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A NOVEL ARCHITECTURE FOR POWER NETWORKS WITH DISTRIBUTED GENERATION - CONCEPT OUTLINE

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Abstract: Providing a secure power network is already a complex task but as network complexity grows with each new distributed generation connection so the problem of assurance for the next source connection becomes more and more protracted. A fundamental change to the network architecture may be necessary and an architecture based on cells containing both generation and loads has been proposed by some researchers. This paper proposes a novel power cell interface, replacing the conventional power transformer with an “active transformer” in order to provide a controllable, flexible and robust connection that will facilitate greater network management and business opportunities and new power flow control features. Copyright © 2006 GARLICK

Keywords: Active transformer, converter control, distributed generation, large power networks, renewable energy sources, system control.

1 INTRODUCTION

Figure 1 shows the recently commissioned wind farm development at the Kentish Flats in the Thames estuary, one of the UK Department of Trade and Industry (DTI) and the Crown Estate first round sites. In December 2003, a second round of licences for off-shore wind farms was announced. Twelve developers were successful and 15 site leases offered, with a potential generation capacity ranging from 64 to 1200 MW, the largest being 1,200 MW at greater than 12 miles offshore. Existing power distribution networks have not been designed to accept extensive distributed generation and the size and distance offshore of the proposed generation presents new technical challenges to their connection.

The DTI and the Office of Gas and Electricity Markets (Ofgem) created and jointly chaired the Distributed Generation Co-ordination Group (DGCG). The Group was concerned with a wide range of issues related to the connection and operation of distributed electricity generation in Great Britain, (Cooke, and Baker 2002; Collinson, 2003). The issues included the consideration and making of recommendations as to any research and development action that may be helpful to achieving Government targets for the generation of electricity.
from renewable energy sources. A key objective of DGCG Workstream 3 (WS3), was to establish how to facilitate the connection of distributed generation to distribution networks, without driving reinforcement costs high and without impairing the quality and reliability of the supply to customers. The problems and the solutions that the group proposed were categorized in terms of managing fault levels, voltage levels and network power flows. STATCOMs and Active Network Voltage Control solutions were identified as long term solutions requiring significant additional research and development. This paper describes a novel active network solution that addresses directly the problems identified by the DGCG.

2 BACKGROUND

2.1 Distributed Generation

With the introduction of larger scale distributed generation, e.g. wind farms or larger biomass projects, system stability and fault current capability needs to be assured before each new energy source can be connected. This is already a complex task but as the power network grows with each new connection so the problem of assuring stability and fault capability connection becomes more difficult. The Distribution Network Operators’ (DNOs) ability to increase the capacity of the current network is thus limited and a more flexible, active network will be needed to assure future electrical supplies and network development.

The stable control of power flow and voltage have been key issues since the early days of electrical power generation and distribution (Steinmetz, 1920) and has been an ongoing concern as networks have grown to meet the increasing demand for electrical power (Tesserson et al., 1988). The integration of large wind farms, particularly those proposed for the more extensive off-shore sites, into existing power networks presents new management and control challenges for network engineers. The current approach is to examine each proposed connection and assess its compliance with the Grid Code (NGC (2004), Bolik, 2003) to determine the need for any special network support of control measures. These measures are generally costly and cannot be undertaken lightly.

Control technologies, such as HVDC and Static Compensators (STATCOMs), are sometimes specified as control measures. These are based on power electronic devices and may prove to be the only feasible and economic way of complying with current Grid Codes in the near term. Development of these control technologies is currently being undertaken in industry where the equipment is manufactured.

HVDC can offer some significant benefits not normally available to network operators. They allow power flow control and frequency decoupling and considerably increase the potential for meeting the Grid Code requirements. Further, the reduced operational power losses and cabling requirements for longer connections provide some cost advantage over an a.c. connection. Recently, small on-shore wind farms have been successfully connected using “HVDC Light”; e.g. 8MW scheme at Tjaereborg, Denmark, this scheme uses voltage source converters (VSC) with IGBT devices.

Contemporary schemes are however unlikely to meet all future integration needs and a fundamental change to the network architecture and its control is proposed to facilitate network development and robust integration of a high penetration of renewable energy generation.

2.2 Network Architecture

A power distribution system based on a single-phase high frequency resonant link was described by Sood and Lipo (1986) and in a subsequent paper, Sood and Lipo (1988), a pulse density modulated (PDM) power converter utilizing zero voltage switching was proposed. Little further research or applications have so far been found of this architecture until the publication of Oates’ patents (2002, 2003) and, Dang (2006) at Nottingham University.

However, research is currently being undertaken on new network architectures at UMIST (Strbac et al., 2004) and ETH Zurich (Geidl, 2004). Both schemes seek to divide power networks into small cells or micro-grids that incorporate electrical generation, storage and loads that are managed and controlled centrally by a dedicated controller. The UMIST scheme is based on the control of power flow and voltage whilst the ETH schemes controls energy. Both schemes use a conventional power transformer as the connection to the rest of the network.

Whatever solutions are eventually used to connect distributed generation to power networks, their capital cost and reliability will be significant considerations.

2.3 Patents

A patent by Oates (2002) describes an electrical substation, a “solid state substation”, based on high frequency d.c. link power converters that overcomes some of the limitations of conventional tap-changing power transformers and permits a degree of control usually provided by a static VAR compensator (SVC). He also suggests the application of direct conversion and that “the input switching network may include a resonant circuit”. A high voltage
resonant matrix converter is described in his companion patent Oates (2003). Both d.c. and a.c. supplied converters are described. The resonant configuration enables high voltage operation by overcoming the problems of synchronizing the switching of large numbers, 50 or more, of series semiconductor devices.

While it is possible to connect a large number of devices in series with contemporary silicon semiconductor technology, the cost of a transmission voltage converter is likely to be prohibitive, except in very unusual circumstances. The converter topology is however, better suited to silicon carbide devices currently under development, which operate at much higher voltages than silicon, and may be available in suitable ratings in the next five to ten years. Devices based on diamond semiconductors are also being developed and these would undoubtedly operate at higher voltages than even silicon carbide and could considerably reduce the device count of very high voltage converters.

Pulse width modulation (PWM) control is suggested by Oates (2002) for the d.c. link converters. However, in Oates (2003) control of the current sourced, resonant, matrix converter is not detailed but zero voltage switching is proposed and, therefore, this would occur at twice the resonant frequency.

The combination of high frequency resonant converters and a high frequency transformer that Oates outlines in his two US patents can be considered more generally as an “active transformer”. This is a novel power system device and, little prior research or application in power systems has been found. The work reported in this paper demonstrates, using simulation techniques, the feasibility of the “active transformer” concept as a means of integrating renewable distributed generation. The “active transformer” is used as an interface between a Distribution Network cell and the remainder of the power network for the integration of distributed generation. The aim is to provide a means of continuously controlling bi-directional power flow between the cell and the network such that cell loads can be satisfied first by locally connected wind or other renewable energy generation, which is likely to be variable, and then by power drawn from the network via the active transformer. At times of excess power generation in the cell power can be traded and exported via the active transformer. The active transformer also provides a means of controlling and stabilising voltage and limiting or isolating fault currents in either direction and, if necessary, operating an “islanded network”. The key to the exploitation of the “active transformer” is its versatility and controllability.

The matrix topology of the a.c. supplied converter in Oates (2003) implies the use of space vector modulation (SVM) as the control technique, but this is unlike the conventional modulation technique applied to d.c. link converters for drive applications. Dang (2006) in his thesis gives a broad review of “solid state transformer” converter technology, including resonant direct matrix converters. He concludes that his work would have been more complete if a complete solid-state transformer had been built. Dang (2006) uses a predictive version of this idea to demonstrate control of input current and tank voltage by choosing the switch vector that reduces the line current error to a minimum against an error-squared cost function. This strategy seems to avoid the zero vector trap of a conventional SVC implementation where the zero vector is applied regularly. In effect, the choice of a single “best stationary vector” may be likened to a “bang-bang” controller in which the error remains between limits but is usually non-zero. Thus the application of stationary vectors will nearly always give better solutions than the null vector.

4 CONVERTER DESIGN

The active transformer consists of a supply converter, a high frequency transformer and a load converter. A schematic diagram of the supply converter is shown in Fig. 2. The power circuit of input and load converters may be similar and therefore only the
input converter will be described here. Key design points are the tank circuit and the input current ripple.

In this model, \( V_i \) and \( I_i \) (\( i = a, b, c \)), the input phase voltages and currents are regarded as independent orthogonal variables. The converter switching constraints are that the inductor must never be open-circuited and the output voltage across the tank circuit must never be short-circuited. Dang (2006) expresses these constraints as:

\[
S_{i1} + S_{i2} = 1
\]

And from Kirchhoff’s laws, the state equations of the power circuit are:

\[
\begin{align*}
\frac{dI_a}{dt} &= -\frac{R_I}{L} I_a - \frac{1}{2}\left( 2\Delta \omega \left( S_{i1} + S_{i2} \right) V_T + V_i \right) \frac{1}{L} V_T \\
\frac{dL}{dt} &= c_{tank} S_a S_b S_c \left( I_a \right) - V_T \frac{R_{load, tank}}{c_{tank}} I_a \\
\frac{dI_b}{dt} &= V_T \frac{R_{load, tank}}{c_{tank}} I_a
\end{align*}
\]  

(1)  

(2)  

(3)

where \( L \) and \( R \) are the inductance and resistance of a three-phase inductor at the input, \( L_{tank} \) and \( C_{tank} \) are the inductance and capacitance of the tank circuit and \( V_{tank} \) is the voltage across the tank circuit.

### 4.1 Tank circuit

The tank circuit provides a means of storing energy in a similar manner to the capacitors in a dc link converter. As with the d.c. link voltage, a design aim is to maintain the tank voltage constant. The tank circuit component values are calculated using the standard formulae for a parallel resonant circuit with a load resistance defined at the maximum rating of the converter. The circuit Q needs to balance the need for sufficient energy storage and minimizing circulating current, hence losses in the resonant circuit. A Q of 3 has been used in the simulation, and hence \( L_{tank} = 9.3 \, \mu\text{H} \) and \( C_{tank} = 6.8 \, \mu\text{F} \).

The mean tank circuit voltage must be sufficiently high in order to control the input current. Therefore:

\[
\frac{V_T}{\omega} \approx \frac{2}{\pi}
\]

(4)

where \( V_T \) is the peak voltage between the tank circuit and the supply neutral and \( V_i \) is the peak phase voltage of the input supply. For a three-phase supply voltage of 400 \( V_{\text{rms}} \) line-to-line, the peak tank voltage must be greater or equal to 513 Volts.

### 4.2 Current ripple

The input current ripple must be limited in order to comply with supply quality regulations. From the state equations Dang (2006) gives the change in current through the input inductor as:

\[
\Delta I_i = \frac{1}{L_{ao}} \left( \pi V_i \omega L + 2K \right) \Delta i_i, \quad i = a, b, c
\]

(5)

\[
\Delta I_i = \frac{V_{\text{max}}}{L_{ao}} \left( \pi V_i \omega L + 2K \right) \Delta i_i, \quad i = a, b, c
\]

(6)

where \( \omega_L \) is the tank circuit frequency and \( V_i \) is the instantaneous supply phase voltage. Thus, the magnitude of the input current ripple is approximately given by \( \frac{V_{\text{max}}}{\omega L} \), and is a function of the circuit design, and \( V_i/V_T \).

### 5 Converter control

The initial design aim of the converter control is to maintain a steady tank voltage level and the input phase currents at a defined magnitude and phase related to the supply voltage. The highly non-linear nature of the intended application will eventually require a sophisticated controller.

The resonant converter, Fig. 2, described in this paper is a current sourced inverter whose output frequency is determined by the resonant circuit outlined and was modelled in SIMULINK using library models from Sympowersystem. Switching of the bridge circuit at zero voltage is desirable to minimise converter switching losses.

The scheme Oates (2003) probably had in mind was implemented by Dang (2006), a means of controlling input currents for three phase loads based on orthogonal two-phase d-q system. Similar principles can be applied to the resonant converters of an “active transformer”, i.e. choose a switching sequence to generate the error vector that takes the output voltage or input currents closer to their desired values. This may be likened to a form of “sliding mode” control.

Converter switching is applied at the zero crossing of the tank voltage and therefore occurs at twice the resonant frequency. The tank voltage is a much higher frequency than the input voltage and therefore during a half cycle of the tank voltage the input voltage may be assumed to remain constant. Control of the input current, and hence power flow, relies on the measurement of the peak tank circuit voltage every half-cycle in order to predict the change in input current, \( \Delta i \), during the next-half cycle of the tank voltage. \( \Delta i \) from equation 6 is evaluated for each of the six possible stationery vectors and the null switching vector. Each result is converted to the dq-plane and compared to a current reference derived from the tank voltage, thus producing an error value for each of the seven possible values of \( \Delta i \). Finally, at the next zero crossing of the tank voltage, the
switching vector that produces the minimum error against a cost function is selected and this vector is then used to switch the converter to a new state. Because of the requirement for zero voltage switching, this method measures an error in peak tank voltage but applies the correction at the start of the next half-cycle on the tank voltage. This method assumes that the peak tank voltage does not vary significantly between successive half cycles.

6 SIMULATION RESULTS

The input converter was initially modelled operating into a resistive load of 150 kW peak. Figure 3 shows the resonant tank voltage waveform. Its amplitude is by no means constant but varies, almost cycle by cycle, due to the coarse control of the half-cycle, zero-crossing switching pattern. The effects of an a.c. input voltage can also be distinguished on closer examination, Fig 4.

Figure 3 Input Converter - Tank voltage

Figure 4 Tank voltage expanded

Figure 5 shows that the supply currents are reasonably well balanced with a high frequency ripple of approximately 10% as per the circuit design. The value of the input inductor perhaps should be a little greater to reduce the peak ripple values. These results are similar to figure 4 in Dang (2006).

Some preliminary simulations results of an “Active Transformer” design using a PWM converter as the output converter are presented. The output converter load, at this stage, is resistive and therefore not representative of a power network. Also, the control system design has not yet been optimised, so, for example, the output voltage is not the same as the input voltage as would be required for a power system application.

Figure 5 Input converter - supply currents

Figure 6 Active Transformer – Supply phase volts & amps

Figure 6 shows a supply phase voltage and current that are in-phase. Figure 7 shows the supply currents, which are balanced, as with the currents shown in Figure 5, the ripple could be better controlled with further design and tuning.

Figure 7 Active transformer - Phase currents
Figure 8 shows the tank voltage ripple similar to the resistive loaded converter, Figure 4.

Figure 9 shows the three-phase output voltages, well balanced, but with a total harmonic content of approximately 7%. Clearly, this design would need to be improved considerably for any network application.

7 CONCLUSION

This paper has reviewed the background to the problem being created by the introduction of Distributed Generation into large power networks, and proposes the idea of an “active transformer”. It presents initial results from a simulation study of the concept, including control techniques that can be applied. These preliminary studies indicate that the “Active Transformer” is feasible device and able to control power flow and distribution-side network voltage. However, it is unlikely to be cost effective until the introduction of silicon carbide or other higher voltage devices. The next steps are to improve the output converter design and to identify what test scenarios are necessary to determine fully the active transformer's performance.

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9 REFERENCES


