Scalable Integration of Wind Power on Transmission Systems using Grid Computing

G. A. Taylor, M. R. Irving, C. Axon and P. R. Hobson

Abstract-- **In the UK and also worldwide it is certain that future transmission systems will operate with significantly larger proportions of large-scale wind power generation, both onshore and offshore. Therefore, in order to operate and control future transmission systems securely and efficiently it will be necessary to monitor and control output levels and scheduling much more accurately when connecting such generation to a power system. Traditional operation and control methodologies that are currently employed at the transmission level are highly centralised and are therefore not necessarily best suited to support large-scale integration of wind power. This paper proposes the adoption of a relatively new technology 'Grid Computing' that can provide a scalable, cost-effective and universal solution to the problems associated with the control and monitoring of future transmission systems with large-scale integration of wind power.**

***Index Terms*—Large-scale Wind Power Integration, Distributed Monitoring and Control, Grid Computing.**

I. Introduction

The large-scale integration of wind power on existing transmission networks is an operational and control problem of significant complexity; not only are there a huge number of possible states and transitions requiring massive data exchanges, but the regularity constraints in terms of continuity of supply, frequency and voltage ranges increases complexity further [1, 2]. Any system-wide impact will affect current practice with regard to important areas of network management such as frequency response, reactive power management and power system dynamics. For example, the intermittent nature of wind power generation will require ancillary services such as reactive power compensation to be managed as efficiently as possible in order to enable large-scale penetration without compromising voltage control [3-5]. A further problem is that in order to ensure continuity of supply it is necessary to predict demand levels and distribution requirements with even greater accuracy based on weather forecasts, outages and or other factors. In addition, it is desirable to include the effect of all credible contingencies and longer time horizons for operational planning, further increasing the complexity of the system under analysis [6-8].

A wide range of advanced computational techniques have been applied to the control of power networks, though none with sufficient success or resilience to supplant current 'brute force' solutions. Such techniques have included: knowledge based systems, expert systems, artificial intelligence, and genetic algorithms [9]. Such techniques have failed principally because of the complex nature of the problem and the huge number of possible states and transitions that can require massive data archival and retrieval [9]. Current software and power system models have been developed with a focus on conventional power networks and generation, though there has been limited development specifically considering networks with large-scale deployment of renewables [10]. In such cases statistical and algorithmic estimation is adopted to reduce the computational burden, this is mainly due to severely limited efficiency and effectiveness of available computational resources [10, 11]. As the trend is for power system models to increase significantly in size, detail, and complexity, we propose that the so-called 'Computing Grid' offers a genuine solution that avoids increasing uncertainty in operational modelling and analysis.

'The Grid' is an emerging and exciting software technology which enables the most efficient and intelligent use of distributed or networked computational resources [12-14]. In the way that 'the Web' has revolutionised data exchange, 'the Grid' is set to do the same for computer resources (storage, processing, algorithms) which can be internal to an existing organisation [13], or spread internally and externally across a virtual organisation [14]. A schematic diagram describing a power systems Grid computing structure is shown in Figure 1. Perhaps the most important feature in respect of the power networks problem is that the Grid is scaleable – inherently it is designed to work as well with 100,000 participants (nodes) as it is with 100. Generally the distribution of computing resources requires additional network security, and it is important to note that this is also inherent to Grid computing, yet it can still provide a robust provision of computational resources in terms of self-organisation and major fault tolerance [14]. Data can also be distributed across a network of a virtual organisation with specified levels of security and can therefore be maintained and regularly updated in either a distributed or centralised fashion [13, 14]. There are many potential benefits to the power generation, transmission and distribution community including monitoring, control,

G. A. Taylor and M. R. Irving, Brunel Institute of Power Systems, Brunel University, Uxbridge, Middlesex, UB8 3PH, UK (e-mail: Gareth.Taylor@brunel.ac.uk).

C. Axon, School of Engineering & Design, Brunel University, Uxbridge, Middlesex, UB8 3PH, UK.

P. R. Hobson, Sensors & Instrumentation Research Group, Brunel University, Uxbridge, Middlesex, UB8 3PH, UK (e-mail: Peter.Hobson@brunel.ac.uk).

modelling, planning, regulation and expandable capacity [15-17].

The major areas of research that need to be further addressed when considering the development of universal standards for distributed monitoring and control of power systems with large scale integration of wind power can be categorized as follows [18];

- Algorithmic procedures for performing parallel and distributed processing [19,20].
- Standards for information and data exchange [19,21,22].
- Middleware for the processing and exchange of data between distributed processes and agents [19,23,24].

Grid Computing is being specifically researched and developed by the e-science community in order to universally facilitate the latter two areas and provide an open standard 'plug in' approach to the first area of research [12-14]. A combination of public and private communication networks can be inherently employed with regard to Grid Computing as it is being developed as an extension of the existing Internet. The development of Grid Computing is analogous with the early development of the Web. Levels of data security and Quality of Service (QoS) can be guaranteed through service level agreements between Grid Computing entities and Internet Service Providers [12-14].

Initially the UK e-science community has applied Grid Computing to off-line analyses and simulations of engineering and science problems [12]. Therefore, currently established Grid Computing middleware such as the Globus Toolkit [13] has been developed to offer a platform that facilitates a batch mode execution and scheduling of processes. Current research is being undertaken by the authors of this paper to design and develop enhanced middleware that is applicable to the distributed monitoring, control and analysis of transmission systems and networks with large-scale wind power integration [15,17].

The remainder of this paper is organized as follows; Section II summarises current large-scale wind power developments in the UK; Section III provides an overview of the proposed power system Grid Computing platform; Section IV presents two cases that demonstrate the application of the power system Grid Computing platform; Section V concludes the paper and describes further research

II. LARGE-SCALE UK WIND POWER DEVELOPMENTS

A. On-shore

The largest on-shore wind farm in the UK is currently Scottish Power's Black Law wind farm and is situated in central Scotland halfway between Edinburgh and Glasgow. At present the site comprises of 42 turbines of 2.3 MW each. The first construction phase of 93 MW became operational in March 2005. The wind farm is connected to the GB transmission system at the 275kV substation in Wishaw. The largest consented on-shore wind farm in Europe is currently Scottish Power's Whitelee wind farm and is situated south of Glasgow. Final planning consent has been granted for a 140 turbine 322 MW development with completion of the initial phase planned for 2008 and completion of the final phase planned for Summer 2009 [25]. The majority of future on-shore large-scale wind power developments are likely to be in Scotland and at present it is highly unlikely that will be significant on-shore large-scale wind power developments in England or Wales [25].

B. Off-shore: Round 1

As a result of round 1 of the UK off-shore wind farm development there are 18 individual large-scale development sites of up to 30 turbines around the UK coast, with a typical maxim capability ranging from 60 – 90 MW [25].

As of August 2006 four of the large-scale development sites were operational, seven more developments of mostly 30 or 60 turbines have been approved and the remainder are at the submission stage. The first large-scale offshore wind farm at North Hoyle consisted of 30 individual 2 MW turbines and was commissioned in December 2003 and the second 60 MW farm was at Scroby Sands in December 2004, followed by the then world's largest offshore wind farm, the 90 MW Kentish Flats in 2005 (30 individual 3 MW turbines). Together with the original off-shore pilot project at Blyth this made a total of 213.80 MW of operational off-shore wind power around the UK coast. However, this is possibly only the beginning. All of the above are located 5-10 km off shore in shallow waters (around 10 m). Kentish flats' is connected to local distribution network via a purpose built on-shore 33 kV substation. North Hoyle and Scroby sands are connected to the GB transmission via existing on-shore substations at Rhyl and Yarmouth, respectively [25].

More recently in March 2006 another 30 individual 3 MW turbines became operational at Barrow. This development also included the UK's first off-shore 33/132 kV substation located 7 km from the coast. This enables connection to the GB 132/275 kV substation at Heysham via a 27 km long 132 kV submarine transmission cable [25].

C. Off-shore: Round 2

The second round of off-shore development in the UK is often referred to as the "super wind farms" and commissioning was originally planned for 2006 onwards. At present the earliest commissioning is planned for 2008 subject to consent. Considering the rate of progress of application procedures at present few of the projects will not be commissioned before 2010 at the earliest. In 2003 the UK Department of Trade and Industry (DTI) proceeded to commission a Strategic Environmental Assessment of 3 areas around the UK coast that could be marked for further development of larger-scale off-shore wind farms [2]. It brought together important data from many sources to assist in selecting the most environmentally responsible sites and practices for the second round of offshore wind power development; it was envisaged these developments would be on a larger scale and further out to sea. The second round saw 29 companies register interest in 70 locations comprising more than 20 GW around the UK coastline. Only those companies that submitted an expression of interest were eligible to bid formally for Round 2 sites. The results were announced in December 2003 and concluded that 15 projects, with a combined capacity of up to 7.2 GW, would be allowed to apply for leases to operate offshore wind farms under Round 2 [25]. The majority of these sites have a maximum capacity ranging from 240 – 1000 MW, include several hundred turbines and are typically located more than 20 km from the coast. Individual turbines are expected to range from 2 – 7 MW depending upon the availability of future wind turbine technology and the heights of towers are expected to range between a minimum of 85 and a maximum of 175 metres above sea level. The largest sites such as the 1000 MW London Array in the Thames Estuary will require new 400 kV substations to be built in order to connect the wind farms to the GB transmission system. Off-shore transformer substations will also be required in order to minimise losses when transmitting greater amounts of electrical power on-shore from the wind farms located further out to sea [25].

D. Future Developments

As the GB system operator National Grid states that generation connecting below 50 MW in England and Wales should contact the relevant distribution network operator and similar advice is given to generation below 30 MW in Scotland [26]. Alternatively, only generation above 50 MW and 30 MW respectively would normally be considered for direct connection to the GB transmission system. The number of large-scale wind farms both on-shore and off-shore (greater than 50 MW) connected directly to the transmission systems has been increasing steadily since 2003.

Over the next 5-10 years an exponential increase is expected with regard to large-scale wind farms connected directly to the transmission system. It is expected that these developments will be mainly on-shore in Scotland (potentially 1 – 10 GW) and off-shore in England and Wales (potentially 300 MW – 7 GW) [25]. Such increases will have a major role in increasing electricity generated from renewables in the UK from 3 – 10 % by 2010. Such increases will create significant challenges for National Grid as the GB transmission system operator both at a planning and operational level. With regard to GB system operation major challenges will arise in maintaining adequate frequency response, spinning reserve and voltage control [27,28]. It is already accepted that greater data exchange and closer cooperation between network operators across the UK will be required. As a consequence there is currently support for such activities by the UK electricity industry regulator (OFGEM) through the designation of Registered Power Zones [29]. In the longer term it is also envisaged that such increases will lead to greater interconnection between the GB transmission system and transmission systems in the rest of Europe [30].

III. OVERVIEW OF GRID COMPUTING PLATFORM

In the following section it is assumed that all wind power generators are equipped with computational and communication facilities. Such an assumption is consistent with the exponentially increasing number of devices being connected to the Internet.

A. Distributed Monitoring and Control

It is now becoming widely accepted that a large number of off-shore wind power generators will be connected to European transmission systems in the coming decades [30], utilising renewable energy and reducing carbon emissions. As these generators are connected into the transmission systems it will become necessary to monitor and control their output level and their operation with a much higher degree of accuracy and cooperation between transmission system operators. The standard control technologies that are currently in use at transmission level are not easily scalable when considering very large numbers of off-shore wind power generators operating across Europe in the future. Grid Computing can provide a relatively inexpensive new technology, allowing the output of wind power generators to be monitored and when necessary controlled across large geographical areas. An outline of the power systems Grid-computing platform that has been adopted for the research presented in this paper is illustrated in Figure 1.

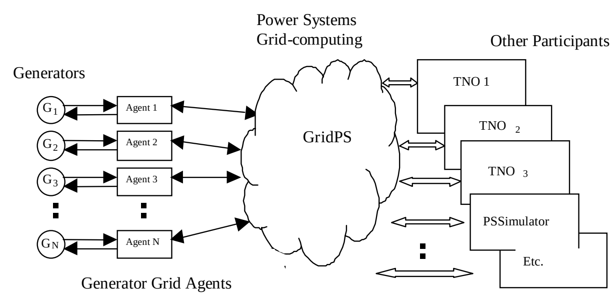

Fig. 1. Overview of a power systems Grid Computing platform.

B. Applications of Grid Computing in Power Systems

At this point in time Grid Computing has the potential to provide a universally adoptable platform for distributed monitoring, control and analysis of interconnected networks with large-scale wind power that will require significantly more data exchange between network operators and across large geographical areas.

Research activity in the application of Grid Computing in power systems is beginning to gain considerable attention from the power engineering research community. Three independent papers were presented at the IEEE PES Annual Meeting in June 2006 by power engineering research groups from Australia [34], China [35] and the UK [16]. The first paper presents a grid computing platform for efficient probabilistic small signal stability analysis using Monte Carlo simulation [34]. The second paper presents the initial developments of a grid computing platform that has the capability to support two applications; firstly the distributed monitoring and control of power systems using a virtual database and secondly power system analysis using distributed parallel processing [35]. The third paper was by the authors of this paper and presented details of a current EU project GridCC that is developing a European wide grid computing platform for the monitoring and control of large-scale power systems [16], the grid computing platform that has been developed in that project is also described in the following section of this paper.

IV. DEMONSTRATION OF GRID COMPUTING PLATFORM

A. Distributed Real Time Power System Simulator

The Brunel Institute of Power Systems is collaborating with the Sensors & Instrumentation Research Group of Brunel University as part of the contribution to the GRIDCC project [17]. The collaboration involves performing realistic computer simulation of electrical transmission networks in order to demonstrate the Grid Computing platform that is being developed within the GRIDCC project [17].

One of the goals of the GRIDCC project was to demonstrate that an existing, monolithic legacy software package, the Power System Simulator (PSSimulator) [33] that was written in FORTRAN 77 and compiled on MS Windows platforms could be executed on a modern Grid computing platform. The FORTRAN driver routine was replaced with a C++ wrapper for the library. This facilitates the communication with the Grid Computing middleware, and in the meantime expands the I/O possibilities beyond the text file I/O used in the original version of the program [33]. Enhanced performance is provided through the employment of threads and a schematic of the deployment of the software on a Grid Computing platform is illustrated in Figure 2. However, it should be noted that the power network demonstrated in this paper is a very simple case that presents no issues with regard to executing the simulation in real time on a single processor. The objective of porting the application to a Grid Computing platform has been achieved, with the PSSimulator now running under the gcc compiler on machines using the Scientific Linux 3 operating system. In the following section we demonstrate the distributed application of the PSSimulator with the use of the Grid Computing middleware candidate Narada Brokering [31] in order to implement a light-weight distributed monitoring facility.

As a further goal of the GRIDCC project [17] the initial middleware candidate will be replaced by the Instrument Element middleware that is currently being developed as part of the GRIDCC project [17].

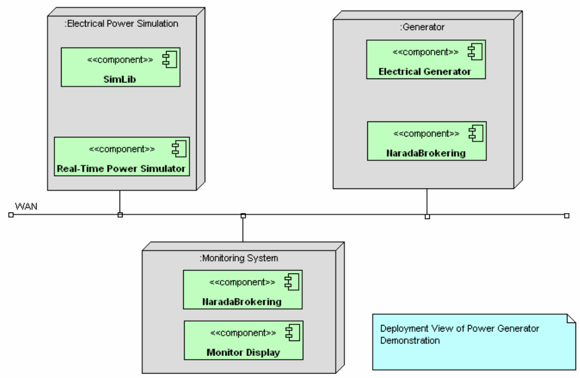

Fig. 2. A UML deployment view of the Grid Computing nodes and their components.

The PSSimulator is a relatively sophisticated software application [33] that simulates the realistic operational modes of conventional large electricity generators plus a network model of transmission lines, transformers and other components. Generators can be in a number of states; Not Generating; Synchronising; Running etc. and their delivered power and AC frequency will vary with time.

Figure 1 illustrates an initial deployment of the software in order to demonstrate the Grid Computing platform. In this deployment the instances of the electrical generators have been executed in a distributed fashion on machines in Italy, Switzerland and the UK. At present the instances only act as message forwarding agents for their representations inside the PSSimulator package that is executed on a local machine. The generator instance then re-publishes the information using NaradaBrokering and the messages are then received and displayed by a light-weight monitoring client.

B. Middleware – Narada Brokering

The distributed application of the PSSimulator uses Narada Brokering [31] which is asynchronous message oriented middleware that employs a publish and subscribe model. A variety of Internet transport and application layer protocols are supported, that includes TCP, UDP and HTTP. The middleware also supports robust messaging and several Web Service specifications such as WS-Eventing and WS-ReliableMessaging [32].

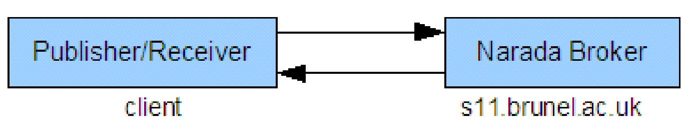

Fig. 3. Computer configuration for demonstration of Narada Brokering.

TABLE I
HARDWARE, PLATFORM AND SOFTWARE SPECIFICATION FOR DEMONSTRATION

Computer	***CPU/ Memory***	***OS***	***Java***	***Software***

Computer	*CPU/ Memory*	*OS*	*Java*	*Software*
s11.brunel.ac.uk	Pentium 4 3GHz, 1GB	Scientific Linux, kernel	J2se jdk 1.4.2	Narada Brokering
client	Celeron 1.3GHz, 512MB	Scientific Linux, kernel	J2se jre 1.4.2	PS Simulator

The purpose of this demonstration is to measure the round trip time of Narada Brokering and check that the results satisfy the real-time requirement of the Power Grid. In this demonstration we have developed a Java program to simulate the operational activities of the power generators as illustrated in Figure 1. We have used the program to measure the real-time performance of Narada Brokering. The Java program forks into up to 1000 threads, where each thread simulates one power generator. The threads start one by one in intervals of 1 second and last 20 minutes. It takes approximately 17 minutes for all the threads to start up. Each thread sends one large message at startup (1 KB) and then sends one small message to Narada Brokering every ten seconds. Another receiver program subscribes to Narada Brokering and receives all the messages [31]. The two programs are located on one machine and the round trip time is calculated at the end of the test. In this demonstration we have adopted TCP as the underlying transport layer connection protocol. However, in future demonstrations the connectionless transport layer protocol UDP will be employed in order to improve speed and efficiency.

C. Initial Results

The horizontal axis in Figure 4 is the number of messages and the vertical axis is the round trip time of the messages. As we can see from the graph, the majority of the Round Trip Time delays are within 0.1 second and all of them are within 0.3 second.

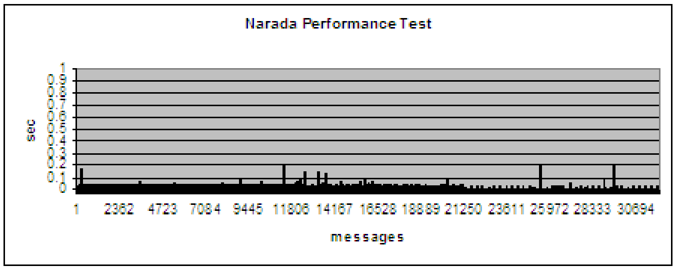

Fig. 4. Round Trip Times obtained from the Narada Brokering demonstration.

Figure 5 illustrates part of the NetLogger visualization of the Narada Brokering demonstration. Each red line represents the lifeline of one message. The vertical axis shows the events, **before_sending** and **received**. The horizontal axis is the timescale and each division is 0.1 second. As we can see from the graph, there are up to ten messages sent within 0.1 second and they all arrived within 0.1 second.

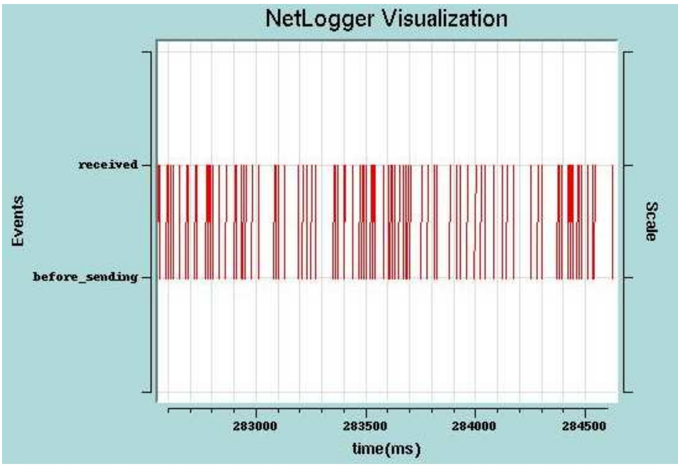

Fig. 5. NetLogger visualization of the Narada Brokering demonstration.

V. CONCLUSIONS AND FURTHER RESEARCH

The test results indicate that the performance of Narada Brokering middleware satisfies preliminary real-time communication requirements of a transmission system or network, which in this research has been selected as 5 seconds. Such an initial value is realistic as there will always be a limit on the total amount of data that can be monitored and processed by any decentralized control scheme. NaradaBrokering has a better performance than R-GMA. Therefore at this stage of the research we can conclude that Narada Brokering has good performance and that it satisfies the initial requirements of a Grid Computing Platform. It is also important to note that the Grid Computing platform as described in Figure 1 can be extended in a generic fashion to include a wide range of simulation tools and model data for both large-scale wind farms and individual turbines.

Fig. 6. Newly installed (October 2005) Combined Heat & Power and PV experimental facility.

The main objectives of the ongoing research can be summarized as follows;

- Completely decouple the generator simulation from the electrical network simulation. Enabling realistic simulation of large numbers of geographically distributed large-scale wind power generators.
- Replace the light-weight monitor with the full IE package developed as part of the GRIDCC project.
- Implement and demonstrate the monitoring and messaging middleware.
- Implement appropriate levels of security within the middleware.

Further research beyond the scope of the current project will also involve the development of Grid Computing applications in voltage control, spinning reserve and frequency response analysis for transmission systems with large-scale wind-power connection. Initial objectives will be to investigate grid computing platforms with existing commercial software tools, such as DIgSILENT [36] and Matlab/Simulink, [37] and also application software specifically developed for Grid Computing platforms for computationally intensive steady-state and dynamic analysis [15-17].

In addition, further experimental developments at Brunel University will give us monitoring access to real power generator instruments, for example an 80 kW Combined Heat & Power Unit as illustrated in Figure 6 that includes photo-voltaic array on the roof of the structure and a planned (1 kW) wind turbine. As part of the research project we will have access to the real-time electrical power data produced by such laboratory scale systems.

VI. References

[1] Ofgem (2003), 'Planning and operating standards under BETTA - An Ofgem/DTI consultation', Consultation Document 23/03 (available at http://www.ofgem.gov.uk)

[2] DTI (2003), 'Our Energy Future – Creating a Low Carbon Economy', Energy White Paper (available at http://www.dti.gov.uk/energy)

[3] B. Richardson and P. Jones (2004), 'Bringing Wind Power Ashore', *IEE Power Engineer*. February/March 2004. Pgs. 33-35.

[4] J. Ekanayake, L Holdsworth and N. Jenkins, 'Control of DFIG Wind Turbines', *IEE Power Engineer*. February 2003. Pgs. 28-32.

[5] J.G. Slootweg and W.L. Kling, 'Is the Answer Blowing in the Wind?', *IEEE Power and Energy Magazine* . 2003, Vol. 1 no. 6, pgs. 27-33.

[6] G.A. Taylor, S. Phichaisawat, M.R. Irving and Y.-H. Song, `Voltage Security and Reactive Power Management', *IMA Journal of Management Mathematics*. 2004, Vol. 15, pgs. 369-386.

[7] G.A. Taylor, M. Rashidinejad, Y.-H. Song, M.R. Irving, M.E. Bradley and T.G. Williams, 'Algorithmic Techniques for Transition-optimised Voltage and Reactive Power Control', *IEEE-PES/CSEE International Conference on Power System Technology*, Kunming, China, 13th-17th October 2002. Vol. 3, pgs. 1660-1664.

[8] S. S. Sharif, J. H. Taylor, and E. F. Hill, 'Dynamic online energy loss minimisation', *IEE Proc.-Gener. Transm. Distrib*. 2001, Vol. 148, no. 2, pgs. 172-176.

[9] G.A. Taylor, Y.-H. Song, M.R. Irving, M.E. Bradley and T.G. Williams, `A Review of Algorithmic and Heuristic Based Methods for Voltage/VAr Control', *5th International Power Engineering Conference (IPEC2001)*, Singapore, 17th-19th May 2001. Vol. 1, pgs. 117-122.

[10] Pregelj, M. Begovic and A. Rohatgi, 'Quantitative Techniques for Analysis of Large Data Sets in Renewable Distributed Generation', *IEEE Trans. on Power Systems*. 2004, Vol. 19, no. 3, pgs. 1277-1285.

[11] J. Contreras, A. Losi, M. Russo and F.F. Wu, 'Simulation and Evaluation of Optimization Problem Solutions in Distributed Energy Management Systems', *IEEE Trans. on Power Systems*. 2002, Vol. 17, no. 1, pgs. 57-62.

[12] T. Hey and A. Trefethen, 'The UK e-Science Core Programme and the Grid', *Future Generation Computing Systems*. 2002, Vol. 18, pgs. 1017 (also available at http://www.research-councils.ac.uk/escience)

[13] P. Marsh, 'Get on the Grid', *IEE Computing and Control Engineering*, February/March 2005. Pgs. 41-45.

[14] Foster, C. Kesselman and S. Tuecke, 'The Anatomy of the Grid: Enabling Scalable Virtual Organisations', *Int. Jnl. of High Performance Computing Applications*. 2001, Vol. 15, no. 3, pgs. 200-222.

[15] M.R. Irving, G.A. Taylor and P. Hobson, `Plug in to Grid-Computing', *IEEE Power and Energy Magazine*. 2004, Vol. 2 No. 2, Pgs. 40-44.

[16] G.A. Taylor, M.R. Irving, P.R. Hobson, C. Huang, P. Kyberd and R.J. Taylor, `Distributed Monitoring and Control of Future Power Systems via Grid Computing', *IEEE PES General Meeting 2006*, Montreal, Quebec, Canada, 18-22 June 2006.

[17] GRIDCC EU ICT Project, 'Grid Enabled Remote Instrumentation with Distributed Control and Computation', http://www.gridcc.org (last accessed August 2006).

[18] G.M. Masters, *Renewable and Efficient Electric Power Systems*, John Wiley & Sons, 2004, Ch. 3.

[19] M. Shahidehpour and Y. Wang, Communication and Control in Electric Power Systems; Appications of parallel and distributed processing, IEEE Press, 2003.

[20] J. Shu, W. Xue, W. Zheng, 'A parallel transient stability simulation for power systems', *IEEE Trans. on Power Systems*. 2005, Vol. 20, no. 4, pgs. 1683- 1689.

[21] J.P. Britton, A.N. deVos, 'CIM-based standards and CIM evolution', IEEE Trans. on Power Systems. 2005, Vol. 20, no. 2, pgs. 758- 764.

[22] A.W. McMorran, G.W. Ault, I.M. Elders, C.E.T. Foote, G.M. Burt, J.R. McDonald, 'Translating CIM XML power system data to a proprietary format for system simulation', *IEEE Trans. on Power Systems*. 2004, Vol. 19, no. 1, pgs. 229- 235.

[23] M.M. Nordman, M. Lehtonen, 'Distributed agent-based State estimation for electrical distribution networks', *IEEE Trans. on Power Systems*. 2005, Vol. 20, no. 2, pgs. 652- 658.

[24] J.A. Hossack, J Menal, S.D.J. McArthur, J. R. McDonald, 'A multiagent architecture for protection engineering diagnostic assistance', *IEEE Trans. on Power Systems*. 2003, Vol. 18, no. 2, pgs. 652- 658.

[25] British Wind Energy Association (BWEA), http://bwea.com/, last accessed August 2006

[26] National Grid, 'GB Seven Year Statement May 2006', http://www.nationalgrid.com/uk/Electricity/SYS/, last accessed August 2006.

[27] Z.H. Bie, Y.H. Song, X.F. Wang, G.A. Taylor and M.R. Irving, 'Integration of algorithmic and heuristic techniques for transition-optimised voltage and reactive power control', *IEE Proc.-Gener. Transm. Distrib.* 2006, Vol. 153, no. 2, pgs. 205-210.

[28] R.Pearmine, Y.H.Song, A.Chebbo, T.G.Williams, 'Identification of a Load-Frequency Characteristic for allocation of spinning reserves on the British Electricity Grid', *IEE Proc.-Gener. Transm. Distrib.* 2006, (Accepted for publication).

[29] J. Douglas and M. Orme, 'Time to Connect', *IET Power Engineer*, April/May 2006, pgs. 31-33.

[30] R. Pool, 'Meet the New Super Power', *IET Power Engineer*, June/July 2006, pgs. 8-9.

[31] Narada Brokering, www.naradabrokering.org (last accessed December 2005)

[32] G. Fox, S. Pallickara, M. Pierce, H. Gadgil, 'Building Messaging Substrates for Web and Grid Applications', *Philisophical Transactions of the Royal.Society: Mathematical, Physical and Engineering Sciences*, August 15 2005, vol. 363, no. 1833, pgs. 1757-1773.

[33] M.Rafian, M.J.H.Sterling and M.R.Irving: 'Real Time Power System Simulation', *Proc. IEE C*, 1987, Vol, 134, pgs. 206-223.

[34] Z. Xu, M. Ali, Z.Y. Dong and X. Li, 'A novel grid computing approach for probabilistic small signal analysis', *IEEE PES General Meeting 2006*, Montreal, Quebec, Canada, 18-22 June 2006.

[35] Q. Huang, K. Qin and W. Wang, 'Development of a grid computing application for electric power system applications', *IEEE PES General Meeting 2006*, Montreal, Quebec, Canada, 18-22 June 2006.
[36] DIgSILENT Power Factory, http://www.digsilent.de/, last accessed August 2006.
[37] Mathworks, Simulink, http://www.mathworks.com/products/simulink/, last accessed August 2006.

VII. BIOGRAPHIES

G. A. Taylor received his BSc from the University of London, UK in 1987 and MSc and PhD from the University of Greenwich, UK in 1992 and 1997, respectively. He was the National Grid UK post-doctoral scholar at Brunel University, UK from 2000-2003. He is currently a lecturer within the subject area of Electronic and Computer Engineering, Brunel University, UK. His research interests include power system and network monitoring, control and optimization.

M. R. Irving is a Professor and Electronic and Computer Engineering subject leader at Brunel University, London, U.K. His research interests include power system optimization and operation. He is also a director of the Brunel Institute of Power Systems, Brunel University, London, UK.

P. R. Hobson was born in Edinburgh, UK in 1959. He graduated from Edinburgh University in with a BSc in Physics in 1981 and was awarded his PhD from University College London in 1985. He is currently a Professor within the subject area of Electronic and Computer Engineering, Brunel University, UK. His research interests include Particle Physics and Grid Computing.