

Benefits of Operating a Four Terminal HVDC Network with a Normally Open Point

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Abstract—It is likely that any HVDC grids will evolve over time and will likely be multi-vendor and use several different technologies. This paper studies a four terminal network where the interconnecting link is operated as a normally open point. This allows the network to be reconfigured in the event of DC side fault, without the need for DC circuit breakers. The network uses the popular Modular Multi-level converter at one terminal and a fault tolerant converter at the other terminal. A simple cost benefit shows the economic advantage of the interconnecting link. The operation of this network is then verified through simulation for a normal operating scenario and a DC fault scenario.

Keywords—HVDC, energy conversion, fault blocking converters, modular multilevel converter, multi-terminal DC

I. INTRODUCTION

High Voltage DC (HVDC) is fast becoming the preferred transmission technology for bulk power transfer, particularly for submarine cable applications. HVDC is more efficient than AC transmission over great distances, and requires no reactive power compensation [1]. As more HVDC links are built in close proximity to each other it may become desirable to interconnect these links and create a multi-terminal DC (MTDC) grid. There are many benefits that come from having interconnected MTDC grids such as increased security of supply and increased penetration of remote renewable energy generation [2]. It is likely that MTDC grids will evolve over time rather than being built all at once [3]. This fact makes MTDC grids likely to be multi-vendor and made out of different technologies as they are made available.

Power flow control in the Voltage Source Converters (VSCs) is simply achieved by varying the current and power flow reversal is achieved by changing the current polarity. This makes the topology better suited for MTDC compared to Classic HVDC technology [1]. The Modular Multilevel Converter (MMC) has recently become the new standard VSC technology [4]. The MMC has several advantages but, in its most power efficient form based on half-bridge submodules (SMs), it is susceptible to DC-side faults [5]. To combat this shortcoming, various solutions exist, ranging from DC circuit breakers to the use of full-bridge SMs in the stack, with a variety of implications for additional cost and additional power losses.

DC circuit breakers are still one of the technical barriers facing MTDC grids, and significant progress has been made with a 200 kV DC breaker being tested by China State Grid

Smart Grid Research Institute [1], [6]. There are two VSC based MTDC grids operating in the world, both of which are in China [7], [8]. Both schemes are small enough that should a DC fault occur in the network that the entire DC network can be disconnected using the AC side circuit breakers in order to clear the fault. This approach is not practical for large MTDC grids, as deenergising the entire grid could drastically affect the connected AC systems. Thus large MTDC grids will require DC protection. Placing a DC circuit breaker at each terminal may be expensive and the size of these breakers is yet unknown. For offshore applications, where space is a premium, the addition of a DC circuit breaker would require additional space on the platform, or it could require an additional offshore platform. An alternative to this consists in sectioning the MTDC grid into zones and placing fast reliable DC circuit breakers between the zones [9].

This work proposes the use of a Normally Open Point (NOP) to section the MTDC grid. This paper studies a four terminal network which uses two different VSCs. Sections II briefly describes the two VSCs used in the study. The case study system is a four terminal network where the interconnecting link is operated as a normally open point which is described in Section III. A simple cost benefit calculation is made to show the advantage of having this interconnecting link. Section IV shows the simulation results of the network for a normal operation scenario, and a DC fault scenario. A short discussion is given in Section V and the paper is concluded in Section VI.

II. MODULAR MULTILEVEL VSCS

A. Modular Multilevel Converter

The MMC was first introduced in the early 2000's and the design makes use of having several energy storage devices connected in series that can be switched into and out of the current path by semiconductor switches [10]. The circuit diagram of the converter is shown in Fig. 1.

The converter is made up of six arms and each arm is made up of a stack of SMs and an arm inductor. Each SM contains a capacitor and two Insulated Gate Bipolar Transistors (IGBTs). The converter produces a staircase AC waveform and the number of SMs in the arm determines how many voltage levels are in the AC waveform. This results in the MMC producing AC waveforms which require little or no filtering when compared with earlier VSCs [5]. This reduced filtering requirement on the AC side minimizes the power losses and the

volume of the converter [11]. The typical power loss figure of a MMC station is approximately 1% [12].

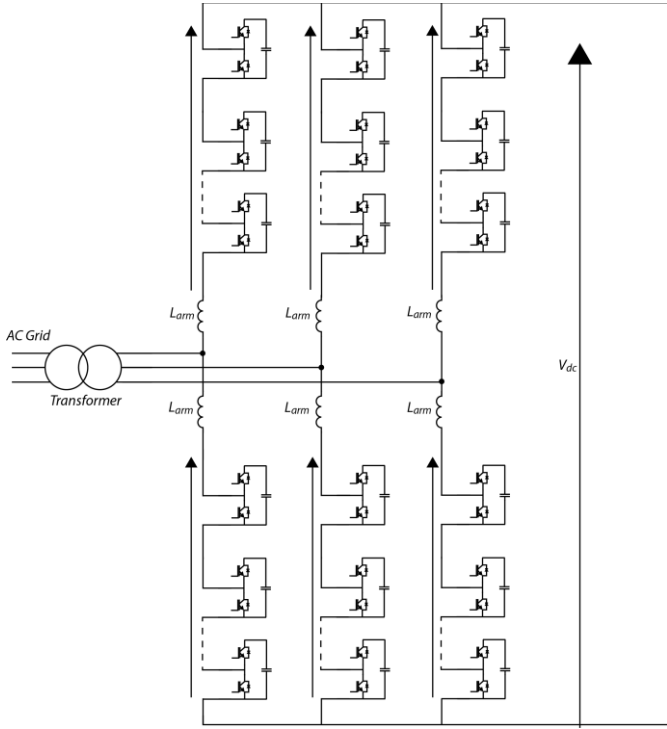


Fig. 1. Circuit diagram of the MMC

The modular structure of the converter means that the topology is easily scalable to high voltages and redundancy can be simply built in to the converter by adding more SMs [13]. However, this design is susceptible to DC side faults, as the converter acts an uncontrolled diode rectifier due to the anti-parallel diodes in the IGBT modules [5]. This results in significant fault current being fed from the connected AC system into the DC system during a DC fault.

B. DC Fault Tolerant Converter

There are several proposed converters which can provide DC fault blocking capability. The full-bridge MMC is tolerant to DC side faults, however this comes with the penalty of increased power losses and a larger volume with two additional IGBTs per SM [5]. An alternative approach is to use the double-clamp SM proposed in [11]. This design also has 50% higher power losses than the half-bridge MMC [5]. Several new hybrid VSCs were proposed in [14], including the Alternate Arm Converter (AAC). The AAC maintains comparable power loss figures with the half-bridge MMC and can provide DC fault blocking capability [5]. The AAC is the fault tolerant converter considered for this research.

The AAC is a hybrid VSC which uses stacks of SMs in the arms of the converter, like the MMC, and alternates conduction between the upper and lower arms of the converter in a similar fashion to the two-level VSC. The circuit diagram is shown in Fig. 2.

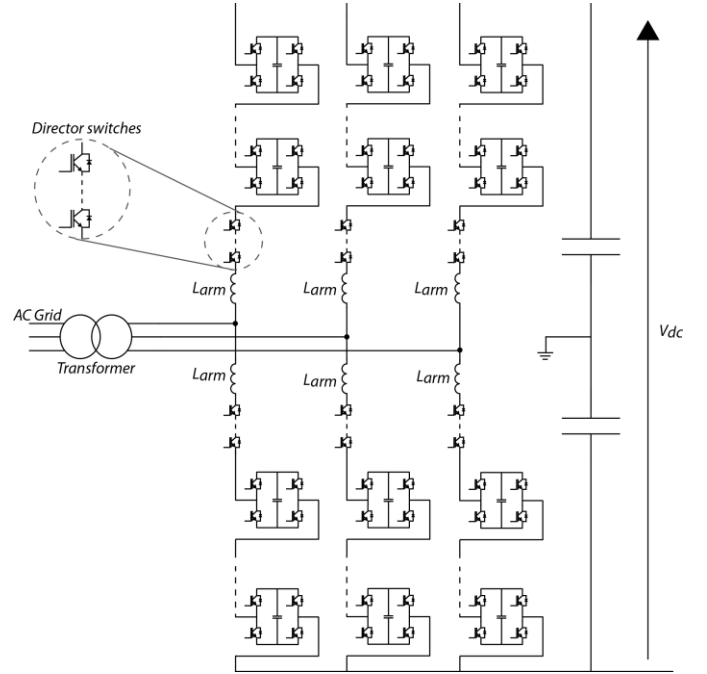


Fig. 2. Circuit diagram of the AAC

This alternating feature is achieved through the use of a series connection of IGBTs called the director switches. The director switches disconnects the arm which is not in conduction. By alternating between the upper and lower arms the total voltage that the arm needs to withstand is reduced. This results in fewer SMs per arm when compared to the MMC. In order to commutate the current from one arm to the other there is a short time period when both arms are in conduction and this is referred to as the overlap period. During this overlap period additional DC currents are circulated within the converter to balance the energy within the converter.

The AAC uses full-bridge SMs as the peak AC voltage of the converter is higher than the DC voltage. An advantage of having full-bridge SMs is that this enables the converter to block DC side faults. The AAC is also able to provide STATCOM services to the connected AC system during a DC side fault. The power losses of the converter are kept low thanks to alternating conduction between the upper and lower arms, and the lower number of SMs in the arm. In [5] a 20 MW converter had estimated power losses of approximately 1%.

III. CASE STUDY SYSTEM

A. Description

The case study system is a four-terminal HVDC network, comprising of two offshore wind generation terminals and two onshore grid terminals. The system is illustrated in Figure 3. The interconnecting link is operated as a NOP. The NOP would consist of two sets of switches which allow the cable section of the link to be charged prior to connecting to the healthy link. The disconnectors, marked Disc in Figure 3, would consist of DC switchgear already installed on the DC platform and would be normally closed. The case study scheme is based on the UK Round 3 Dogger Bank offshore wind development.

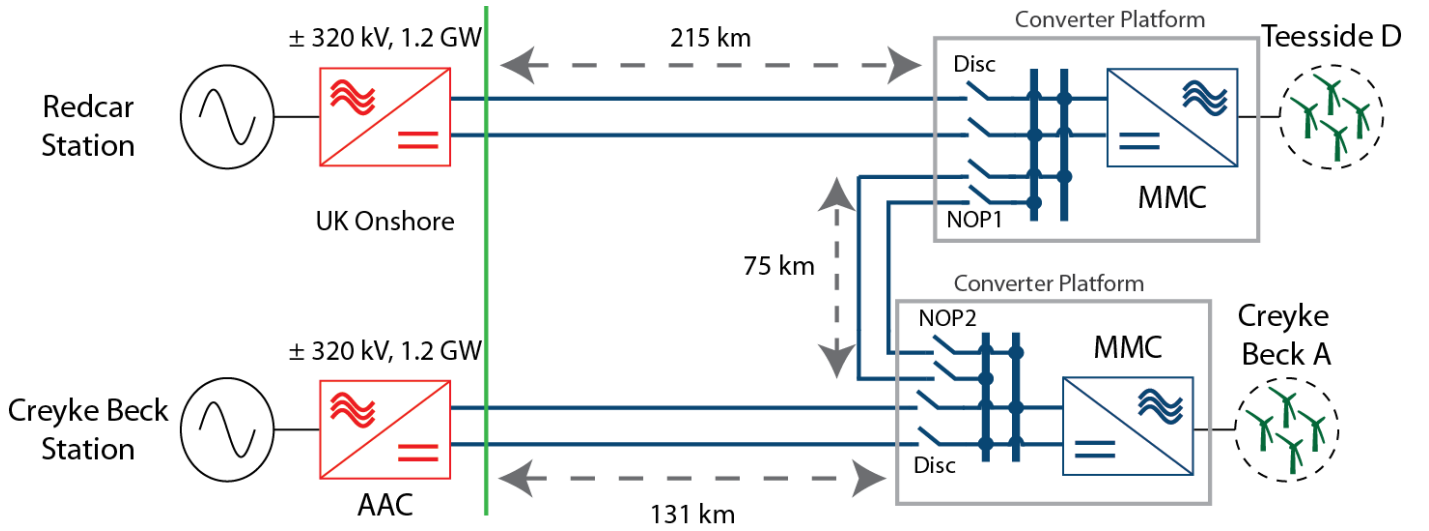


Fig. 3. Case study system

In this system the AAC is placed onshore and the MMC is placed offshore. The MMC is placed offshore for two main reasons. Firstly an increasing number of offshore wind turbines use fully rated converters to feed power into an AC collection network. This implies that the wind turbine converters are capable of limiting their output current in the case of a fault in the DC network hence maintaining the stability of the offshore AC network. This implies that a DC fault blocking converter is not compulsory offshore. The onshore converters are at greater risk because they are connected to strong AC systems. In a simple point-to-point link the AC circuit breakers would be used to protect the link. A MTDC network would require the use DC circuit breakers or DC fault blocking capability to interrupt the fault current.

Secondly, the MMC has a higher technology readiness level, particularly for offshore applications, compared to that of DC fault blocking VSCs which have only recently been proposed. Therefore using the MMC offshore is a more convincing choice given that the technology is better understood and has operational experience. By placing the newer technology onshore, operational experience can be obtained in an easily accessible and known environment. The same reasoning can be applied to DC circuit breakers. The use of a fault tolerant VSC onshore would mean that in the event of a DC side fault, the DC fault current would not be fed from the strong AC system onshore. This reduces the duty on the DC circuit breaker and this could enable the use of slower DC circuit breakers, or the use of readily available DC switchgear. The interconnecting link is operated as a normally open point (NOP) to section the MTDC grid and the grid can be reconfigured in the event of DC side fault. This NOP could be upgraded to a DC circuit breaker in the future giving the link a higher utilization. Sectionalizing the network ensures that the UK infrequent loss of infeed limit, of 1800 MW, is not exceeded in the case of a DC side fault occurring when peak power is being generated by the wind farms [15].

B. Cost Benefit Case for the Interconnecting Link

This section details a simple cost benefit case for installing the interconnecting link and operating it as a NOP. Table 1

shows the availability data for the all of the links, these figures were found using data from [16].

TABLE I. AVAILABILITY DATA

	Creyke Beck	Teesside	Link
Availability	0.988	0.9801	0.9931
Unavailability	0.012	0.0199	0.0069
MTBF (years)	14.79	8.94	25.64
MTTR (days)	65	65	65

It is assumed that the entire network would have a project lifetime of 25 years. It can be seen from Table 1 that there is likely to be three or more cables failures during the lifetime of the project, and the interconnecting link is unlikely to fail, due to its shorter length. Estimated costs are provided for two case for the interconnecting link in Table 2, using data from [17] for case 1 and an estimate from industry for case 2. The additional cost for case 2 is a predicted cable cost for 2020 which aims to reflect the increased water depth in Dogger Bank and the increased power rating of to 1.2 GW.

TABLE II. INTERCONNECTING LINK COST ESTIMATES

Cable Length	Case	Cable Cost (ME/km)	Total
75 km	1	1.32	£99 M
	2	2.5	£187.5M

The amount of energy that is produced by a wind farm is measured using the capacity factor, which is the ratio of energy produced to the maximum potential energy. Offshore wind generation typically has a capacity factor (CF) of approximately 40% [18]. If the CF was much lower than 40% the installation of the interconnecting link would not be worthwhile. If the CF was much closer to 100% then the interconnecting link be limited in the amount of power it could transmit.

The cost of energy, C_{Energy} , is assumed to be £140/MWh which is taken from [19]. This figure is used to determine the

cost of the Expected Energy Supplied (EES) due to the availability, A , of the cable using (1). Where T is the amount of time considered in hours, P_{Rated} is the rated power. The cost of Expected Energy Not Supplied (EENS), when the cable is unavailable to transport energy, is given in (2), and U is the unavailability.

$$C_{EES} = CF \times C_{Energy} \times A \times P_{Rated} \times T \quad (1)$$

$$C_{EENS} = CF \times C_{Energy} \times U \times P_{Rated} \times T \quad (2)$$

Table 3 shows the cost data for the four terminal network. It should be noted that a fault on the cable between Redcar and Teesside D would result in additional power transfer through the Creyke Beck link. This is illustrated for clarity in Figure 4, where the green arrows indicate the power flow in post fault conditions.

TABLE III. COST DATA

Without Link		
	Creyke Beck	Teesside
C_{EENS} for 25 years	£176.6M	£292.9M
With Link		
C_{EES} for MTTR (no fault)	£103.6M	£102.8M
Faulted link	Teesside	Creyke Beck
C_{EES} during fault	£205.7M	£204.1M
Increased revenue	£102.1M	£101.3M
No. of faults	2	1
Total additional revenue	£204.2M	£101.3M

The total additional revenue from both cables is likely to be £305.5M. Now considering the cable cost, for Case 1 a single fault on either link would cover the cost of the cable, resulting in £206.5M in the likely scenario of three faults on the network. For Case 2 at least 2 faults occurrences on the network would cover the cost of the cable. The additional revenue for Case 2 would be £118M.

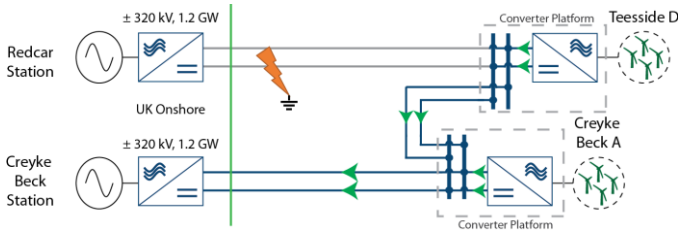


Fig. 4. Power routing after a fault on the Teesside link

IV. SIMULATIONS

The case study system was modelled in MATLAB Simulink® using the SimPowerSystems library. The VSCs are modelled using reduced dynamic average models, which are detailed in [20], [21]. Using reduced order models enables time efficient computation of the case study system while maintaining good accuracy of the system dynamics. The cable was modelled using distributed parameter line. The network data

is given in Table 4. Two scenarios were simulated, a normal operating scenario and a DC fault scenario.

TABLE IV. NETWORK DATA

Parameter	Value
DC voltage	± 320 kV
Rated power	1.2 GW
Redcar – Teesside cable length	215 km
Creyke Beck cable length	131 km
Interconnecting cable length	75 km
Cable resistance	11.3 mΩ/km
Cable inductance	0.212 μH/km
Cable capacitance	0.362 mF/km

A. Normal Operation Scenario

The system model was simulated for normal operating conditions to show that the AAC and MMC operated in a single link. Figure 5 shows the DC cable voltage and the power at each terminal of the link. The MMC is in power control mode and the AAC is in voltage control mode. This shows that the AAC and MMC can be connected in the same DC network.

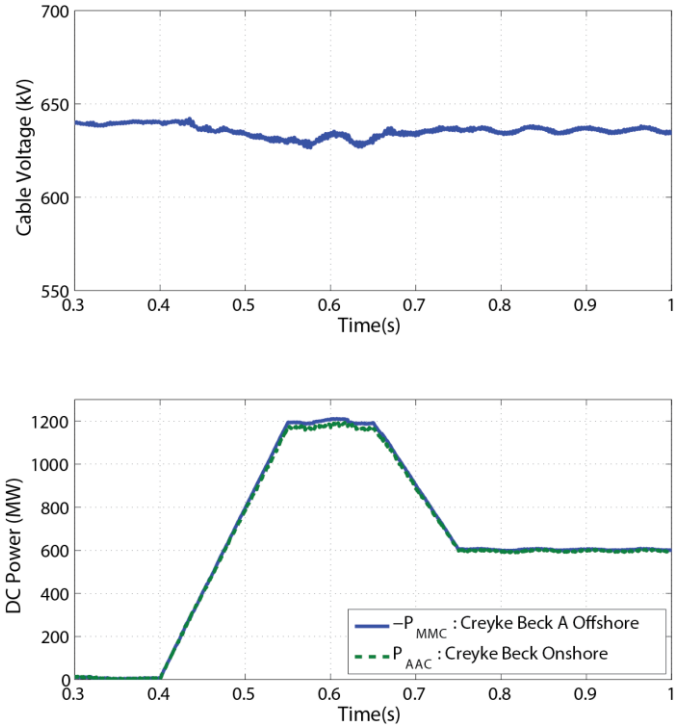


Fig. 5. Power transfer on Creyke Beck link

B. DC Fault Scenario

A permanent DC line-to-line fault was placed half way along the cable between the onshore station, Redcar, and the offshore wind farm at Teesside D. It is assumed that both converters are operating at 0.5 pu power prior to the fault. The fault was applied at 0.55 s into the simulation, as shown in Figure 6. The voltage of the faulted link oscillates before it falls close to zero. This is caused by reflections of the voltage in the cable.

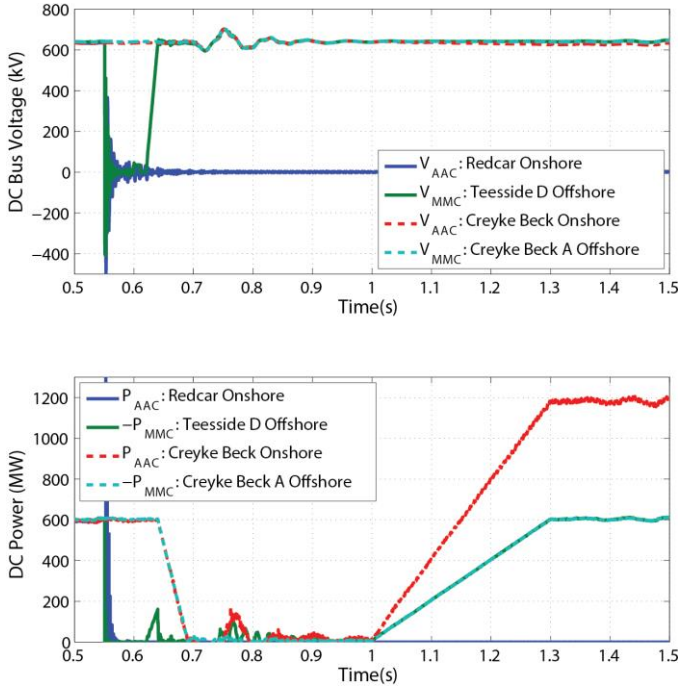


Fig. 6. DC line-to-line fault case

The post fault switching pattern is detailed in Table 5.

TABLE V. SWITCHING SEQUENCE

Time (s)	Action
0.55	Fault happens on Redcar – Teesside link
0.551	MMC at Teesside D blocked
	Power ramped down on Teesside windfarm
0.6	Open DC switch (Disc) at Teesside MMC
	MMC unblocked
0.61	Close NOP 1
0.62	Charge DC bus and interconnecting cable section
0.64	Ramp down power of healthy link
0.7	Close NOP 2
1	Power ramped back to 0.5 pu from both offshore converters

The interconnecting cable section and DC bus capacitors are charged using the energy stored in the SM capacitors of the MMC. In practice the timings shown in Table 5 are likely to be much greater to ensure that the network is safely reconfigured, the process could take the order of tens of minutes, up to hours. The timings for this simulation are kept short to allow the results to be displayed in a single plot.

Figure 7 shows the onshore AAC at Redcar station providing 0.4 pu reactive power support to the connected AC network just after the DC fault. It also shows that the AAC successfully blocks the DC side fault.

V. DISCUSSION

There are several benefits to operating a DC link between two point-to-point links as a NOP. Firstly, by using a fault tolerant VSC onshore, the requirement for a DC circuit breaker in the offshore environment is reduced. It can be seen from the DC fault case that the healthy link is not affected by the fault event, and the disconnected offshore wind farm can be reconnected at a time when either demand in the onshore AC network is low, or when there is little to no energy being

supplied from the wind farm. From the availability data it can be seen that it is highly likely that there will be a DC side cable fault during the life time of the project. The cost of the interconnecting link and installation is recovered in the event of one fault event for the cost of the cable for Case 1, and two fault events would cover the cost for Case 2. Although the increased revenue may not be substantial, the cost benefit does show a positive economic effect of installing the interconnecting link. It is unclear who might fund the link as the UK intends to have offshore transmissions operators (OFTOs) own the transmission assets to shore. The funding of the link would be dependent on whether the same OFTO owns both point-to-point links or not.

The study presented in this paper assumes that 0.5 pu power is being produced by the wind farms prior to the fault. The link is rated for 1.2 GW and so the combined power from both wind farms cannot exceed 1.2 GW. Thus, one of the wind farms must have energy curtailed to ensure this limit is not exceeded. It may be preferential to prioritise the power from the wind farm which has the shortest route to shore, to reduced losses due to the cables.

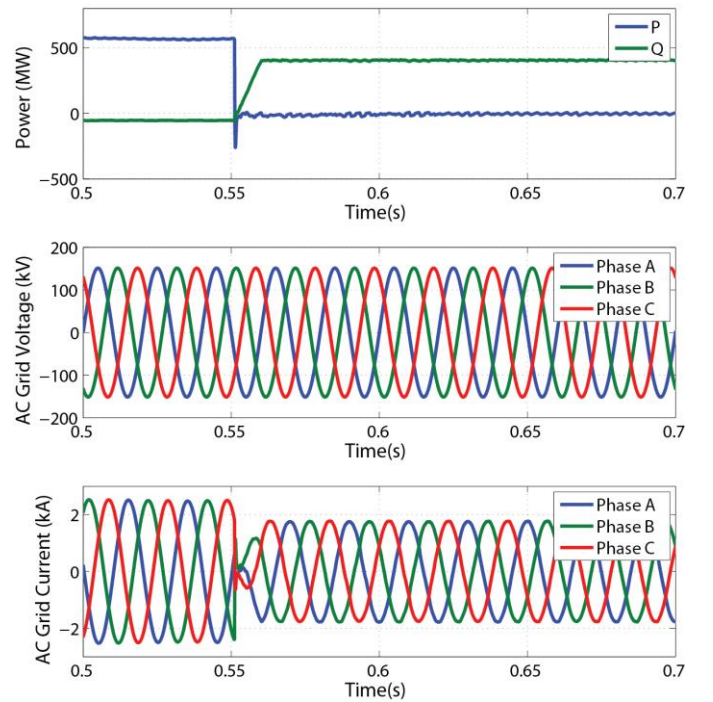


Fig. 7. STATCOM operation of the AAC at Redcar station

VI. CONCLUSION

This paper investigates a protection scheme for a four-terminal HVDC network which does not require the use of DC circuit breakers. The interconnecting link is operated as a normally open point, sectioning the network. Fault tolerant converters are placed onshore to limit the fault current from the strong onshore AC system in the event of DC side fault. A simple cost benefit analysis shows that the interconnecting link greatly reduces the amount of energy lost in the event of DC side cable faults. The four-terminal network is simulated for normal operating conditions and a DC fault scenario. The DC

fault scenario shows that the network can be operated with a NOP, allowing the network to be reconfigured and to increase the amount of energy supplied while the faulted link is repaired.

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