EPSRC RESEARCH REPORT

An appraisal of the usefulness of combined AC and DC transmission in the development of oil and gas Fields

1. Introduction

This report describes the work carried out under research grant GR/L25707/01 into the use of AC and DC electrical power transmission in the development of offshore oil and gas fields. The grant was awarded through the Marine Technology Directorate as part of **MARINE 96** (MARine Innovation Exercise 1996).

The last twenty five years have seen a significant increase in the required generating capacity on offshore installations, from around 6 MW to the present levels of almost 100 MW on the largest production platforms (1). These increased power requirements and the smaller gas fuel reserves of newer fields necessitate the import of liquid fuel. This fuel deficiency, along with the desirability of reducing the maintenance workforce on installations makes supply from a remote source an attractive proposition. When the initial grant application was submitted, electrical interconnection of offshore power systems was limited to a small number of installations physically close to each other. Electrical interconnection offers the advantage of a reduction in both the installed generating plant and spinning reserve. Constraints associated with the large capacitance of long subsea cables, such as voltage instability (2) and the impact of harmonics (3), along with the use of differing supply frequencies have prevented the large scale AC interconnection of offshore installations.

Previous work by the principal investigator addressed the problems of harmonic distortion on isolated offshore installations (4) and harmonic resonance on installations connected by short subsea cables (5,6). The work completed during the current research programme has built upon this understanding of system operation and identified the limits of traditional AC interconnection and assessed the practical alternatives offered by DC interconnection. The use of an active harmonic damper to overcome resonance problems with AC interconnection has been investigated. The designers and operators of offshore installations have been kept informed of progress through seminars, informal contact and research publications.

2. Objectives

Five objectives were setout in the original grant proposal:

i. to assess the changing electrical load requirement on isolated offshore oil and gas installations;

ii. to review the current state-of-the-art technology in FACTS and HVDC and assess its usefulness in the offshore environment;
iii. predict the steady state and transient characteristics of offshore systems interconnected with DC transmission links;
iv. assess the capital and running costs of combined AC and DC transmission for this application;
v. report the findings of the research in the technical press.

In the case for support the need to involve offshore operators in the research programme was identified to ensure the industrial relevance of the research programme. The researchers have responded positively to the suggestions they have received from offshore engineers.

1. Achievement of the research objectives

The starting point for this project was to understand the electrical power requirements of current and future offshore installations. A seminar held at Heriot-Watt University during the first phase of the research programme was attended by engineers from a number of companies involved with the design and operation of offshore electrical systems. Companies represented included Amoco, BP Exploration, BHP, Total Oil Marine, and BeaSEMA. Contact with these companies gave the researchers access to design information describing existing offshore facilities including the BP Forties, BHP Douglas, and the Total Alwyn-North and Dunbar installations. These installations all feature short electrical interconnections between platforms. Using this information the researchers were able to quickly assess the changing electrical load requirement on isolated offshore oil and gas installations (i.e. satisfy objective (i)).

It became clear that increasing numbers of PWM voltage-fed inverters are used to supply variable speed ESPs (electrical submersible pumps). These ESPs enhance oil recovery rates but their impact on the power system was not well understood. There had also been a move away from gas turbine driven export oil and gas compressors. Large electrical variable speed drives are now being used and the impact of energising the relatively large input transformers of such drives on isolated systems was a cause for concern due to nuisance tripping of other transformers. These topics were identified as being worthy of further academic research, as a knowledge and understanding of such systems will be required to successfully implement either an AC or DC interface with existing installations which include such loads.

In harmonic studies, variable speed drives are generally treated as rectifier loads because they normally have a thyristor or diode rectifier to interface with the supply. Previous models, developed to analyse the harmonics and voltage distortion produced by such loads, assume that the rectifier can be considered as a harmonic current source (7-9). The performance of the voltage-type PWM drive system was analysed by the researchers using both laboratory tests and the

SABER time-domain simulation tool. It was found that the fault level of the input supply system had a significant effect on the waveshape of the current drawn from the supply by the voltage-type PWM drive. The harmonics generated by the drive cannot therefore be treated as conventional current sources when viewed from the supply side.

Assuming a constant DC voltage, the conduction period of the diodes in the input rectifier were found to depend on the AC input inductance and the inverter output power. During conduction periods, the constant DC link voltage appears across the AC terminals of the input rectifier which results in a "flat-top" voltage waveshape. Using a modulation function to represent the conduction period, a model which represents the drive as a harmonic voltage source was developed. This model requires only the drive output power and the impedance of the supply to determine both the current and voltage harmonics at the input rectifier terminals. The model developed during the current research programme is described in an IEE Proceedings paper (10) which also makes a comparison between current fed DC drives and voltage fed PWM AC drives. Both drives are commonly found on offshore installations.

The difficulties caused by the transient inrush current associated with energising transformers had previously been reported (11,12) and coupled electromagnetic models developed to predict their magnitude and duration (13). Surprisingly no information had been published on the particular case of a large transformer being closed onto a generator busbar as found on an offshore installation. Recordings provided by BHP Petroleum showed voltage and current transients lasting for over 10 sec following the breaker closing on a large transformer. Using a coupled electromagnetic model of the transformer, generator and AVR, a series of time-domain simulations were performed using SABER to investigate this complex phenomena. The researchers found that in an offshore system, the transformer inrush current will last for a significant period of time, causing a voltage drop on the generator busbar to which the AVR will respond. The DC component of the initial voltage dip on the system busbar will push other on-line transformers into saturation and may result in nuisance tripping. As the AVR response is lightly damped, the voltage oscillation modifies the inrush current of the transformer being energised, and the overshoot in voltage is seen by all transformers and other loads connected to the system. Traditional methods of calculating inrush currents would give erroneous results when applied to offshore systems due to the close coupling between the power system components. The researchers have reported their findings in an IEE Proceedings paper (14) and at two conferences (15,16).

A survey of the current state-of-the-art technology in both FACTS and HVDC revealed that conventional HVDC systems, which require large input phase shifting transformers, DC line reactors, and extensive AC harmonic filters were physically too large and heavy for offshore use. Significant advances had been made in the development of power electronic converter equipment utilising IGBT devices and a prototype medium voltage DC transmission system known has

"HVDC Light" supplying 3 MW at 20 kV had been developed (17). The power rating and transmission voltages in this system were very similar to those required for offshore interconnection. The FACTS device identified as being most suitable for offshore use was the shunt active filter. The active filter provides the harmonic components of the load current so that the supply current remains sinusoidal. There is now interest in applying such filters generally in utility systems to improve power quality (18,19). In this case, the function of the active filter is now to attenuate resonance rather than to compensate for a specific load current distortion. This technology could possibly be applied to AC interconnected offshore platforms to overcome the problems of harmonic resonance due to the shunt capacitance of subsea cables. (Objective (ii) satisfied).

The researchers had previously identified the practical limits for harmonic distortion and resonance on Total's Alywn-North and Dunbar systems which are linked by a 22 km subsea cable (5,6). An existing SABER time-domain simulation of this electrical system was modified to assess the relative advantages and disadvantages of replacing the existing AC subsea cable with an alternative HVDC Light link. Extensive computer modelling and analysis showed that this technology could be readily applied to existing systems, offering an alternative to AC interconnection. The DC interconnection is not limited by the transmission distance, the sending and receiving AC ends of the system are de-coupled and this allows harmonics generated by local loads to be treated independently. The DC interconnection is able to provide very fast control, so that the system can be designed to give good transient performance during a disturbance such as direct-on-line (DOL) starting of large machines and energising transformers. It should therefore be possible to supply existing production platforms with such loads from a HVDC Light link. A transactions paper describing the steady state and transient performance of both AC and DC interconnected systems, as well as an assessment of the relative advantages and disadvantages of the two alternative systems has been published (20). (Objective (iii) satisfied). The researchers later received the Institute of Marine Engineers' prestigious Stanley Gray Award (Offshore Technology) for this paper.

The use of an active harmonic damper to attenuate harmonic resonance of an interconnected system was investigated. An interconnected power system configuration similar to Alywn-North and Dunbar was used as a test system (modelled using the SABER and EMTDC simulation tools). The active filter consists of a PWM bridge connected to the AC power system through a coupling reactor. The modulation does not control current directly, instead, the harmonic components in the system busbar voltage are used to generate a compensating signal proportional to each measured harmonic. Since each harmonic frequency is compensated independently, the method does not suffer from the disadvantages of passive tuned filters. By changing the control gain for each individual harmonic, the active filter can be controlled as an adjustable inductance or capacitance which modifies the resonant modes of the system. The required control algorithms are relatively simple to implement. The time-domain simulation showed that the active harmonic damper can be successfully applied to an interconnected offshore system with a large drilling load which would otherwise be unstable due to a harmonic resonance. The active harmonic damper continues to operate during harmonic transients which would occur during work-overs on a drilling rig and it can also be used as a VAr compensator to provide voltage support at the end of a long subsea cable. A complete description of the problems of harmonic resonance on an interconnected offshore and how they can be overcome using an active harmonic damper have been described by the researchers in an IEE Proceedings paper (21). The use of an active filter to provide voltage support at the remote end of a subsea cable during DOL starting of large induction motors was also published at a recent conference (22).

In the final year of the three year research programme, there were two staff changes which unfortunately disrupted the good progress which had been made during the initial two years. This disruption, along with difficulties in obtaining reliable costing for equipment, prevented the satisfactory completion of objective (iv). All other project objectives were satisfied.

2. Output resulting from the research programme

The outcome of the research programme supported by this grant is an increased awareness of the present limitations of electrical power systems on offshore installations. In response to the needs of offshore electrical engineers the problems of harmonic distortion due to the recently introduced voltage-fed PWM drives have been investigated and a simple model developed to calculate their impact on the power system. Transient inrush currents and their effects on AVRs have also been examined.

Two methods have been investigated to overcome the difficulties of harmonic distortion and resonance in interconnected offshore power systems. The use of an HVDC Light system has been shown to overcome many of the problems associated with conventional AC interconnection. The power electronic converters used in this system are relatively small and lightweight which makes them ideal for offshore use. The researchers have shown that they can interface with the many and varied loads on existing installations. As DC links are not limited by transmission distance they are also suitable for bulk supply from the mainland. The researchers have found that the active harmonic damper can successfully mitigate resonance problems on existing and future AC interconnections. This will allow the designers of offshore power systems to use longer AC cable runs than at present and so supply remote satellites from existing production platforms.

The work completed during this research programme shows that for the design of future offshore installations, designers can look towards increased electrical connectivity between installations to meet their power requirements. The limitations of existing systems can be overcome by using either HVDC Light interconnections or active harmonic dampers for AC interconnection.

3. Use of research funds

The three principal components of funding provided for staff, computing hardware and specialist software.

The staff component has been very well spent in employing Dr Li Ran as a research associate. He demonstrated a particular aptitude for modelling electrical engineering systems using SABER, EMTDC, ERACS and Matlab. These computational skills along with his exceptional knowledge of electrical power systems and power electronics have made a significant contribution towards the success of this research programme. Dr Ran worked on this project for twenty-three months, before joining the staff of the University of Northumbria at Newcastle, as a full time lecturer in Electrical Engineering. Dr Ran was replaced by Dr Daniel Tooth, an experienced researcher in power electronics who joined the engineering staff of Aligent Technologies after ten months. Mr Yehdago Habtay continued work on this project for a period of three months. A small component of the staff cost was used to support Mr Iain McCrone, the Computing Officer who maintained the computer hardware and software used in the project.

The HP720 computer workstation purchased for use on this grant has been invaluable to this project. This system along with an additional personal computer and other peripherals provided appropriate platforms for hosting the SABER, EMTDC, and ERACS simulation programs, which were at the centre of the power systems analysis performed during this research programme.

4. Dissemination of results

It has been shown in the previous sections that the output of the research programme has already been widely published through four proceedings and two conference papers. The oil and gas industry has been kept informed of progress through seminars held in Edinburgh and Aberdeen. The research programme clearly has direct applications for offshore oil and gas operators and contact with them during the project has furthered active research (23,24) and consultancy work (25-27). The work programmes on offshore interconnection, specialist consultancy for offshore companies and other research programmes (including a study of fast transients in electrical machine windings (28,29) and switching overvoltages on high voltage transmission networks (30)) have run concurrently with a beneficial interchange of information between the different programmes taking place.

5. Future work

The work completed during this research programme has acted as a catalyst for a number of other research areas at Heriot-Watt University. A Ph.D. student is currently working on the use of Advanced Static VAr Compensators for offshore use, and Newage International a major manufacturer of generator sets for marine and offshore use has provided a scholarship to fund a three year research programme.

At the current time BP Exploration is undertaking a design feasibility study to install a DC interconnector between the North-East of Scotland and the decommissioned Forties Echo platform (31). The success of the first phase could lead the way to tie in other North Sea operators and result in 68 platforms being interconnected. The technology investigated during this research programme may well be operational supplying North Sea installations in a relatively short time. The research team at Heriot-Watt University look forward to assisting in the development of this practical extension to their theoretical work.

As a result of the UK Government's commitment to the Kyoto climate change targets, an increasing proportion of the UK energy needs will have to come from renewable energy sources. The DC interconnections described in this report will provide a convenient way of exporting power from large offshore wind farms back to the mainland.

The Electrical Power and High Voltage Engineering Group at Heriot-Watt University is active and continues to grow and diversify its research activities. The EPSRC funding that has contributed to the development of this activity has been well spent.

6. References

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