Adaptive intelligent power systems: active distribution networks

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Abstract

Electricity networks are extensive, well established and a key part of the infrastructure that supports industrialised society. These networks are moving from a period of stability to a time of potentially major transition. This change is being driven by a need for age-related renewal on a large scale, governmental policy commitments to harness cleaner and renewable sources of electricity generation and power industry structural changes. This paper seeks to identify the need for an evolution towards active distribution networks and innovations in electricity transportation. In order to realise such networks, several key electrical power technologies and innovative information systems are required, including:

- **wide-area, co-ordinated, active control** across large-scale electrical power systems providing for flexible network operation including strategic islanding of power system sections under specific operational modes

- **adaptive and integrated protection/control systems** to provide flexible, optimised reaction to network fault conditions, unusual transient behaviour and post-event recovery

- **power electronic-based network management devices** for network interfacing of distributed generation sources and voltage/power flow management in active networks

- **real-time network simulation and performance analysis** to provide both decision support for system operators and inputs to energy management systems and distribution management systems

- **advanced sensors and measurement** for the acquisition and transfer of critical measures and to achieve higher degrees of network automation and more deterministic system control

- **highly distributed and pervasive communications** to allow for flexible network reconfigurability and the transfer of real-time power system data for improved automation and monitoring

- **data interpretation through the use of intelligent systems methods** for automated reasoning deployed to the substation and plant levels potentially co-ordinated by **intelligent agents**

- **novel transmission and distribution systems designs** to challenge conventional electrical system designs considering variable voltage/frequency network designs, offering more flexible, sustainable options.

1 Background and introduction

Within mature international economies, electricity networks are extensive, well established and a key part of the infrastructure that supports industrialised society. These networks are moving from a period of stability, many decades in length, to a time of potentially major transition. This change is being driven by a need for age-related renewal on a large scale, governmental policy commitments to harness cleaner and renewable sources of electricity generation and power-industry structural, economic and regulatory changes. In the developing nations, the corollary challenge is for the design and construction of sustainable electricity infrastructures and generation sources required for economic and societal development. It is noteworthy that potentially innovative solutions to these different requirements may provide a convergence in network technologies, designs and operational strategies.

With reference to the UK situation, this sea-change is a time of opportunity for businesses, the power sector, and for consumers. Considerable network investment is needed and this has been reflected in the price controls recently announced by the industry regulator, the Office of Gas and Electricity Markets (Ofgem), for the distribution network companies. Our networks largely came about through state investments in the 1960s and 1970s and Ofgem has referred to the challenge as 'rewiring Britain'. Since deregulation of the electricity supply industry in 1989/90, there have been major technical and commercial changes. The industry is now 'rationalised' and, at the same time, more fragmented in its different approaches to solving the common challenges of an ever more demanding customer base, an ageing infrastructure and an increase in the volume and variety of distributed generation sources. The future challenge is to provide a more flexible infrastructure allowing novel electricity distribution and transmission networks to withstand demands that will be placed on them by novel generation types (including possible new-generation nuclear and clean coal), increasing demand, harnessing our renewable energy potential, facilitating demand-side participation and supporting low-carbon energy systems in an affordable, safe and environmentally acceptable manner.

This paper seeks to identify the need for an evolution towards **active distribution networks** and innovations in electricity transmission, including the potential for sub-sea grids, high-voltage DC systems and more radical future network technologies employing greater automation and distributed intelligent systems i.e. **smart networks**.

Additional references and sources of analytical output on advanced network technologies can be found via the Electricity Networks Strategy Group (ENSG: http://www.ensg.org.uk/) and its Distribution Working Group (DWG). The DWG draws its membership from all parts of the UK distribution sector, including network operators, equipment manufacturers, Ofgem, consultancies and academia. The *Technical Architectures* report of the Distributed Generation Co-ordinating Group (DGCG, a forerunner of the DWG) specifically highlights the need for co-operative working across the sector if a liberalised electricity industry is to take on major technological changes such as active, intelligent networks. It is noteworthy that Ofgem has recently introduced the Innovation Funding Incentive (IFI). This incentive has stimulated the network operators to fund development and testing of academic research outcomes for the purposes of network investment and evolving electricity network designs, technologies and operational strategies to more sustainable basis.

2 Electricity network architectures: current state of technology

Traditional electrical power system architectures reflect historical strategic policy drivers for building large-scale, centralised, thermal- (hydrocarbon- and nuclear-) based power stations providing bulk energy supplies to load centres through integrated electricity transmission (HV-400kV, 275kV and 132kV) and distribution (MV, LV-33kV, 11kV, 3.3kV and 440V) 3-phase systems.

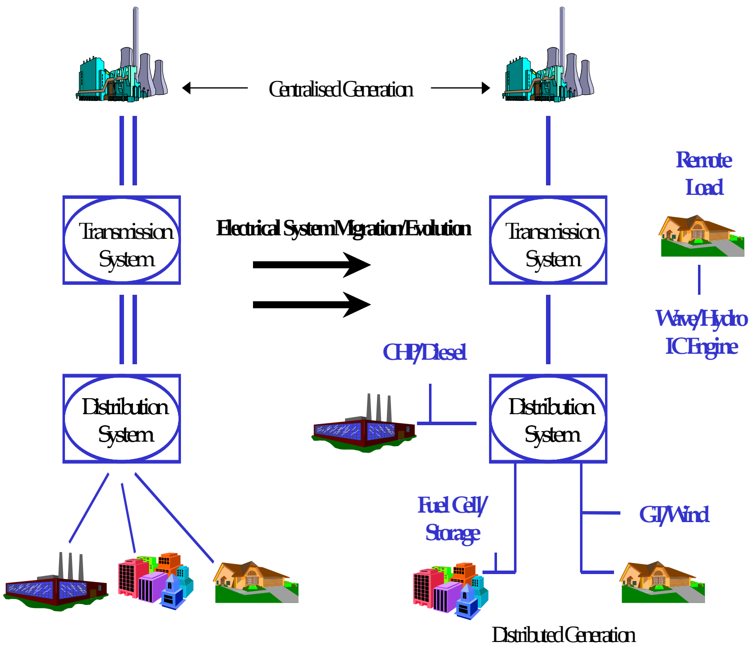
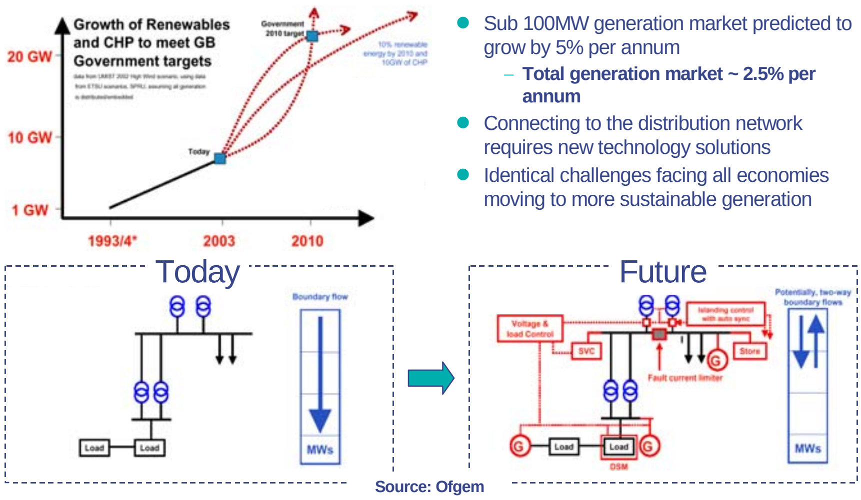


Figure 1: Evolution of Electrical Power System Architectures

In the mature economies, these designs have been predominant, but, as a result of industry restructuring and international policy drivers for low-carbon, renewable energy production, they have been underinvested and now questioned as to their future sustainability with regard to anticipated future energy scenarios that may compromise their ability to support innovation. The hierarchical control structures for these traditional designs differ across the transmission and distribution levels, with greater automation (and complexity) obvious at the high-voltage levels and centralised control-room-based operational management and reasonably pervasive stem protection. At the distribution level, conventional network design has led to less sophisticated system control and management structures with lower levels of automation in place.

Given the significant growth and penetration of renewable sources and other forms of distributed generation, there are now increasing pressures on distribution networks to cope with new system stability (voltage, transient and dynamic), power-quality and network-operational challenges brought about by embedding generation sources that would have been, more typically, larger-scale, thermal and connected to the grid at the transmission levels. Consequently, we are approaching a problem inversion situation where, similar to conventional transmission networks, more active network strategies and technologies will be required at the distribution level.

Figure 2: Drivers for the development of active distribution networks



The term **active** is significant because the medium voltage distribution network (unlike the high-voltage transmission network) has traditionally been a passive means to pass power from bulk-supply points to customers. Quality of supply has been ensured by planning a degree of redundancy and by some centralised ability to switch connection points, albeit at a relatively low response rate. Single-circuit radial distribution lines are vulnerable to faults and the first priority of power-system protection schemes is to isolate faulted sections and plant.

Restoration of customers who are off-supply can be relatively lengthy because automated restoration relies on methods run by controllers that are written for only a small number of scenarios. If the scenarios don't apply, restoration is through manual control. Voltage profiles in the network are assessed at the planning stage and transformer tap changers (perhaps with line-drop compensation) used to accommodate load variations. The inclusion of distributed generation (DG) calls for a greater degree of control, including control of DG reactive power. It is therefore not straightforward to integrate new DG, and the connections that can be immediately allowed are well below the full potential of the network were it **actively managed**. Active network management is about integration of DG into network operation rather than its straightforward connection. Active network management can also make use of other distributed resource, such as storage, to relieve constraints that arise in networks where energy use and demand patterns have changed. Technical analyses by the Department of Trade and Industry (DTI) Centre for Distributed Generation and Sustainable Electrical Energy (Imperial, Strathclyde and Manchester) has demonstrated that, by employing active network management methods, distribution networks can accommodate ~3 times more DG connections than equivalent networks without active management.

The notions of **active distribution networks** and **intelligent/automated power systems** have gained currency in recent years and are well reflected in the UK in the technical focus of the DTI, Ofgem and the DWG of the Electricity Network Strategy Group (http://www.ensg.org.uk/) and in the technical programmes addressed in the Engineering and Physical Sciences Research Council (EPSRC) Supergen activities such as *Future Network Technologies*, *Highly Distributed Power Systems* and *Energy Infrastructure* (http://www.epsrc.ac.uk). Internationally, the EU-Technology Platform and the Electrical Power Research Institute (EPRI) of North America are also promoting work in this area, such as *IntelliGrid* (http://www.epriintelligrid.com) and several projects under the *Advanced Distribution Automation* portfolio. There are three reasons why increasing attention is being paid to active distribution systems. First, there are increasing customer expectations for reliable power delivery and high quality of supply. Second, there are policy-driven desires to facilitate connection of relatively small generation (and potentially storage) devices into the MV and LV systems. In Europe, this is largely driven by the desire to exploit local-scale renewable energy. However, in the USA, the driver is power system network congestion management. A third factor, particularly strong in the UK, is the desire of the distribution network operators themselves to better manage their assets from the points of view of asset utilisation, deferral of reinforcement and strategic replacement of ageing assets.

3 Innovation requirements: future developments and research

The realisation of **active distribution networks** and **intelligent/automated power systems** is predicated on the availability, through underpinning basic research and collaborative strategic research, of several key electrical power technologies and innovative information systems and methods. These include:

- **wide-area, co-ordinated, active control** across a (relatively) large-scale electrical power system, rather than on a feeder-by-feeder basis providing for flexible network operation, including strategic **islanding** of power system sections under specific operational modes (c.f. **power cell** concept proposed by Energinet.dk of Denmark: http://www.Energinet.dk). Such control requirements may be satisfied by the use of complex system methods and candidate

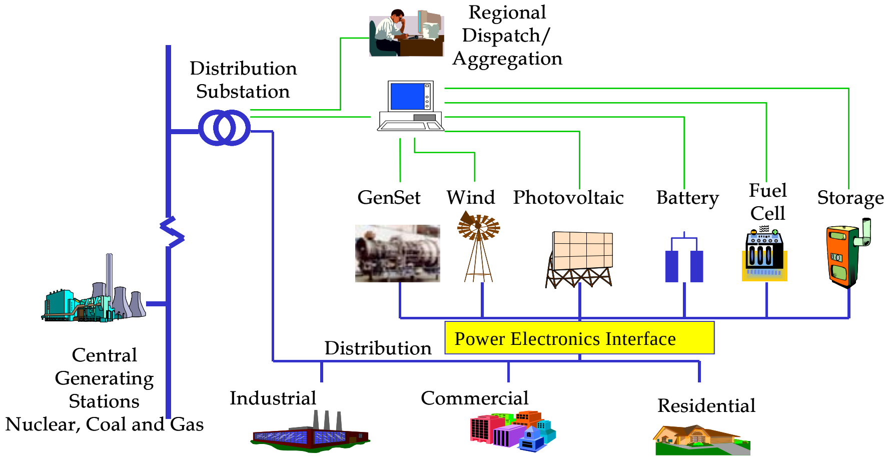


Figure 3
A schematic of a semi-autonomous power system or power cell capable of managed islanding from the main grid

techniques such as individual channel analysis and design (ICAD) for large-scale multi-input-multi-output problems

- **adaptive and integrated protection/control systems** are required to provide flexible, optimised reaction to network fault conditions, unusual transient behaviour and restoration/reconfiguration for post-event recovery. The requirement for adaptability stems from the significant number of power systems' operational modes and configurations that could occur with potentially many hundreds of generating sources (and thousands in the case of deeply embedded generation at the micro-grid level). The research would require novel algorithms capable of recognising new transient phenomena brought about by complex interactions between large numbers of generator controllers, network management controllers (typically power electronics based) and active loads. It's important to note the need for the development of methodologies for system state estimation (at both distribution and transmission levels) based on wide area measurements so that this information can be used in conjunction with advanced active control and protection systems

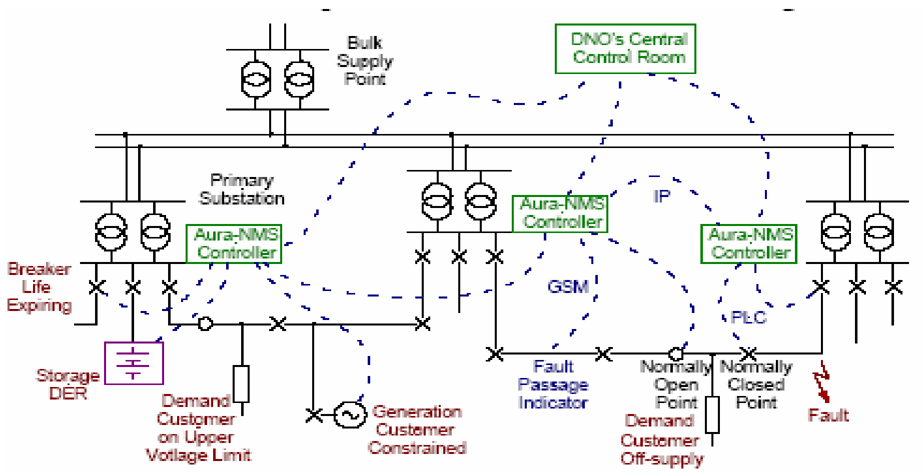
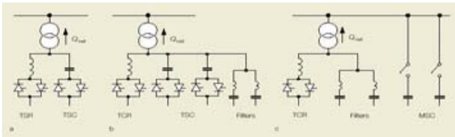
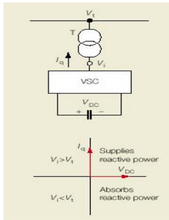


Figure 4: Example of a distribution network configuration showing the concept AURA (ABB)-Network Management System controller deployment and an open-ring style of feeder they would control to relieve network congestion, control voltage on feeders with DG and manage restoration of customers off supply. The necessary system communications would range from existing SCADA and new peer-to-peer links introduced between substations. Source: Professor D. Botting, ABB.

- **power electronic-based network management devices** for network interfacing of DG sources (asynchronous electrical machines, DC sources and synchronous AC sources) and voltage/power flow management in active electrical power systems, that is, providing at the distribution level the same power quality and network configuration management as is provided at the HV levels via flexible AC transmission systems (FACTS). The research challenges in this area lie in new devices and materials for high-current, high-voltage switching, new device configurations/systems and the control of these switching devices to optimise network support



Static VAR Compensators



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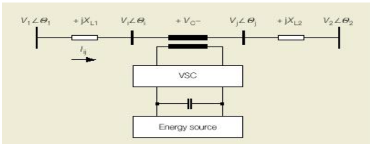
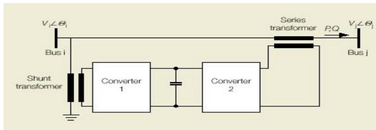


Synchronous Static Series Compensator



Unified Power Flow Controller

Figure 5: FACTS device configurations that can be replicated at the distribution level

- **real-time network simulation and performance analysis** are key to providing both decision support for system operators and inputs to energy management systems and distribution management systems (or their combination). This may be achieved through the development of novel models and algorithms as well as new power-system data structures (e.g. common information model, CIM). The research need lies in novel power systems and plant models, stable algorithms for their execution, their integration on common simulation platforms and software design for analysis on real-time simulation hardware

- **advanced sensors and measurement** are necessary for the acquisition and transfer of critical measures and to achieve higher degrees of network automation and more deterministic system control. This would support not only the deployment and operation of distributed (but co-ordinated) controllers, but would also deliver critical plant health data necessary for the purposes of strategic asset management and optimal use of system capacities. Research challenges come from the need for multiple measurement capabilities to acquire, for example, current, voltage, frequency and possibly temperature, vibration and pressure from a singe device, while demonstrating EMI and harsh environment withstand characteristics. For example, optical methods and UHF electromagnetic techniques for the capture of partial discharge and high frequency transient data show great promise

- **highly distributed and pervasive communications** links with concern for latency, variability of latency and reliability. This is an essential enabling technology to allow for flexible network reconfigurability and the transfer of real-time power-system data to facilitate improved automation, control, protection and monitoring. This will range from power line carrier, optical broadband, wireless and internet protocol through to GPS for the purposes of real-time phasor measurements and the data synchronisation necessary for wide-area control

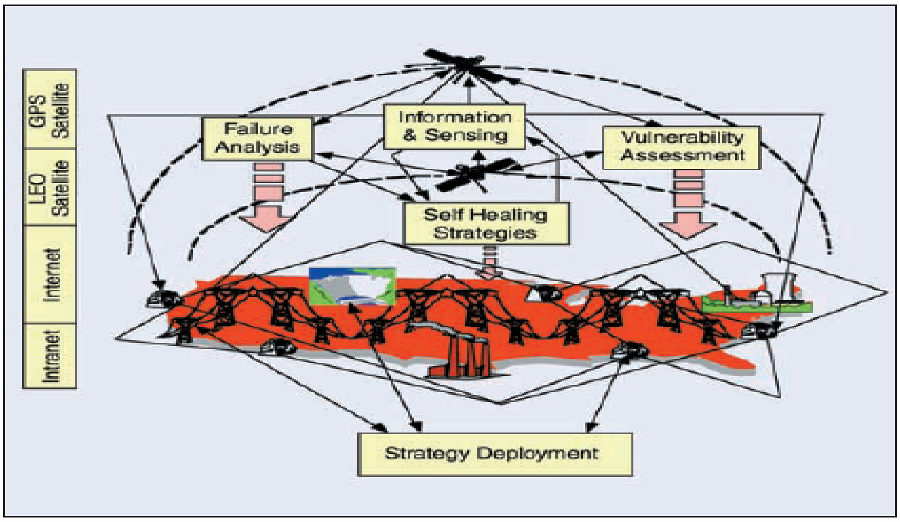


Figure 6: Concept wide-area measurement and communications for electrical power systems. Source: Heydt, G.T., Liu, C.C., Phadke, A.G. and Vittal, V. 2001. *IEEE Computer Applications in Power*.

- **data interpretation through the use of intelligent systems** methods such as knowledge-, case- and model-based reasoning methods deployed to the substation and plant levels potentially co-ordinated by **intelligent agents***.* Such methods are now being made robust and can derive key information through the automatic interpretation of operational data and the delivery of information in a variety of formats appropriate to real-time control through to longer-term planning horizons. Research challenges include specific interpretation and data-mining techniques, knowledge capture and codification, dynamic and open software platforms to integrate several intelligent system methods, machine learning and intelligent agent design and application

- **novel transmission and distribution systems designs** are key research issues in that, with the advent of advanced power electronic systems, low-carbon energy targets and (typically) remote renewable energy sources, traditional electrical power system designs are being challenged with respect to electrical energy transportation voltage and frequency. To harness remote renewable energy resources, the opportunity to employ high-voltage transmission systems must be considered. This is also true for a prospective sub-sea grid infrastructure for which optimal network designs and operational codes must be identified to exploit tens of GWs of off-shore power potential while connecting to the main land-based electrical system in a stable and controllable manner. A variable voltage/frequency system design is also an attractive prospect at the deeply embedded levels where innovative microgrid designs can take advantage of power electronics, advanced control methods and pervasive communications facilities to distribute power most effectively.

3.1 Reference to the Technical Architecture Project for future developments and research

The Technical Architecture Project was initiated through objectives set by the DTI/Ofgem DGCG (now succeeded by the ENSG involving the DWG and the Transmission Working Group (TWG). The objectives of the activity were to reach an informed position on the need for electrical power system evolution and to identify the technical, environmental and economic challenges impacting on electrical networks and to examine new network designs, technologies and operational strategies that would mitigate future investment risks by making them more 'future proof'.

A number of key references and ground rules emerging from the Technical Architecture Project that are relevant to the main recommendations for future developments and research made in this paper include:

- Network development must be adaptive, recognizing a considerable bandwidth of uncertainty.
- Uncertainty will be ongoing, so future proofing has to be part of network design.
- Developments should consider technical issues jointly with safety, environmental, commercial and regulatory factors.

- Development should consider distribution *and* transmission factors, ensuring cross-coupling of ideas and developments, and avoiding artificial divisions.
- Development should accommodate rapid prototyping and demonstration of new technology.
- Technology and products should benefit from international best practice and open sourcing.
- New technology, once proven, should be rolled-out rapidly to maximise benefits.
- Designs should seek simplicity (escalating or uncontrolled complexity is a potential risk).
- Enabling technologies can be identified for generic development, for example:
    - voltage control
    - fault level control and fault management
    - power flow control devices
    - islanding capability
    - ancillary services capability
    - energy storage
    - demand side management
    - Distribution Management Systems, Energy Management Systems & Remote Terminal Units
    - power electronics
    - communications
- Network migration paths should recognise the potential for eventual islanding capability.

These ground rules complement the recommendations in this paper and reflect significant discussion and analysis carried out in partnership between industry, government and academia.

4 Conclusions

This paper has sought to identify the major research challenges facing electrical power networks and the strategic urgency with which redesign of a key infrastructure must be undertaken. The UK has a leading position in power industry restructuring, environmental policy and in pertinent academic disciplines. Therefore we have an opportunity to find innovative solutions, which not only serves to create a new electricity system for the next century, but also provides major economic advantages in providing technical solutions and designs for an international market that is currently (or soon to be) facing similar electrical network crossroads.