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The Architecture and Control of Large Power Networks With Distributed Generation

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SUMMARY

This paper briefly summarises the evolution of transmission and distribution networks since the late 19th century, and explains that the introduction of significant amounts of distributed generation may bring about a future fundamental change to the network architecture. Providing a secure power network is a demanding task, but as network complexity is expected to grow with the connection of large amounts of distributed generation, so the problem of integration, not just connection, of each successive generator becomes more protracted.

A fundamental change to the network architecture may eventually become necessary and a new architecture, perhaps based on power cells, containing generation, energy storage and loads has been proposed by some researchers. This paper describes a novel power cell interface. It makes the case for the conventional power transformer to be replaced by an Active Transformer, the objective being to provide a more controllable, flexible and robust connection that will facilitate greater network management and business opportunities, and new power flow control features.

The Active Transformer design is based on an a.c. link system described by Thomas Lipo in 1986 and an a.c.-a.c. high-frequency direct converter design demonstrated by Dang in 2006. It consists of a resonant, supply-side converter, a high frequency transformer and a resonant, load-side converter. This paper describes a model of the Active Transformer, built in Simulink®, and presents the results of simulations that demonstrate its action to control current in a resistive load.

KEYWORDS

Active transformer - Converter control - Network management -Network architecture.

1. NETWORK ARCHITECTURE

1.1. Historical review

There are few comprehensive studies of the development of the British Electrical Network but “Electricity before Nationalisation: A study of the Development of the Electricity Supply Industry in Britain to 1948” [1] by Leslie Hannah is essential reading. The study was commissioned by the Electricity Council of Great Britain, which gave the author free access to a considerable collection of documentation. Hannah’s study does not focus on a technical history, but more on the central policy-making relevant to the development of the national network. However, he does describe the changing nature of electricity supply network, from one with numerous inefficient stand-alone systems with no standards to larger, more integrated networks where control was divided between private companies and municipal authorities by legislation. He thus gives the background to the development and the processes of change that are important in understanding the network that we have today and how it may change in the future. A more recent review was undertaken by Eunson and Martin [2] who gave a very comprehensive account of the UK network development over the period 1880 – 2000. What becomes clear very quickly is that the change processes were led by consumer demand for electricity; technical innovation and development often lagged behind the demand for more power. However, neither reference gives a clear view of the complexity of the architectural changes that occurred, except in the most general terms.

Many of the early major technical problems were discussed at national institution meetings, for example, in the UK, in meetings of the Institution of Electrical Engineers (IEE) whose proceedings date from the 1880s. An extraordinary meeting of the I.E.E. was held in association with the American Institute of Electrical Engineers on 16 August 1900 in the US National Pavilion in the Paris Exhibition [3]. This was a grand setting to discuss the relative advantages of alternating and continuous current for the supply of electrical power. This meeting underlined the fact that the technology of the electrical supply apparatus was international, but that the supply systems were designed to meet local or national requirements.

1.2. Contemporary power networks

Interconnection and integration have not been without their problems. The control and stability of power flow and voltage were issues of electrical power distribution that grew out of the developing network of interconnected distribution systems in 1920 [4] and in 1988 [5]. There are ongoing concerns of stability today as networks continue to grow and develop to meet an increasing demand for more electrical power in a deregulated environment.

Although electrical power networks have grown in size and structure, they all have similar characteristics [6], which in effect describe their architecture:

- i) they are built around three-phase systems operating at constant voltages
- ii) primary sources of energy are converted to electrical energy by synchronous machines
- iii) power is transmitted to consumers over considerable distances via complex networks of subsystems and cables,

in addition in many contemporary networks:

- iv) generation, transmission, and distribution are vertically integrated and centrally controlled.

Unlike the largest power stations, which are connected to high-voltage electricity transmission systems, distributed generation (DG) is connected to regional distribution networks at lower voltages. Distributed generators are mostly, though not exclusively, those generating power from environmentally-friendly, renewable energy sources, such as on-shore/off-shore wind, tidal and biomass energy, or from combined heat and power (CHP) plants. It is anticipated that electrical power generated from renewable energy will, over the next twenty years, become a significant part of the total generating capacity of the European Union (EU).

Contemporary distribution networks are designed and operated to accept bulk power from the transmission system and to distribute it to consumers, i.e. for the connection of loads not generators. Because of differing local conditions and load requirements, this design strategy has led to many bespoke networks with different operating and design restrictions in different regions, and hence to constraint managed networks and DG connection schemes.

In the UK the amount of distributed generation is still relatively small and from an operational point of view it has been “connected to” rather than “integrated with” the network as a negative load and did not disturb the network integrity. In some quarters this is called a “fit and forget” strategy [7]. This DG connection strategy reinforces the essentially passive nature of the power network and precludes it from contributing to network ancillary functions that are traditionally assigned to the larger generators.

In the event that the connection type strategies of the past years do not fully meet all future integration needs, a fundamental change to the network architecture and its control is suggested that may facilitate further network development. If significant amounts of DG are to displace large central generation and its ancillary facilities, then the present legislative framework, as well as the network architecture, must change to enable DG to contribute to the network support activities [8]. Whatever solution or solutions are eventually used to fully integrate distributed generation, their capital cost and reliability will be significant considerations.

1.3. Future networks

Throughout the 130-year history of the electricity supply network there has been a dependence upon a steady development of technology to meet a growing demand for electrical power. Experience has shown that the power industry has generally been conservative in its adoption of new technology and radical change, tending to err on the side of caution to maintain a robust, cost efficient and reliable supply.

We have seen the capacity of power networks expand through a demand led and technical advance change process from an abundance of small-scale isolated systems to the large-scale, bulk power transfer, complex network that we have today. We can see that this history presents two significant changes of network architecture:

- i) isolated to interconnected systems
- ii) interconnected systems to a bulk power transmission system.

These changes happened slowly, but not without cost implications and much legislative, commercial and technical debate. However, change happened and we should expect change to the network to continue, much as Lord Kelvin predicted:

“What I am seeing today is the dream of my life realised. I don’t know what electricity is, and cannot define it – I have spent my life on it – I do not know the limits of electricity but it will go far beyond anything we conceive today.”¹

So what will be the network architecture of the future? Will the current architecture be able to expand without further change, will it revert to an interconnected network of the late 1920s and early 1930s or will there be a more gradual change to an active network?

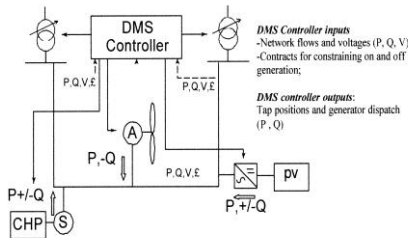


Figure 1 An active network²

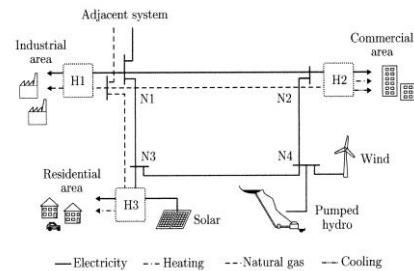


Figure 2 Sketch of interconnected energy hubs³

A fundamental change to the network architecture and its control could perhaps be envisaged. Research into new network architectures is being undertaken, however, given the past history of slow architectural change, no change to the network is likely in the short term. Botting [9] gives a good view of the architecture issues facing the UK’s power networks. Roberts [10] describes a possible short-term solution of a more sophisticated SCADA architecture taking on an active control role. Network architecture is also being researched at the University of Manchester [11] based on a distribution cell and at ETH Zurich [12] based cells of interconnected energy hubs. Both schemes seek to divide power networks into small cells that incorporate electrical generation, storage and loads. The cells are managed and controlled centrally by a dedicated controller, but there are no new power control devices described in published papers. Another possible solution is a power distribution network based on a more controllable primary interface, such as a high frequency resonant link described by Sood and Lipo [13], a solid state substation described by Oates in his patent [14], or more generally an Active Transformer.

2. THE ACTIVE TRANSFORMER

2.1. Background

The “Active Transformer” consists of a resonant supply-side converter, a high frequency transformer and a resonant load-side converter. Its function is to provide a means of continuously controlling bi-directional power flow between a power cell and a network such that cell loads can be satisfied first by locally connected distributed generation, which will not be constant, and then by power drawn from the high voltage network via the Active Transformer. At times of excess power generation in the cell, rather than balancing the cell load/generation by generation curtailment, real and reactive power can be exported and traded via the Active Transformer. The Active Transformer could also provide a means of controlling and stabilizing distribution network voltages and limiting, or isolating, fault currents in either direction. A pseudo “islanded network” control capability may also be

¹ Lord Kelvin – from his speech on the opening of Neptune Bank Power Station on Tyneside in 1901.

² [11] slide 9

³ [12] Figure 2.3 page 13.

was replaced with a more robust design, a loop-shaping H_∞ controller, whose design generally followed the step-by-step loop-shaping procedure detailed in [16]. The simulation results using the H_∞ controller are shown and are comparable with the PI results shown in [15], but with robustness guaranteed.

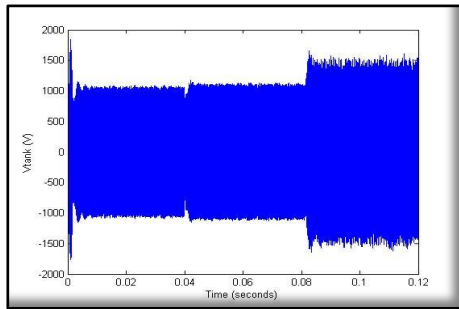


Figure 4 Resonant circuit voltage - H_∞ controller
100% load change at 40 ms, 300 V change at 80 ms

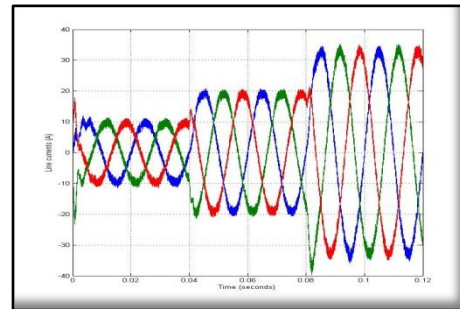


Figure 5 Line currents - H_∞ controller
100% load change at 40 ms, 300 V change at 80 ms

The effects of sliding mode control are clearly seen in the “noisy” variation of the peak resonant circuit (tank) voltage, Figure 4, and in the 20 kHz ripple on the supply line currents indicated by the thickening of the traces, Figure 5. The amplitude of the ripple current is determined by the value of the line inductors, but no attempt was made to reduce this by refining the design from [15] in order that clear comparisons between the two voltage controls could be made.

3. ACTIVE TRANSFORMER

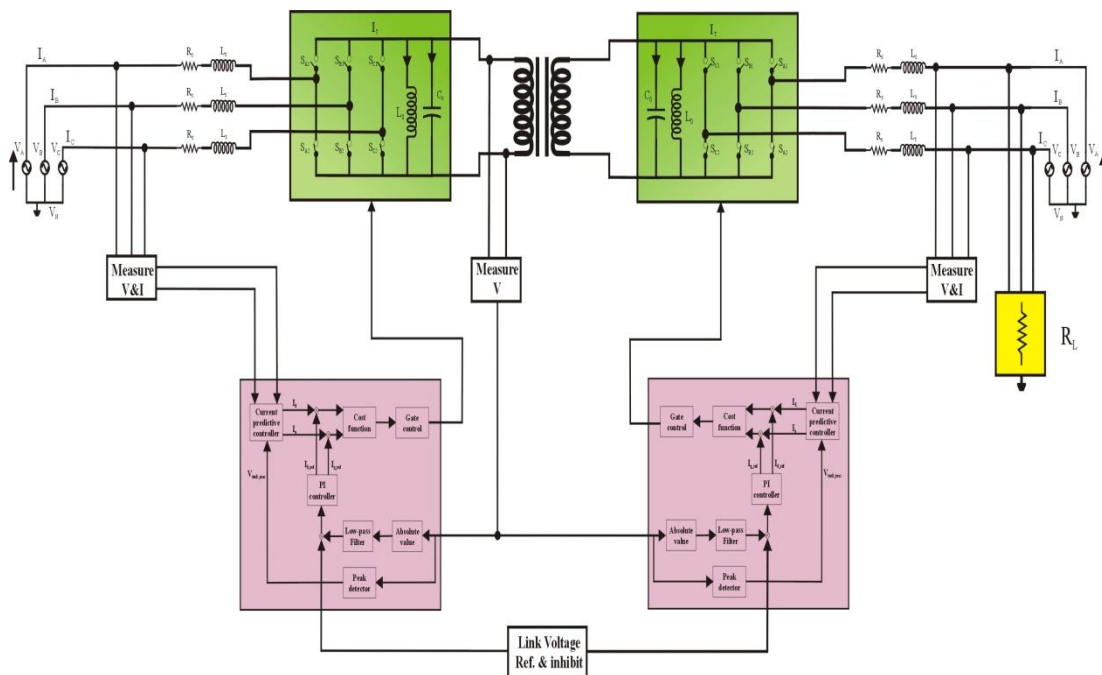
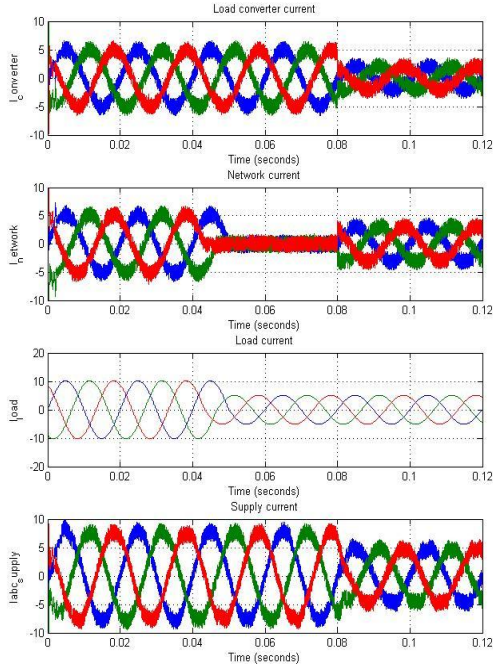


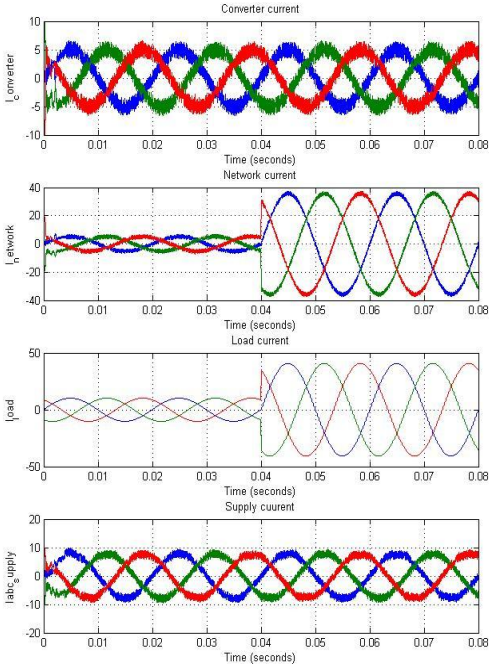
Figure 6 Active Transformer schematic diagram

The MATLAB/Simulink[®] converter model was used to build a model of the Active Transformer, a schematic diagram of which is shown in Figure 6. A similar design to that of the supply-side converter was used for the load-side converter model. The concept of an Active Transformer facilitates the control of power flow, whether it is required to flow from the transmission network side (supply-side) in the forward direction to the distribution

network side (load-side) or vice versa in the reverse direction from the distribution network to the transmission network. For power flow control in the forward direction, the supply converter would be required to control the source line currents, the phase angle between the supply line voltage and current, and the a.c. link voltage. Whereas the load converter would be required only to control the current (and hence the power) fed to the distribution network. This means that the supply and load converters were of similar topology and design for ease of reversal of power flow, but the voltage control was omitted from the load-side converter control and the direction of current flow through the load-side line inductors is reversed. With this particular arrangement a system load and a generator load (or infinite bus) is required on the distribution network to control network voltage, as the load converter can not control both load voltage and current simultaneously.



**Figure 7 Active Transformer
100-50% load change @ 40 ms
10-5 A demand change @ 80 ms**



**Figure 8 Active Transformer
5-20 kW load change @ 40 ms**

The results of step changes to the resistive load and the load-side converter demand are presented in Figure 7. From an initial condition where the Active Transformer and the network generator are sharing the load current equally, a load change, at 40 ms, from 32 to 64 ohms is recorded. Note that the load-side converter demand does not change, but that the network current reduces to near zero. Under these conditions the disadvantage of sliding mode control is very evident, i.e. a ripple current is always present, even for a zero demand. At approximately 80 ms the load-side converter demand is changed from 5 to 2.5 A. The load current remains constant and the network current increases accordingly, in phase with the converter current to maintain the load current.

The supply line currents remain consistent throughout. The results of an exceptional load change from 5 to 20 kW are shown in Figure 8 where the Active Transformer control has been set at a fixed demand. The supply and output currents remain unchanged and the additional load current is then supplied by the network.

4. CONCLUSIONS

Because of the effects of climate change, the UK is planning to derive much more electricity from distributed generation using renewable energy sources. The full integration of distributed generation, such as large off-shore wind farms, will bring many technological challenges that may lead to significant changes to contemporary network architectures. Networks are already becoming more “active” with increased monitoring and control facilities but the demand for more significant change, such as the introduction of smaller interconnected autonomous power networks, has yet to be established. Should architectural change become necessary, power electronic converters will be an important means of facilitating greater control. This paper has demonstrated, through simulation, some of the features of an Active Transformer that could provide advanced network management and control features. To be cost effective, power converters will need to operate at distribution network voltages and hence commercial quantities of silicon-carbide or other high-voltage power devices will be needed.

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