gaining planning consent for some network reinforcements.

Through AuRA-NMS, DNOs were looking for a way of moving from bespoke single issue active network management solutions to a more generic solution that can be rapidly deployed for a variety of MV networks and deal with multiple issues in a coordinated manner, e.g. power flow management, steady state voltage control, restoration, and minimization of losses. During the course of the programme a number of approaches to each of those control tasks were investigated and the most promising prototyped. In some cases, those approaches exploited intelligent systems techniques.

The selection of intelligent system techniques was based on the DNOs' requirements for flexible and extensible solutions which were also fault tolerant and whose performance degraded gracefully in the presence of measurement errors, model error (error in the model the techniques use to generate solutions) and communication problems. The interested reader will find more details of these requirements in [4] [5].

At the time of writing AuRA-NMS was moving to a trial deployment stage of its development. Readers interested in the nature of that deployment can find details in [6]. In this paper we focus on the intelligent systems techniques used and the rationale for their selection.

A. AI techniques for power flow management

In the context of AuRA-NMS, power flow management involves the management of distributed generators in a manner that thermal limits of plant are not exceeded. Thermal limits place a limitation on the firm DG connections that a network can support without having to reinforce the network. Alternatively, DG network access can be limited during the network conditions where thermal limits would be exceeded. If the possibility of curtailment of generation is rare over the course of the year, then it can be more economic for generators to connect to the network under an agreement that their output can be curtailed when network conditions dictate. During the research phase of AuRA-NMS, a number of different approaches to power flow management were investigated:

- A current-tracing approach [7];
- An OPF-based approach [8]; and
- an approach based on the AI technique of constraint programming (CP) [9].

For the moment, we will focus on the AI technique. The constraint programming approach involved modeling the power flow management problem as a constraint satisfaction problem (CSP). Each controllable item of plant is considered a variable in the problem [9]. That variable can have a number of discrete values, i.e. control responses. Solving the CSP becomes one of searching for assignments of those discrete values such that a set of constraints is not violated. These constraints are: that the network access rights must be respected (contractual constraints) and that power flows remain within limits (the power flow constraint). Search is guided using a preference constraint, which can be thought of as the constraint programming equivalent to an objective function. The preference constraint is used to search for solutions that meet the contractual and power flow constraints but maximize DG access in a best first manner. To this end, an off-the-shelf CSP solver and an off-the-shelf load flow engine were integrated on ABB's COM6xx series substation computer.

Full details of the constraint programming approach can be found in [9], including case studies on two very different networks.

The rationale for investigating constraint programming was that a network agnostic solution that would degrade gracefully was required. As the constraint programming approach was model-based (but not in AI terms), it could be applied to different networks simply by changing the model. If network access agreements changed, these too could be potentially updated. However, the fact that the approach could produce a set of ranked solutions offered the possibility of graceful degradation in performance. Should an attempted solution not remove a thermal overload, then the next ranked solution could be applied. Given that model error is inevitable, this was seen as a strength of the technique.

Like OPF, the approach is fairly computationally intensive, so tests were run on the substation computing platform used by ABB to assess how long it would take to compute a solution under different network conditions. Tests showed that solutions under normal conditions could be calculated in 1–2 seconds for the case study networks. Under worst case scenarios, requiring complete traversal of the entire search space, this was still achieved in under 10 seconds for the more complicated network. Hence, on currently available hardware, computing solutions in adequate time-scales was deemed feasible for the test networks.

To date the prototype software implementation for the CP approach has been tested using a real-time testing environment developed by the authors. The real-time simulator runs on a dedicated PC and uses a quasi-stationary model of the network under test, running an AC load flow engine once a second to evaluate flows around the network. The simulator also includes a number of controller models that simulate the control response of tap-changers, breakers, trip/trim control of generators, power factor set-point control and real power set-point control, which introduce inter-tap delays in the case of transformers and generator ramp and trim rates. Results of 'closed-loop' testing using this simulator can be found in [9]. An example network that was used for testing is shown in Figure 1, while Figure 2 shows the software integrated with the COM6xx unit, and Figure 3 shows the simulated real time generator response.

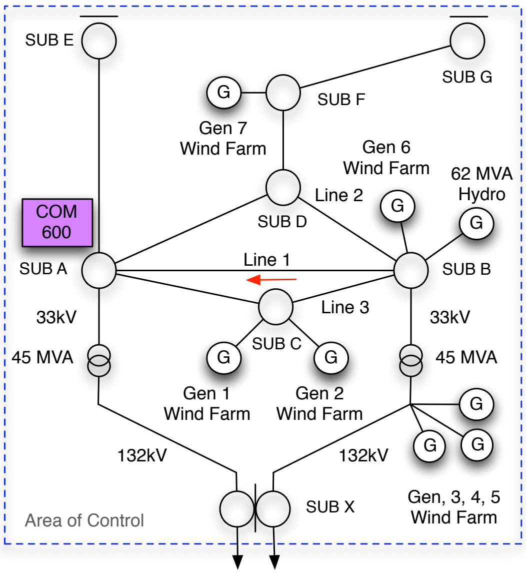

Fig. 1. Interconnected 33kV network with distributed generation and an overload on line 1

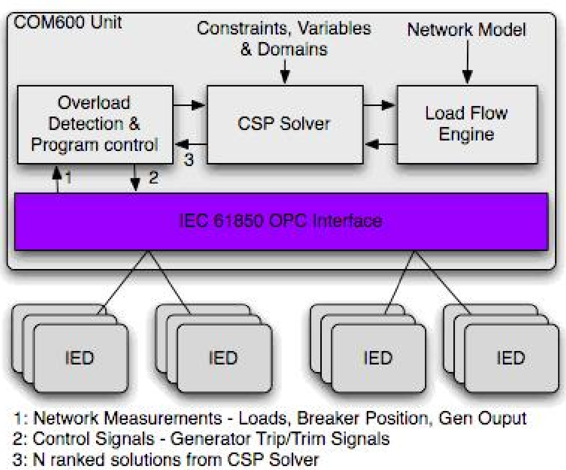

Fig. 2. Power flow management software running on a COM6xx unit, interfacing to external IEDs for acquiring measurements and issuing control commands.

In addition to the AI technique of constraint programming, we also investigated the online use of a conventional power systems analysis tool, OPF, for power flow management, developing prototype software to run on the COM6xx. That work is discussed in Section IV.

B. AI techniques for voltage control

One of the effects of increasing levels of DG on distribution networks is the problem of voltage regulation, normally voltage rise issues. A range of approaches have been investigated for voltage control [10], [11], [12], [13], [14], [15], [16], [17].

During the development of AuRA-NMS two AI techniques where considered for coordinated control of steady-state voltage: a constraint programming approach and a case-based reasoning approach. The rationale for exploring the use of constraint programming was similar to that of its use for power flow management. Since the general approach is similar to the power flow management problem, we will not discuss it here. CBR however, offers a interesting alternative.

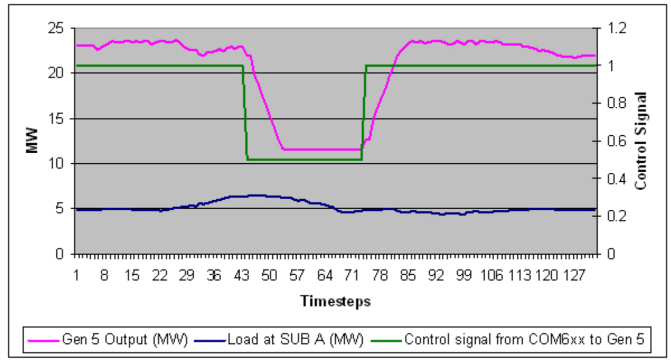

Fig. 3. Control signal from COM6xx and generator response that signal. Data was captured from a real-time test using OPC data logging tools

The rationale behind the use of the CBR approach to voltage control was developed by Phil Taylor at Durham University. Rather than calculate a solution online using a analytical approach, such as OPF or CP, Taylor suggested that a pre-enumerated set of solutions to voltage excursion problems could be created offline. When the system was online, finding a solution to a particular voltage excursion would involve finding appropriate solutions from the pre-enumerated set. As long as that set was not excessively large, the approach would be fast and avoid problems associated with the non-convergence of load flows or OPFs.

Like the constraint programming approach, the CBR approach to voltage control can offer several solutions to the same problem. Should a solution fail, other solutions can be applied, leading to a degree of graceful degradation.

Details of the CBR approach and initial results of testing can be found in [18].

C. AI approaches to restoration

The approach to restoration developed during the AuRA-NMS programme by the University of Cardiff did not employ intelligent systems techniques, however, a large body of work for the use of AI approaches to restoration exists [19], [20], [21], [22], [23], [24], [25].

III. Intelligent Systems for Smart Grid Architecture

To fully realize the vision of a distributed, intelligent grid, the architecture itself is as important as the decision-making functionality. The system must have certain properties, namely:

- Flexibility, to accommodate different utilities' needs,
- Extensibility, to keep pace with changing requirements,
- Open access, allowing functionality from different providers to interoperate,

- Fault tolerance, to handle noisy data and degrade gracefully in the presence of partial failure.

Less essential, but certainly desirable, are extended capabilities such as utilizing all available data within a utility to influence operation, and allowing utilities themselves to select the level of automation for a given situation or scenario. These sets of requirements will be considered in turn below.

A. Distributed and Robust Deployment

Multi-agent systems (MAS) technology has previously been suggested for providing the systems integration capabilities required for a variety of power engineering applications [26]. Such applications, including diagnostics, condition monitoring, and distributed control, display many of the same requirements individually as the unified smart grid vision presents.

A multi-agent system comprises a set of intelligent agents co-operating to achieve their goals or tasks, assigned by the agent designer. An intelligent agent is said to display flexible autonomy [27], through a mixture of reactivity, pro-activeness, and social ability. Each agent can display a different mix of these qualities as appropriate for meeting its current goals.

These properties of individual agents lead to a multi-agent system with particular properties. The system can be flexible, in that each agent can react to changes in network conditions and utility objectives to meet new constraints or operational needs. The system can be extended by deploying new agents as functionality is developed, allowing staged deployment of different management capabilities. Mechanisms of MAS can be employed to create a fault tolerant system, such as deploying duplicate agents with the same capabilities to take over responsibilities in the case of partial system failure, and distributing agents across different physical locations through platform federation [4].

The criterion for open access can be met by employing standards for communication between agents within the system. Since agents interact by messaging, standards-conformance in the structure and protocols of messaging allows agents with different designers to meaningfully communicate about data, the state of the network, or any proposed control actions. The standards created by the Foundation for Intelligent Physical Agents (FIPA) have become the de facto standard for many MAS for power engineering applications [28]. However, these standards only cover the protocols, message structure, and content grammar, leaving out the content lexicon, or ontology, which is the application-specific set of terms used for communicating about a given domain. Since the field of power engineering applications is relatively restricted, and the points of meaningful communication occur at a high level, it has been suggested that an *upper ontology* for power engineering applications could be derived [28]. This would allow agents to discuss high-level concepts such as network topology, control actions, and items of plant. This upper ontology could be based on existing data standards, specifically the Common Information Model (CIM) and IEC 61850.

Indeed, MAS technology has already been deployed at a utility[29], for the application of post-fault analysis. This shows that the essential requirements for smart grid functionality of flexibility, extensibility, open access, and fault tolerance can be met by MAS.

B. System Self-Management through Condition Monitoring and Selectively Devolved Control

Wide area monitoring of the network will be required to support the growing decision-making functionality described above. However, this increased system observability coupled with new communications links offers intelligent system applications further to the automation capabilities previously outlined. These may be loosely termed self-management capabilities, where the intelligent network system can monitor its own operation and adapt as appropriate. Two particular examples of this functionality will be considered here, specifically the use of asset health information as an input to control decision-making, and the ability to selectively devolve automation from the control room to local intelligent controllers.

1) On-line Asset Health Monitoring: Two 275/132kV 180MVA transformers at a substation in the UK are nearing the end of their design life. The owner utility wants to keep this plant in service for as long as possible without too great a risk of failure in service. To achieve this, the transformers are under intensive monitoring with a wide set of on-line sensors, allowing engineers constant access to the latest measurements. The utility desires the detection of anomalous transformer behavior on-line, potentially giving early warning of failure.

For this application, the intelligent system technique of Gaussian Mixture Modeling was selected to model the normal behavior of transformer parameters. Two months of data were selected as representative of normal operation, and used to learn a Gaussian Mixture Model of the relationships between transformer oil parameters and environmental parameters including ambient temperature and load current [30].

Anomaly detection is achieved by comparing new on-line measurements with this model. Any changes to the relationship between environmental conditions and transformer behavior are highlighted by the model returning a low probability of these measurements occurring.

The anomaly detection capabilities are wrapped as agents, and operate within a wider condition monitoring multi-agent system that includes dissolved gas analysis and partial discharge diagnosis [30]. This system exploits the deployment benefits of agent technology described above, allowing the appropriate mix of diagnostic and anomaly detection functionality to be flexibly deployed for a given substation, and using standards-conforming social ability to allow system extensibility.

This system has been collecting data on-line since August 2008. To date, 22 anomalies have been detected, all of which have been caused by transient sensor faults.

Within the context of intelligent network operation, on-line asset health monitoring such as this has a role to play in providing information for decision-making functionality. The occurrence of anomalous behavior and diagnosable faults could, for example, alter the dynamic rating of assets such as transformers, or reduce the number of permissible operations for tap changers or circuit breakers.

This condition information already exists within utilities, but the logistical challenges of making it available in the control room and the knowledge required to act upon it appropriately mean that asset health is rarely a consideration for control engineers. However, if health assessment and operational decisions are both devolved to local areas of the network as multi-agent systems, with associated benefits of open access and extensibility, the results of one can be used to influence the other.

C. Selectively Devolved Control

One of the concepts developed during AuRA-NMS was the notion of selectively devolved goal driven network control. The concept was developed through discussions with DNO control engineers. The engineers wished to be able to assign AuRA-NMS an area of network and set the control goals for that area. Those goals could be: the regulation voltage within certain limits; operation of the power system within thermal limits; automatic restoration; and the reduction of losses. Engineers would set system goals, and the ANM system would be left to to make decisions on how to meet the goals.

From the control engineer's perspective, selectively devolved goal driven control means that goals can be assigned to the ANM system in a way which best suits the control engineer at that time, providing more flexibility than having a control scheme that can be simply enabled or disabled. MAS could be used to implement such an approach.

IV. Comparison with Conventional Approaches

If intelligent systems are to enter the "Smart Grid" toolbox then, in addition to demonstration, their performance with respect to other methods needs to be understood. Studies which compare the performance of intelligent systems techniques with more conventional approaches are rare. As part of the science undertaken as part of AuRA-NMS, competing techniques were subject to comparative testing. By way of an example we can highlight the testing of the constraint programming and OPF approaches to power flow management.

The power flow management problem can be formulated as an OPF [8]. This leads to two questions: can solutions be calculated in a feasible timescale; and is the approach robust enough?

During the AuRA-NMS programme, a commercially available OPF engine was integrated with ABB's COM6xx unit, acquiring measurements from the simulated network via simulated IEDs in a similar manner to the constraint programming approach in Section II-A. In terms of timescales, when the OPF did converge, it did so in around a second on both networks. Initial results can be found in [8]. It is the authors' hope to fully publish results from that testing in the near future; however, those initial results indicate that while the OPF we used could, given no errors in measurements, the model, the communications link, or estimation of the network state, result in greater energy yield over the CP approach, the robustness of the optimization under those errors or changes to network state, repeatedly led to non-convergence of the OPF and thus failure of the approach. CP on the other hand, in the initial testing, displayed greater robustness and graceful degradation. From the DNOs' perspective, solutions have to be robust. While optimal solutions are desired, robustness takes precedence.

However, this opens up the possibility of a hybrid approach that uses the strengths of one technique to compensate for the weakness of the other. By combining the approaches, energy yields may be "optimized" using OPF while using CP to provide alternative solutions and graceful degradation when OPF fails.

V. Power Systems Analysis for the Smart Grid

The investigation of intelligent systems techniques for power systems analysis has a long history. While a review of that history is out of the scope of this panel paper, AI approaches to optimization for different power systems planning and operation support problems frequently appear in IEEE Transactions on Power Systems. The move to increasingly active distribution networks with stochastic generation, energy storage, and controllable and observable load is going to change the way these networks are planned and operated. So, while there is a requirement for tools and techniques to provide future energy networks with "smart" control functionality, and architectures which provide the appropriate flexibility and extensibility, tools and techniques to aid the planners of future energy networks will also be required. Intelligent systems techniques may have a role to play in that arena in areas where conventional techniques fall short.

Life cycle management for "Smart Grids", when that process is defined, will require support tools. It remains to be seen if conventional analysis tools will suffice.

VI. Conclusion

The "Smart Grid" vision for future networks represents a potential sea-change in the way networks are planned, maintained and operated. In this paper we have discussed the role intelligent systems techniques from the perspective of our experience in that area. Practical examples in the form of an active network management system and related condition monitoring and post-fault analysis systems have been used to illustrate those potential roles where a degree of deployment and demonstration has already taken place.

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