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Hybrid HVDC for the Supply of Power to Offshore Oil Platforms

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Abstract-- A HVDC hybrid system, comprising a line commutated thyristor HVDC converter and a STATCOM, is proposed in this paper for supplying power to offshore oil platforms that do not have their own generation. The proposed system combines the robust performance, low capital cost and low power loss of a line commutated HVDC converter, with the fast dynamic performance of an equivalent VSC Transmission system. The paper describes the principles and control strategies of the proposed system. PSCAD/EMTDC simulations are presented to demonstrate the robust performance of the system using case studies of various operating conditions such as black-start, load perturbations, AC fault conditions and disturbance caused by the starting of large local induction machines.

Index Terms— Control design, Converter, HVDC transmission, Static VAR compensator, STATCOM, Oil platform

I. Introduction

An oil platform typically requires tens of MW, a large proportion of which may be direct on-line started induction machines for pumps and compressors. Many oil platforms are located hundreds of kilometers away from an onshore grid connection but often a number of platforms are located in close proximity to one another. Offshore oil platforms usually have their own gas turbine generation as a submarine cable AC connection from onshore is impractical due to the cable charging current issues. However, gas turbines are expensive to run and require regular maintenance outages during which the production capability of the platform may have to be reduced due to insufficient power supply.

A High Voltage Direct Current (HVDC) scheme using line commutated thyristor converters is often the most economic means of transmitting power over long distance and/or for interconnection of asynchronous AC networks. It provides high reliability, requires little maintenance and can be operated as an unmanned station. However, line commutated converters need an AC voltage supply to commutate and therefore can not supply power to networks without synchronous machines, (e.g. oil platforms) without using synchronous generators or compensators. VSC Transmission schemes, using

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Voltage Source Converters with self-commutated devices such as IGBTs provide a technical solution, but have a higher capital cost and power loss than a thyristor based line-commutated HVDC solution.

Synchronous or static compensators have been proposed to enable line commutated HVDC converters to be connected to very weak AC networks [1] [2], and reference [3] proposed synchronous and static compensation including a STATCOM for connecting a passive load. Little information was given regarding the coordination of the HVDC scheme and the STATCOM. Furthermore, the dynamic performance shown in [3] during large load switching was not satisfactory for a practical application.

The hybrid HVDC interconnector proposed in this paper combines the best technical and commercial features of line-commutated HVDC and VSC Transmission technology. The system comprises a thyristor based HVDC converter with series capacitors [4] and a STATCOM and can be used for connecting island loads to a main grid system. A similar system has also been proposed by the authors for transmitting power from large windfarms to the main grid over long distances [5]. The STATCOM can be based on the chain link topology, which has very low power loss [6], or other VSC topologies such as the 2-level or multilevel converter [7]. Regardless of the STATCOM topology chosen, it is rated much smaller than the whole scheme rating and the solution gives an overall power loss which is substantially lower than that of an equivalent VSC Transmission scheme [7]. Because of the use of the series capacitors with the HVDC converter no switched capacitor banks are required for compensating the converter, minimizing the area occupied and the complexity of the power circuit. The paper describes the principles of the proposed hybrid system and its main control strategies regarding the AC frequency/voltage control, automatic power balancing, black start and direct online starting of large induction machines. PSCAD/EMTDC is used to validate the system performance under various operating conditions. System operation during AC faults is also investigated. Issues regarding the rating of the STATCOM are discussed. Finally, the proposed hybrid system is compared to a VSC Transmission solution.

II. PRINCIPLES OF THE PROPOSED HYBRID SYSTEM

The single-line diagram of the proposed hybrid HVDC system offshore terminal is shown in Figure 1. The onshore terminal may be a simple line commutated HVDC converter station. The offshore system comprises a Capacitor Commutated Converter (CCC), a STATCOM, and a passive filter. The oil platforms have mixed loads including direct line started induction machines. The STATCOM could also be connected using a separate transformer depending on the system optimization.

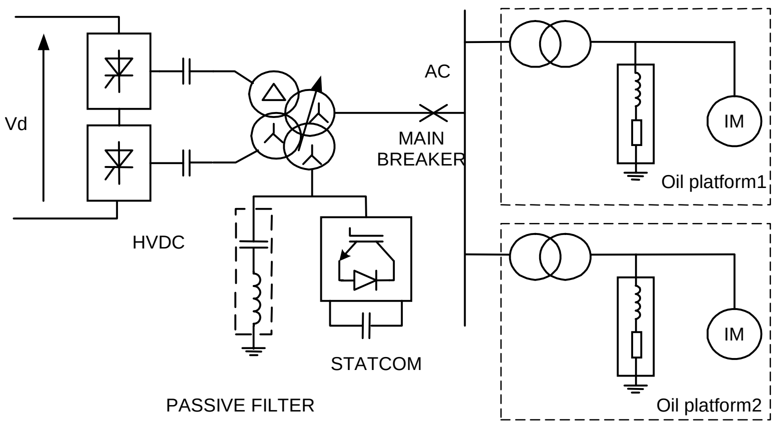

Figure 1 Schematic diagram of hybrid HVDC system supplying power to offshore oil platforms

The STATCOM provides both the necessary commutation voltage to the HVDC converter and reactive power compensation to the network during steady state, dynamic and transient conditions. It also provides limited active power support to the network during transient conditions such as load switching. The capacity of the STATCOM to provide reactive power compensation is determined by its electrical rating whilst its capacity to provide active power support depends mainly on the energy storage in the internal DC circuit. The studies reported in this paper consider the use of conventional DC capacitors only, with relatively limited energy storage. Larger energy storage could be provided by using batteries, flywheel, SMES, super capacitors etc.

The passive filters limit the harmonic voltage at the platform's AC bus and provide additional reactive power to the network. Because of the use of the CCC the reactive power absorbed by the converter is small, therefore the harmonic filter can also be small. The STATCOM could be designed to provide active filtering at low order harmonics, to help meet the harmonic requirement. Additional capacitor banks may be used to provide compensation during starting of large induction motors and for slow load cycle variation of reactive power and may be placed anywhere in the network, if required. These last two options must be considered at the feasibility stage when determining the rating of the STATCOM.

III. SYSTEM CONTROL

The main requirements of the control system are to control the frequency and voltage on the oil platforms. A simplified control block diagram for the offshore station of the proposed hybrid system is shown in Fig. 2. The receiving HVDC converter (inverter) is in DC current control, whilst the sending HVDC converter (rectifier) is in DC voltage control (not shown), an arrangement pioneered on the Korea to Cheju HVDC link [8]. This avoids the need to send the current order, which is generated by the STATCOM DC voltage controller, to the rectifier controller by fast telecommunication. Fibre optical communication can be used to optimise the system performance further.

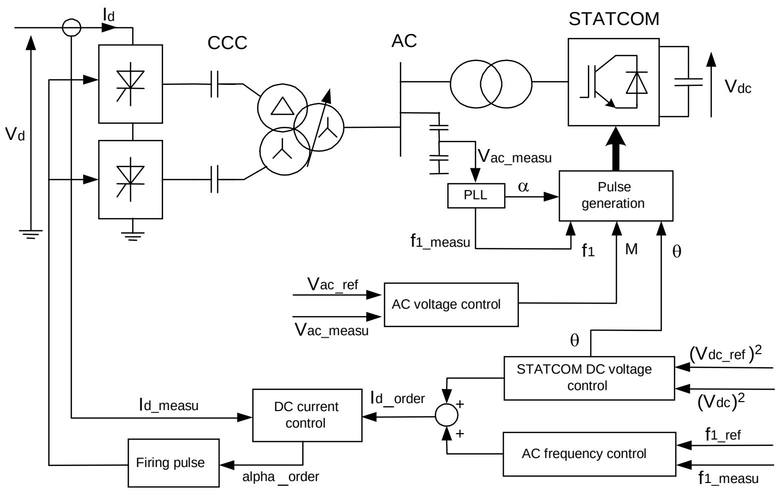

Fig. 2 Schematic diagram of the control strategy

The proposed control strategy co-ordinates the combined system of HVDC converter and STATCOM. The AC voltage and frequency of the platform's AC network bus are controlled and consequently the active and reactive powers of the HVDC scheme and the STATCOM remain balanced. This is similar to a VSC Transmission solution supplying a dead network, where the inverter end of the VSC Transmission scheme needs to output AC voltages with appropriate frequency and amplitude and the control system does not need to identify whether the power is active or reactive. The main control functions of the hybrid scheme are described in the following paragraphs.

A. Active power and AC frequency control

In steady state the STATCOM controls reactive power and active power is only needed to compensate its power loss. However, if the network load is suddenly increased, the AC voltage magnitude will tend to drop and its phase angle will become lagging relative to the phase angle of the STATCOM output voltage. Consequently, active power will flow out of the STATCOM, and as a result the energy stored in the DC capacitor reduces and so does its voltage. Thus, the STATCOM DC capacitor energy/voltage is an immediate indicator of any change of the active power in the network and therefore, it is used to rapidly change the current order for the HVDC inverter. The power balancing equation of the system can be expressed as

$$V_d I_d = V_{dc} \cdot C \cdot \frac{dV_{dc}}{dt} + P_{load} \qquad (1)$$

where V_d and I_d are the DC voltage and current of the HVDC converter, V_{dc} and C are the voltage and capacitance of the STATCOM DC capacitor and P_{load} is the active power consumed by the load. The above equation can be rewritten as

$$\frac{dV_{dc}^{2}}{dt} = \frac{2}{C}\left(V_d I_d - P_{load}\right) \qquad (2)$$

Therefore, it can be seen that V_{dc}^2 can be used as a state variable. Since P_{load} is not accessible to the control system, the V_{dc} control loop needs to have sufficient bandwidth to reject the disturbance caused by P_{load}. As can be seen from Fig. 2, the inputs to the STATCOM DC Voltage Controller are the squares of the DC voltage reference $V_{dc\_ref}^2$ and the DC voltage measurement V_{dc}^2 which represent the energy stored in the DC capacitor. The output is the DC current order for the HVDC inverter.

The STATCOM DC voltage controller also controls the DC capacitor voltage by adjusting the phase shift between the STATCOM output voltage and the AC network voltage. Consequently, the instantaneous AC frequency will change for a given change in phase shift θ. The change is used to modify the converter DC current order by the AC frequency control block whose other input is the reference frequency for the network. This signal and the one from the STATCOM DC voltage controller are combined to generate the HVDC converter DC current order as can be seen from Fig. 2. The frequency of the platform's AC network voltage is measured via a Phase Locked Loop (PLL) and is then used as the frequency reference for the STATCOM AC output.

B. AC voltage control

Any change of the reactive power in the network will cause the AC voltage amplitude to vary. The amplitude of the AC voltage is regulated by the output voltage amplitude of the STATCOM. This in turn regulates the reactive power from the STATCOM. The inputs to the AC Voltage Controller are the AC voltage reference V_{ac_ref}, and the AC voltage measurement V_{ac_measu} as shown in Fig 2. The DC voltage controller provides a reference angle for the PWM switching pattern generator as described previously in Section A.

C. Black start

It is assumed that only emergency generation exists on the offshore oil platforms. Therefore, the system must be capable of recovering from a complete shutdown. This is referred to as a black start. Before starting the system, it is necessary to disconnect the loads from the HVDC converter and the STATCOM by opening the main circuit breaker shown in Fig. 1. Then the STATCOM DC capacitors are pre-charged using a small auxiliary power supply. The DC capacitor continues to be fed by the auxiliary power supply until the HVDC converter starts to import power, as the STATCOM has to provide the converter system losses. When the DC capacitor is fully charged, the STATCOM output voltage is ramped up (giving smooth energisation of the transformer) and then the HVDC converter can be deblocked and start to transmit active power. The network load is then gradually increased.

D. Starting a large induction machine

Offshore oil platforms have relatively large induction machines in situ which may be required to be put into service at any time. Therefore, the hybrid system must continue to operate successfully during these scenarios. Induction machines absorb large amount of reactive power during starting (4-6pu). Therefore it is important that the system controller is informed prior to the starting of large machines. When the system receives such a request from an operator, the STATCOM controller energises the required extra capacitor banks so that the STATCOM moves into the inductive region and its capability for providing capacitive reactive power compensation is increased prior to the machine being energized. The controller supervises this sequencing and will delay starting the machine until the required additional capacitive reactive power is available.

IV. Simulation Studies

The hybrid system was studied using EMTDC/PSCAD. The HVDC system is a monopolar scheme rated at 300MW/300kV modified from the benchmark model proposed in [9]. The rectifier is a conventional 12-pulse converter connected to an AC source with a Short Circuit Ratio of 5. The inverter has series capacitors as shown in Fig. 1. For the purpose of this study, the STATCOM is modeled as a 2-level VSC switched at 1350Hz and rated at +/-100MVar. Its DC capacitor has a total energy storage of 4MJ when charged at its rated voltage. Two passive harmonic filters are used. One is rated at 60Mvar, tuned at 12th/24th and the other is a 12MVar high pass filter. Six loads are considered in the study and are listed in Table I. Large induction machines are included as this is usually the load condition on oil platforms. Loads 1, 2, 4 and 6 are connected to the system via a 250MVA transformer while Loads 3 and 5 are connected via their separate transformers rated at 50MVA, respectively. The mechanical loads of the induction machines are assumed to be proportional to the cube of machine shaft speeds. Table II shows the operational sequence of the studied system, where it is assumed that the DC capacitor is fully charged before the sequence begins.

TABLE 1 LIST OF THE TYPE OF LOAD CONSIDERED FOR THE STUDY

Load	**Load type**	**MVA**	**cosϕ**	IM Rated speed	IM Inertia (pu)*
1	passive	50	0.95		
2	passive	40	Pure capacitive		
3 (Motor 3)	Induction machine	40MW	0.9	1470rpm	1.5
4 (Motor 2)	Induction machine	40MW	0.9	1470rpm	2
5 (Motor 1)	Induction machine	30MW	0.9	1470rpm	1
6	passive	40	Pure capacitive		

* Rated inertia is defined as ω_N/T_N, where ω_N and T_N are the rated angular speed and torque of the three motors respectively.

TABLE 2 OPERATIONAL SEQUENCES OF THE STUDY

Time (s)	**0-0.1**	**0.2**	**0.4**	**0.8**	**1.0**
Event	Ramp up AC voltage by STATCOM	Deblock HVDC converter	Load 1 switched on	Load 2 switched on	Load 3 switched on
Time (s)	**1.8**	**2.6**	**2.8**	**3.6**	
Event	Load 4 switched on	Load 6 switched on	Load 5 switched on	Load 2 switched off	

Fig. 3 shows the simulation results for the operating sequence listed in Table 2. The voltages, Currents and speeds are shown in per unit value, 1pu being the respective rated values. For active and reactive power 1 per unit is defined as 300MW and 300MVar respectively.

The system is started with all loads disconnected. The STATCOM is de-blocked and ramps up the AC voltage and absorbs reactive power to offset the filter capacitors. When Load 1 is switched on the STATCOM temporarily provides active power to the network, Fig. 3(e). As a result, the STATCOM DC capacitor voltage reduces at 0.4s. The HVDC converter current increases to provide real power to the network and the STATCOM DC capacitor voltage gradually increases to its normal value. A direct connected induction machine absorbs a large amount of reactive power when it is started and the hybrid system controller provides for this scenario by energizing capacitive reactive power support prior to machine starting. This is shown in Fig. 3 where, prior to starting an induction machine (Load 3) at 1.0s, a capacitor bank (Load 2) is switched on at 0.8s, causing the STATCOM to immediately move into the inductive range and provide reactive power balancing. The STATCOM now has a large reactive power support capability and the system is ready for the starting of large induction machines.

When the 40MW induction machine (Load 3) is switched on at 1.0s, the STATCOM immediately provides the reactive power required by the machine. As the machine accelerates and reaches its rated speed its reactive power absorption reduces and the STATCOM moves back to the inductive region as can be seen from Fig. 3 (f). This process repeats at 1.8s when Load 4 is switched on. A second capacitive bank (Load 6) is switched on at 2.6s to provide the extended reactive capability for the STATCOM, to allow the starting of Load 5.. At 2.8s Load 5 is switched on and the machine reaches its rated speed at 3.2s. Since all of the induction machines have now been started, one capacitor bank is switched off at 3.6s and the STATCOM provides the reactive power balancing of the AC system on the platforms. The STATCOM then operates at low current to minimize its power losses.

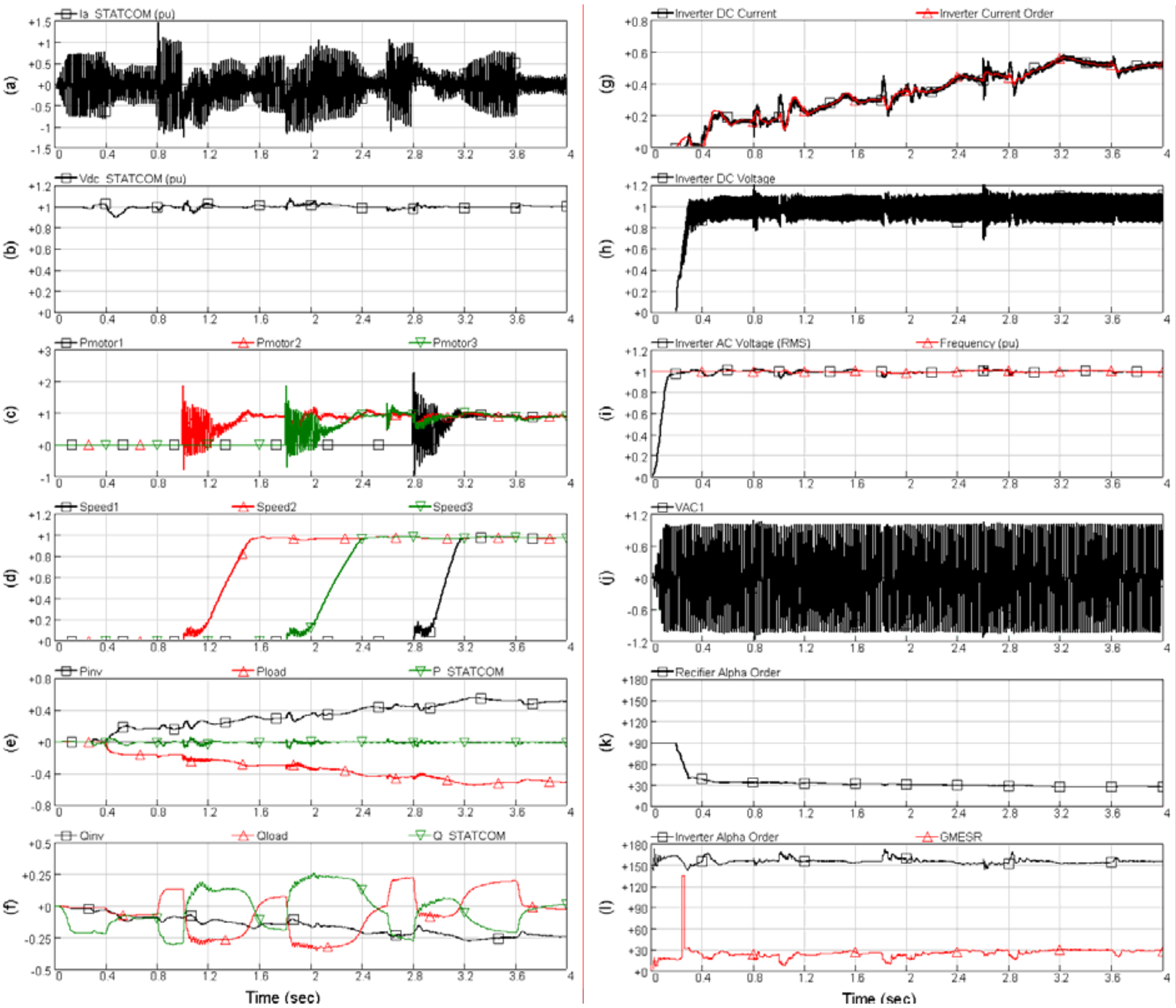

Fig. 3 Simulation results of black start and various load switching, (a): STATCOM AC current; (b) STATCOM DC link voltage; (c) Induction machine active power; (d) Induction machine speed; (e) Active powers of HVDC inverter, load and STATCOM; (f) Reactive powers of HVDC inverter, load and STATCOM; (g) HVDC converter DC currents; (h) HVDC inverter DC voltage; (i) Network AC rms voltage and frequency; (j) Network AC voltage; (k) Rectifier alpha order; (l) Inverter alpha order and gamma measurement

The HVDC rectifier controls the DC voltage, and hence its value stays almost constant throughout the operating conditions shown in the case study. Fig. 3 clearly shows that the proposed hybrid system gives stable operation and is well controlled over the whole operating range simulated.

In order to investigate the system performance during AC fault conditions, a simulation of a three-phase to ground fault on the rectifier side has been carried out. The total loads on the oil platforms are lumped into one 100MVA passive load with a power factor of 0.95 and three induction machines rated at 30MW, 80MW and 80MW respectively. The total active power transmitted by the HVDC converter before the fault is about 280MW. Figs. 4 shows the simulated results. The fault occurs at 0.4s and is cleared at 0.6s.

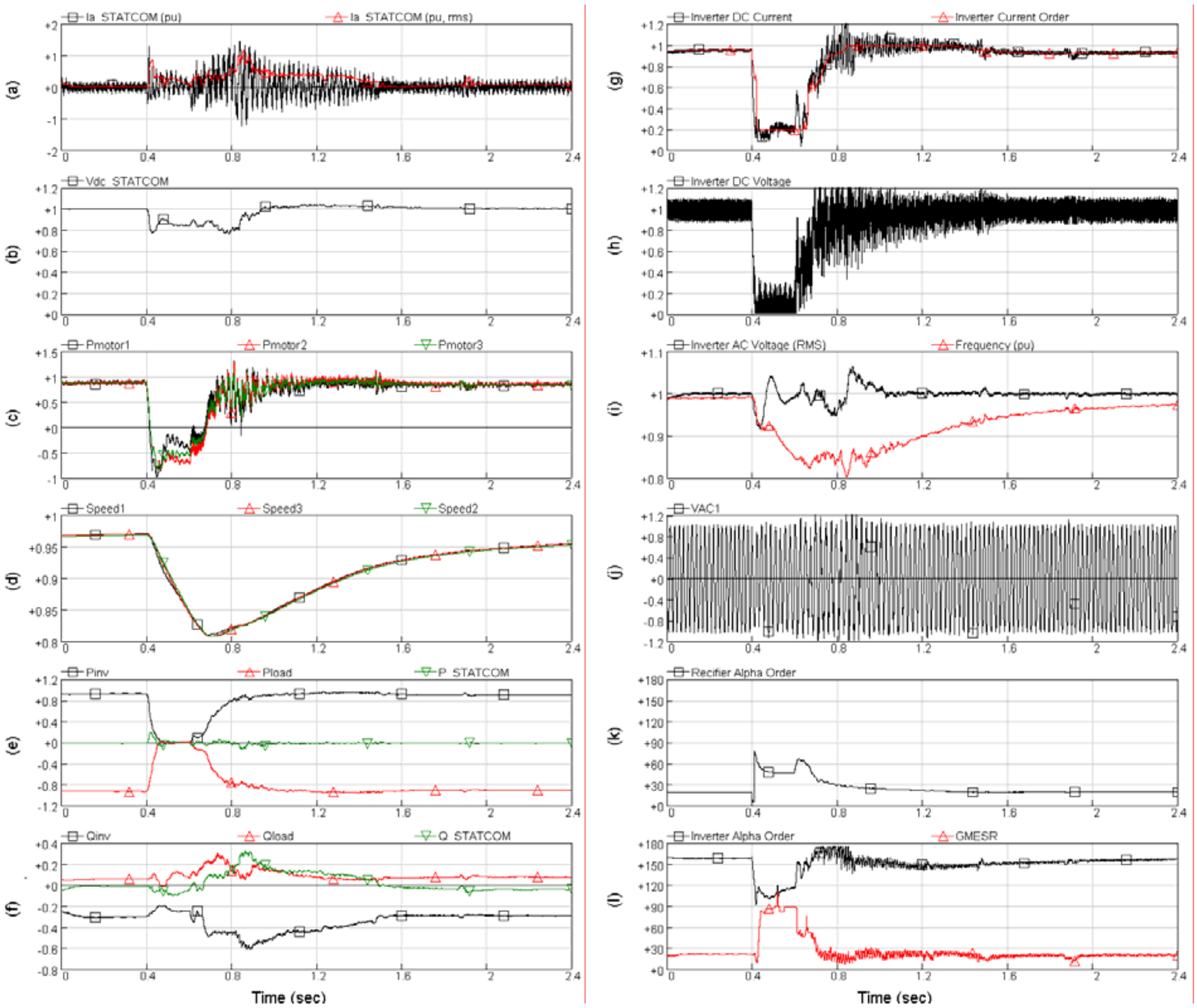

Fig. 4 Three-phase to ground fault on rectifier side (same axes as in Figure 3)

The three induction machines are operating near their rated power and speed prior to the AC fault. When the fault occurs, the HVDC transmitted power drops to zero. The STATCOM temporarily outputs active power to the network and consequently the STATCOM DC capacitor voltage reduces. In order to preserve the STATCOM DC capacitor voltage, the network AC frequency is allowed to reduce and the three induction machines go into regenerative mode as can be clearly seen in Fig. 4 (c). Because of the large frequency drop normal under frequency protection cannot be used here. During the fault period, the HVDC scheme circulates 0.2pu current to balance reactive power on the offshore network. After the fault is cleared, the HVDC transmitted power is gradually increased. After fault clearance the HVDC rectifier DC voltage order ramps up from 0.9pu to 1.0pu over a one second period to help prevent commutation failure, as the inverter side AC voltage may be low and may have high harmonic distortion. The STATCOM DC capacitor voltage and the AC voltage frequency are gradually increased. The three induction machines reaccelerate and the whole system settles down within approximately one second of fault clearance. Fig. 4 shows that the system performance is stable and satisfactory for such a fault scenario and load condition.

If a fault collapses the offshore AC voltage, the HVDC inverter is likely to have repetitive commutation failures and both the STATCOM and HVDC inverter may need to be blocked. During the fault, the machines will slow down at different rates, each determined by its respective mechanical load and inertia. When the fault is cleared, the machines will have different speeds and it is not possible to reaccelerate them without inducing high inrush current. Therefore, the main circuit breaker might need to be opened and the system may have to go through the black start sequence.

V. DISCUSSIONS

A. STATCOM rating and energy storage

The system can be designed to allow for greater load variation on the offshore platform and provide for less AC voltage disturbance if the rating of the STATCOM is increased. Since the energy storage on the DC side of the STATCOM is used to balance the active power during transient system conditions the capacity of this energy storage may also be increased to provide more stable operation and less voltage variation. These options should be taken into account during the feasibility stage since they will impact on the both the capital cost and the physical size of the offshore equipment.

B. Comparison with VSC Transmission solution

An equivalent VSC Transmission solution can also provide excellent performance during load switching. However, like the proposed hybrid system, the overload capability is limited. Under fault conditions, the performance of these two schemes are also similar. The capital cost of the VSC Transmission solution is likely to be higher than the proposed hybrid system particularly for relatively high power ratings. The power loss of a VSC Transmission solution is also likely to be much higher than the hybrid scheme. The exact break even point for the two schemes depends on the power rating, load conditions and loss capitalization.

VI. CONCLUSIONS

A hybrid scheme, which comprises a CCC based HVDC scheme and a STATCOM for the supply of power to offshore oil platforms, has been presented in this paper. The principle of the proposed system and the control strategy has been described. Black start, steady-state operation and dynamic performance during load switching have been demonstrated by simulation results and the scheme has shown satisfactory responses. Direct online starting of large induction machines has been shown to be feasible and an operating strategy has been provided and validated by simulation. The system performance during three-phase AC fault on the rectifier side has been studied. The proposed system has been shown to be suitable for on offshore oil platforms where the proportion of induction machine load to passive load is usually large. The proposed hybrid system has much lower power loss than an equivalent VSC Transmission scheme and lower capital cost for high power rating. The hybrid scheme may also be a good solution for connecting island loads, and for offshore wind farms.

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