Offshore DC Grids as an Interconnection of Radial Systems: Protection and Control Aspects

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***Abstract*—This paper presents a topology for dc grids which enables very robust dc fault protection with moderate costs, good operating flexibility, and simple controls. It is postulated that radial dc systems are best suited for limited-size local dc grids. Radial topology enables robust and fast protection selectivity using only local signals and exploiting the advantages of hybrid dc circuit breakers (CBs). To enable flexible expansion options to national/international systems, it is suggested to interconnect star points of radial systems using dc/dc converters. DC/dc converters enable inherent isolation of dc faults and provide firewall between radial dc grids. Each interconnecting cable is protected by a dc/dc at one end and a hybrid CB at the other end. The control options for dc/dc converter and the radial grids are analyzed. A detailed simulation model of six terminal dc grid with two-star points is presented. The power systems computer aided design (PSCAD) simulation results confirm dc fault isolation and good control performance of the proposed topology for a range of dc fault contingencies.**

***Index Terms*—DC/dc power conversion, dc power systems, dc power transmission, high voltage dc (HVDC) converters, HVDC transmission, wind energy.**

I. Introduction

THE DEVELOPMENT of dc transmission grids is among the most significant technical challenges in power engineering. With the interest in offshore wind power and advances in modular multilevel voltage source converters (VSC) converters, there is a growing demand for developing high voltage dc (HVDC) grids. The backbone of future European super grid will be constructed based on dc grid [1].

Currently, only point-to-point HVDC exist in many installations worldwide. The dc grids are built by interconnecting multiple dc transmission lines, however, the topologies, protection, and operating methods are still uncertain. As dc cables have very small impedance without any reactance ($f = 0$), the dc faults will cause widespread voltage collapse in the grid and the fault currents will be large. DC grid fault current interruption should happen on the rising slope i.e., before fault current reaches steady-state which gives only few ms for protection action [2].

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Fast and low-loss hybrid dc circuit breakers (CBs) have been developed recently [3]. The cost of these units will be of the order of 30% of VSC converter costs and the losses are negligible. However, prototypes have been demonstrated as an isolated component only. As a single unit with a local current sensor, these dc CBs can reliably clear dc faults within 2–5 ms assuming that interrupting current is not above 5–10 kA. There is no realistic possibility for significantly increasing further the semiconductor interrupting current capability.

A dc-grid wide protection system is the next unresolved and probably the most significant technical challenge. The main difficulty is the protection selectivity in large grids and within very short time period of 2–5 ms. Some promising dc grid protection approaches have been reported in [4]–[6]. The differential protection method in [4] is accurate but requires several milliseconds communication delay between dc CBs and perhaps more in case of long dc cables. Any delay in fault clearing implies that fault current continues to increase. The practical rating of dc CBs and costs will therefore limit the length of dc lines and the number of dc lines that can feed dc fault (i.e., dc fault level). The traveling wave detection method in [5] and the dc grid zoning in [6] do not require communication but may not be able to offer high accuracy considering low dc impedances and very short decision time.

It will be very challenging to achieve high dc power transfer security (comparable to ac transmission) if meshed dc grid topologies are adopted and dc CBs are used solely as protection means.

The use of dc/dc converter as a dc CB has been proposed in [7]–[9]. DC/dc converters enable ideal isolation of two dc systems since they will not propagate dc faults. They can also connect dc systems of different dc voltage levels and with different dc technologies. However, dc/dc converters have approximately 180–200% VSC converter costs and also the operating losses of around 2% should be considered. Clearly, dc/dc converters cannot be used for isolation of all cables in meshed dc grids.

Gomis-Bellmunt *et al*. [10] present a comprehensive cost comparison of dc grid topologies. The conclusions are derived solely on the cost and operational basis, but practical aspects of protection system are not evaluated in depth. Additional limitation of this paper is that the size of considered systems is modest.

With traditional ac transmission systems, the grid topology is determined based on the costs and operational priorities, with the understanding that protection system can

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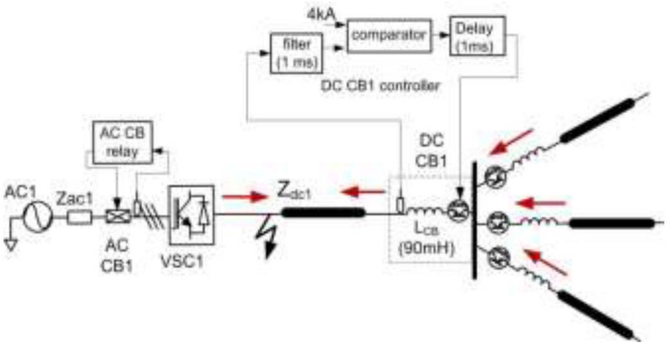

Fig. 1. Radial dc system protection.

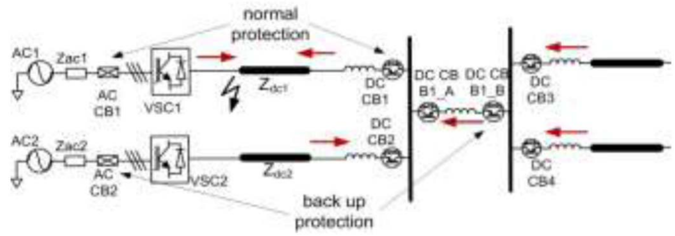

Fig. 2. Radial dc system with back-up protection based on split bus.

be developed later using standard approaches. In case of dc grids, we may need to consider topology and protection system in parallel from the earliest stages. In this paper, we focus on developing dc grid topology which will facilitate reliable protection system within the dc CB component constraints.

The aim of this paper is to develop building principle for dc grids of any complexity (any number of terminals and geographical size) and with highly reliable protection. The proposed dc grids will be tested on a six-terminal dc grid test system using a detailed PSCAD simulation model.

II. Radial DC Grids

A. Protection Method

The main purpose of a dc grid (connecting numerous VSC terminals) is to provide opportunity for each terminal to trade power with any other terminal. Depending on the topology, the costs, losses, operating flexibility, and power security will vary.

The main purpose of the grid protection system is to rapidly isolate the smallest grid segment in case of a dc fault, in order to enable uninterrupted operation of the remaining part of the grid. Depending on the topology, there will be more or less loss in capacity in the post-fault topology.

A radial dc grid has a single star point connecting VSC terminals with radial dc cables as shown in Fig. 1. There is no terminal-to-terminal connection. This topology is not normally used with ac transmission but they are common in distribution systems and it has other operational and cost advantages and disadvantages which are studied in [10].

The main disadvantage is the loss of capacity (one VSC terminal) for a dc cable fault. This problem can be limited by restricting the size of VSC converter within the maximum power loss criterion according to national grid codes (1800 MW in U.K.). The redundancy can be achieved by adding a new radial cable with a VSC (not just a cable as with meshed ac grids), connecting to the star point.

This topology has a very important advantage since it enables development of a simple, accurate, and robust grid protection system. Each dc cable can be isolated from the grid using a single dc CB located at the star point dc bus.

Fig. 1 shows the radial dc line protection system, where the given numerical values are used in the model in Section IV. The protection consists of a dc CB, a current sensor, and a controller. A trip decision is made if the local current sensor detects current over a threshold (set at 4 kA in the test system) and in positive direction. Only the local sensor is used to make trip decision. The selectivity is therefore very simple and robust. For any dc fault only one dc CB sees a positive current (all other dc CBs see negative current, as shown by red lines). This is a significant advantage over meshed dc grids.

Since there is no communication with any other component, the protection can operate as fast as hardware dynamics and processing speed will allow. Reference [2] indicates that hybrid dc CBs could be operated within 2 ms.

At the other end, the cable is isolated using a conventional ac CB as with any HVDC system. The mechanical ac CB will have operating time one order of magnitude slower (20–50 ms), but this has no implication for dc grid.

The radial dc lines can be of any length since there is no need for communication along dc lines.

Any number of dc cables (terminals) can be connected to the star point, but the steady-state fault level is dependent on the number of dc lines. Nevertheless, the steady-state fault level may not be a limiting factor since fast dc CBs will interrupt the current on a rising slope. Consider the worst case of infinitely strong 320 kV dc system which gives infinite steady-state fault current. The dc fault current rise equation is

$$L_{\mathrm{CB}}\frac{\Delta I}{\Delta t} = V_{\mathrm{dc}} \tag{1}$$

where L_{CB} is the series reactor inside dc CB, Δt is the operating time, and ΔI is the fault current increase from the load current. Assuming $\Delta t = 3$ ms and $\Delta I = 7$ kA, we get the requirement for $L_{\mathrm{CB}} = 137$ mH. This is a reasonable inductor size which is in agreement with [2] indicating that there is no practical limit on the number of dc lines inside the radial dc grid.

The above protection strategy is applicable only to radial topologies with a single star point, and clearly cannot be used with meshed dc grid. The selectivity becomes an issue if any additional dc CB sees positive current during dc faults.

B. Back-Up Protection Options

Fig. 2 shows the radial system with a back-up protection. A split bus is introduced with two bus-bar dc CBs (dc CB B1_A and dc CB B1_B). Note that dc CBs are unidirectional, and a bidirectional component can have a common inductor only. In case that dc CB1 fails to operate for a preset time interval, then dc CB B1_B and ac CB2 would open with a larger loss in capacity, i.e., loss of terminals 1 and 2.

The failure modes of hybrid dc CB are not yet clear, but it is known that all semiconductor switches have a driver-level hard-wired overcurrent protection. This internal

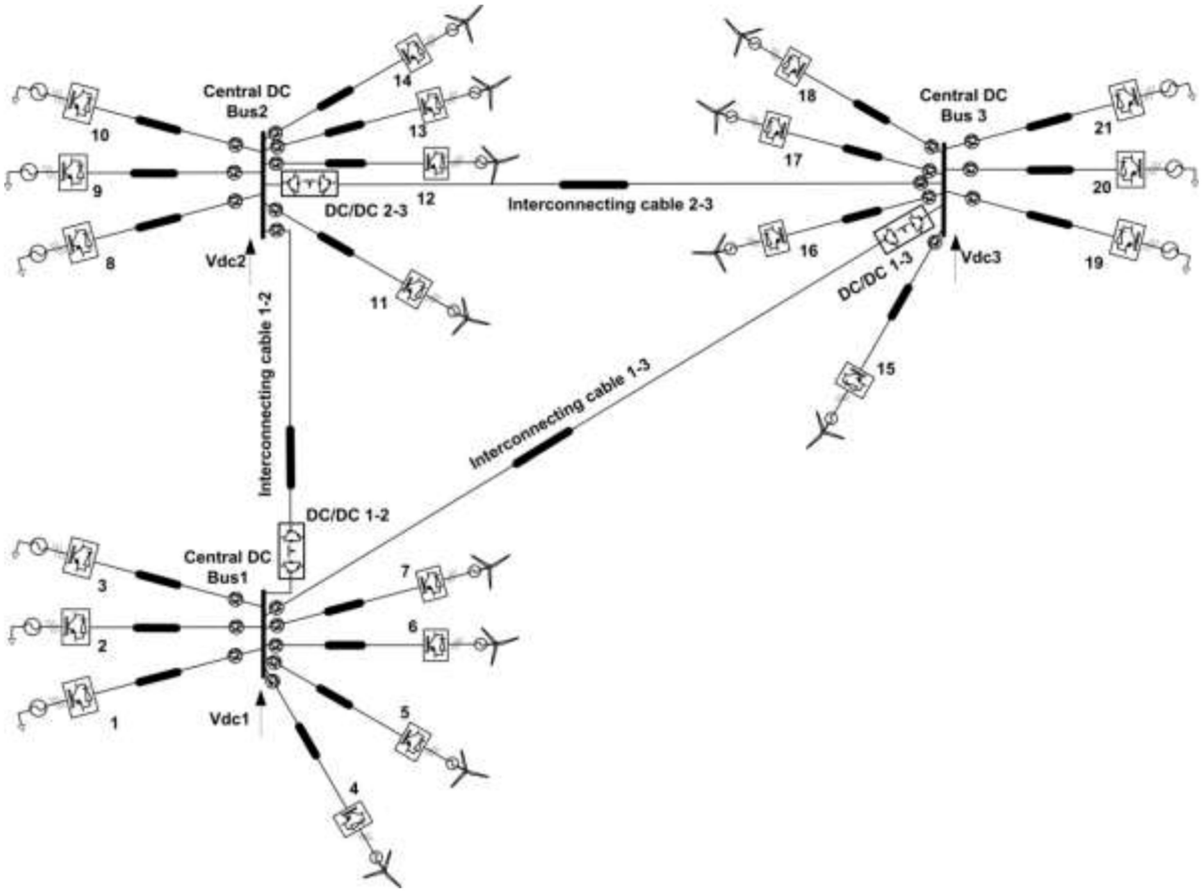

Fig. 4. Twenty-one (12 offshore + nine onshore) terminal dc grid with three radial dc systems.

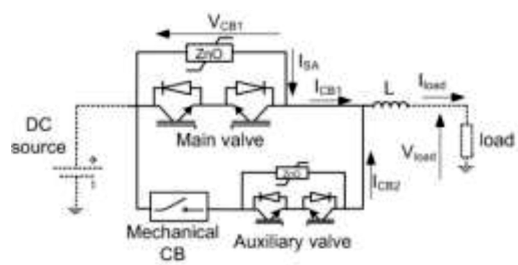

Fig. 3. Hybrid dc CB.

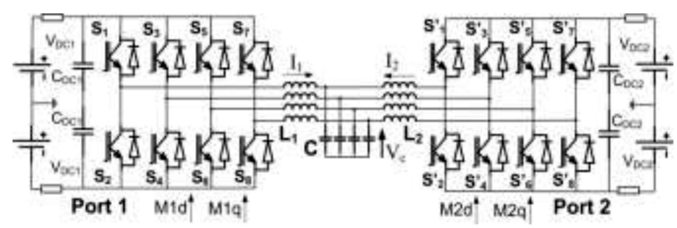

Fig. 5. Four-phase dc/dc converter.

switch self-protection is inaccurate and inaccessible to control but it is very robust and reliable since the complete logic including the sensor is at the valve assembly. It is proposed that this switch self-protection can also be used as last-defense option for dc grid back-up protection. Fig. 3 shows the topology of hybrid dc CB [8]. The normal load current path is through the mechanical CB and the auxiliary valve. In case of protection system failure, there will be a very large current through this path. This large current will activate the driver-level hard-wired overcurrent protection in the auxiliary valve of dc CB1. The auxiliary valve insulated gate bipolar transistor (IGBT) will open immediately interrupting thus the fault current. Nevertheless, the auxiliary valve will see large open circuit voltage (full dc voltage) which is much larger than its blocking forward capability. The overvoltage will destroy IGBTs which are configured to fail in open circuit. This back-up protection method therefore does not require any additional dc CBs and the loss of capacity is minimal. On the downside, this implies destruction of a dc CB. Note that all other dc CBs will see large negative which will be conveyed by their diodes and which have better overcurrent capability.

Therefore, considering the cost of additional dc CBs, it is not clear if grid operators will demand full additional back-up protection systems. Back-up protection is not considered further in this paper.

III. Interconnecting Radial DC Systems Into Large DC Grid

A. Topology and Protection

A single radial dc grid will not be adequate as the geographical area increases. Even in smaller geographical area, increasing number of terminals will call for another star point because of reliability reasons.

TABLE I
COMPONENTS FOR 21 TERMINAL DC GRID

	Interconnected Radial Grid	Ring Grid
DC CB	24×0.3pu=7.2pu	42×0.3pu=12.6pu
DC/DC	3×2pu=6pu	0
total	13.2pu	12.6pu

It is proposed in this paper to interconnect the star-points of different radial systems using dc/dc converters. Each interconnecting cable has a dc/dc converter at one end and a dc CB at the other end, as shown for a 21-terminal dc grid in Fig. 4. The main reasons for using dc/dc converters are as follows.

1) They inherently prevent dc fault propagation. A fault at one radial system will be seen as open circuit at the other system. No communication or fast control is required.
2) They enable different dc voltages at the two radial systems.
3) They facilitate power control in the interconnecting cable.
4) The two radial systems become decoupled and therefore different technologies, control, and protection (different vendors) can be used.

On the downside, dc/dc converters have high costs and the on-state losses. Fig. 5 shows high power dc/dc converter from [8] but other topologies can also be used.

In a dc grid of n_t terminals, the costs and operational priorities will determine the number of star points n_s. Then, the number of dc/dc converters will be n_s, while the total number of dc CBs will be $n_t + n_s$. Expansion of dc grid is simple. A new VSC terminal requires a radial cable with dc CB connecting to the nearest star point. A new interconnecting cable requires additional dc/dc converter and one dc CB.

Although individual dc/dc cost is high, the total cost of a dc grid is comparable with other topologies, as shown in the following example. Table I shows the total dc grid component rating for the 21-terminal test system in Fig. 4, where base is the VSC converter rating (all VSC have the same rating). Also, each dc CB has 0.3 p.u. rating corresponding to the VSC on the same dc line [7]. Considering very fast operation in radial systems, dc CB rating is not sensitive to fault level. A dc/dc converter consists of two VSCs and therefore the rating is 2 p.u. As a comparison, using a ring dc grid topology, we would need 2 dc CBs at each dc cable and the total cost becomes similar as shown in Table I. Note also that the ring topology would require much larger rating for many cables and probably for dc CBs because of the protection delays. The operational and cost comparisons between topologies are given in depth in [10] and are not elaborated further.

B. Grid Control

Each radial dc grid is considered as a separate system for control development. This simplifies controls and provides safeguard against spreading of instabilities and blackouts. Each dc terminal controls local power with additional dc voltage droop feedback as it is common practice in dc grids [11].

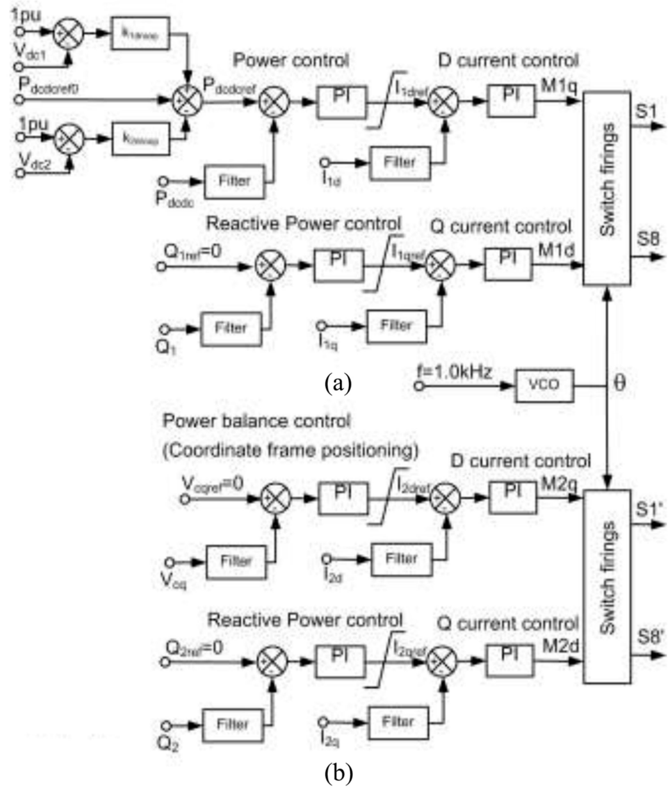

Fig. 6. DC/dc converter controller. (a) Port 1. (b) Port 2.

The proposed controller for dc/dc converter is shown in Fig. 6. At the inner most control level, there is current d and q components control, which prevent semiconductor overcurrents. The middle control layer regulates active and reactive power at each port. The port 2 balances power by keeping coordinate frame aligned with the capacitor voltage ($V_{\mathrm{cq}} = 0$), where an in-depth analysis of dc/dc converter design and modeling is given in [8]. The dc/dc converter regulates the power in the interconnecting cable at the value P_{dcdcref0} which is determined by the dc grid dispatcher.

It is proposed that the power reference is moderated with dc voltage droop feedback from both dc grids (V_{dc1} and V_{dc2}). The two grids are practically decoupled and disturbances normally occur on only one radial grid at a time. The dc/dc converter in this way draws power from a healthy grid in order to stabilize a grid under disturbance. The radial dc grid will see dc/dc converter as any other VSC terminal.

An alternative control method is to use dc voltage control for dc/dc converter. In case of small grids, this method will imply significant coupling between the two dc grids and possible frequent dc/dc converter saturation. However, in case of large systems with many terminals such as control method may become attractive as a stand-alone control for an embedded dc/dc converter.

IV. SIMULATION VERIFICATION

A. Test System

The test system is shown in Fig. 7. It consists of two, 3-terminal radial grids. Each radial grid has two on-shore 1 GW VSC terminals and one offshore 1 GW wind farm. Such

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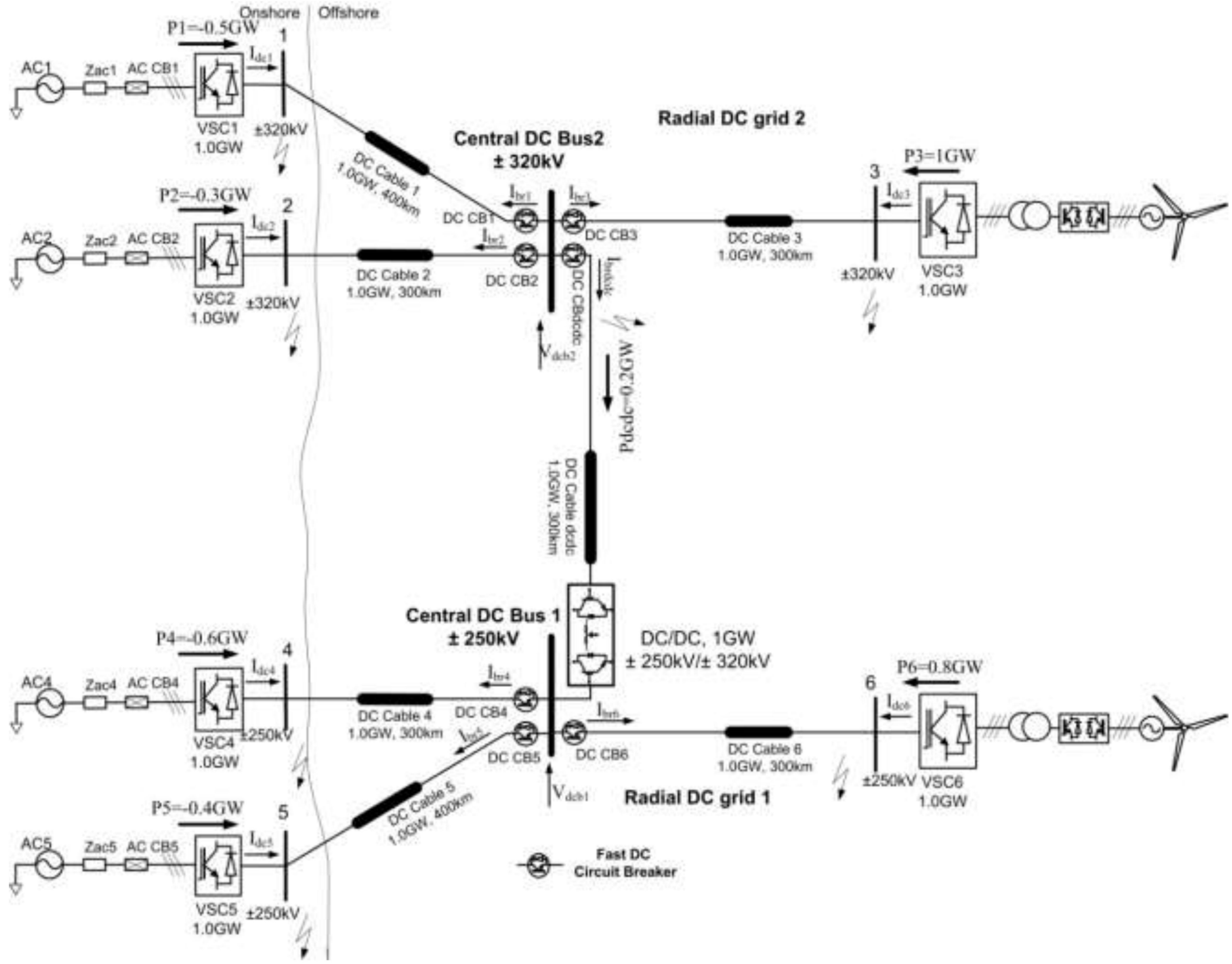

Fig. 7. Test system: 2 + 4 terminal dc grid with two radial dc systems.

star topology resembles the U.K. East HVDC Interconnector and other first-stage European dc grid projects (COBRA cable) which are being studied. All the component ratings and steady-state power flows are shown in Fig. 7. The dc voltage levels at the two star systems are purposely selected to be different in order to demonstrate the flexibility of the topology.

The dc/dc converter test system data are shown in Table II in the Appendix. Although two-phase converter is studied as least cost option in [8], the high power converters will require more phases because of semiconductor rating limitations. A four-phase topology is therefore selected to eliminate ground harmonics currents and also to improve reliability (tripping a phase enables three-fourth power transfer).

The 1 GW wind farms are modeled in detail as a single equivalent variable speed machine by scaling-up detailed 5 MW permanent magnet synchronous generator machine model as presented in [12]. The VSC converters and controls use standard representation according to [11] or [12]. All the controls are modeled in full detail (including all PLLs) but converters use average nonlinear models. The converter and ac system data are given in the Appendix, in Tables II and III. The ac systems have short circuit ratio of 30 with $X/R = 10$, as seen in table IV.

One terminal in each star-grid (VSC1 and VSC5) is set to control dc voltage, as it would be normal practice with small dc grids. The remaining onshore VSCs (VSC2 and VSC4) control local power with dc voltage droop feedback. The wind farm VSC converters inject all the available wind power and have no contribution to dc grid control (no droop feedback).

The dc cables are modeled in detail using frequency-dependent distributed parameter model from PSCAD library. The complete model is built on PSCAD platform.

The protection system model is developed for each dc cable as shown in Fig. 1. Each dc CB is modeled as an ideal switch with 90 mH series reactors.

Fig. 7 indicates all the dc fault locations that are studied. In all cases, the system operates in steady-state shown in Fig. 7, and at 3 s a pole–pole zero-impedance dc fault is applied. Also, small signal disturbances are tested but they give less control challenges and for lack of space they will not be shown.

B. DC Fault on Radial Cable

Figs. 8–10 show system response following a permanent pole–pole fault at dc terminals of VSC4. In Fig. 9, we can see that dc CB4 interrupting current is 8 kA. The remaining two dc CBs on the same star grid (dc CB5 and dc CB6) see negative

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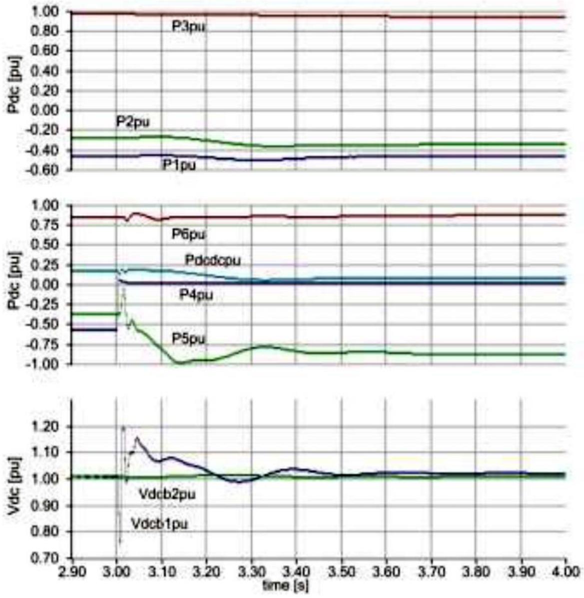

Fig. 8. Fault on VSC4 dc cable. Terminal powers and dc voltages.

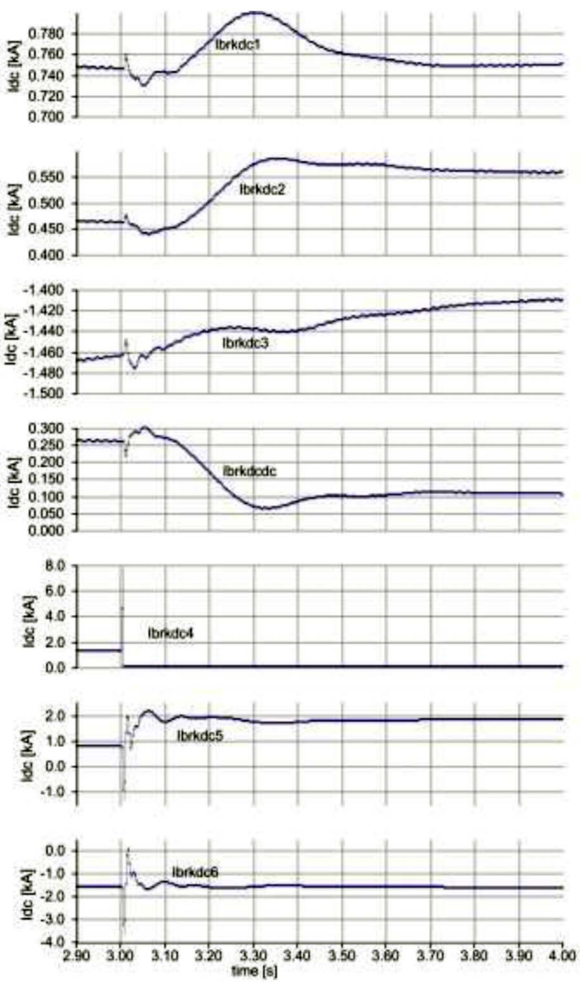

Fig. 9. Fault on VSC4 dc cable. Currents in seven dc CBs.

current and therefore selectivity is very simple. On the terminal side, the faulted cable is isolated by ac CB4 according to standard practice with HVDC dc fault management (not shown for brevity).

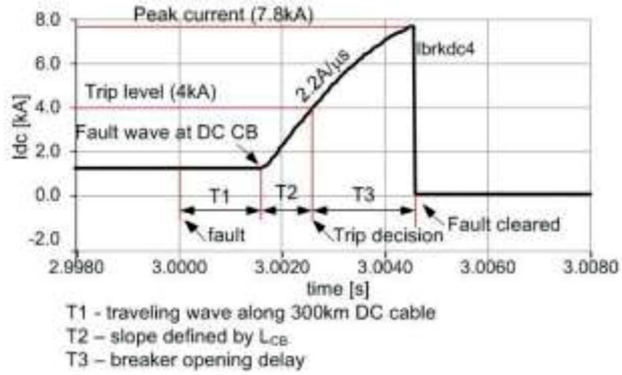

Fig. 10. Fault on VSC4 dc cable. Current in dc CB4.

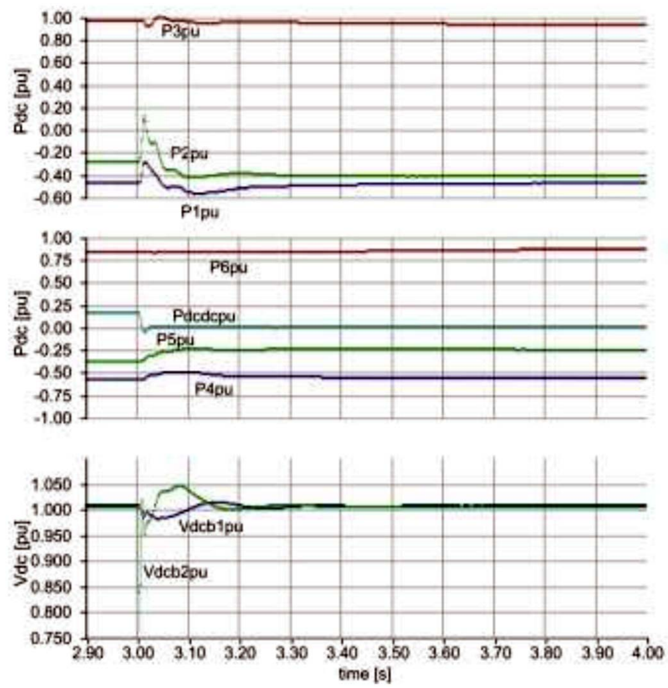

Fig. 11. Fault on dcdc cable. Terminal powers and dc voltages.

The top three graphs in Fig. 9 confirm that CBs on grid 2 do not see any notable current disturbance. Fig. 10 shows actual dc CB current around the fault instant and illustrates the operating delays. The finally selected 90 mH reactor gives acceptable peak current of around 8 kA. A reactor of 40 mH gives around 15 kA peak current which would be beyond the switch turn-off capability.

Fig. 8 illustrates that terminal five rapidly increases power in order to maintain local dc voltage at 1 p.u. A particular concern with radial grids is the star point voltage which cannot be directly controlled. The simulations, however, show that the star point dc bus 1 voltage (V_{dcb1}) is well bounded even for most series contingencies. In Fig. 8, it settles at slightly higher value since cable 4 has different resistance from cable 5. It is seen that dc/dc converter reacts to V_{dcb1} increase by reducing the power transfer. The top graph in Fig. 8 confirms that grid 2 is not affected by this significant outage on grid 1. VSC2 converter gradually increases power transfer to compensate for the dc/dc converter power reduction.

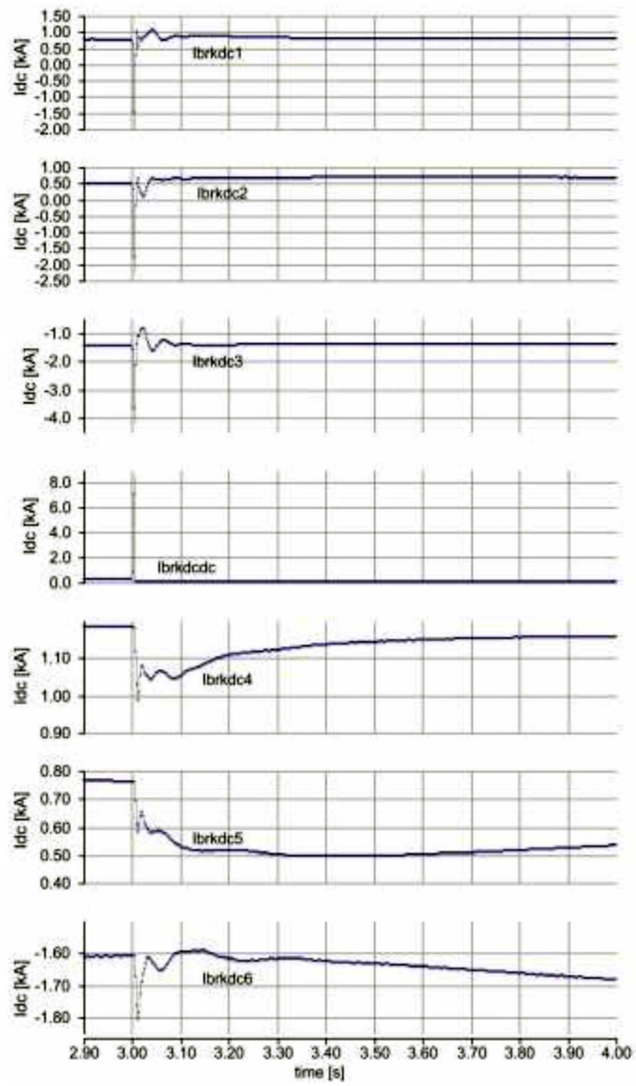

Fig. 12. Fault on dcdc cable. Currents in 7 dc CBs.

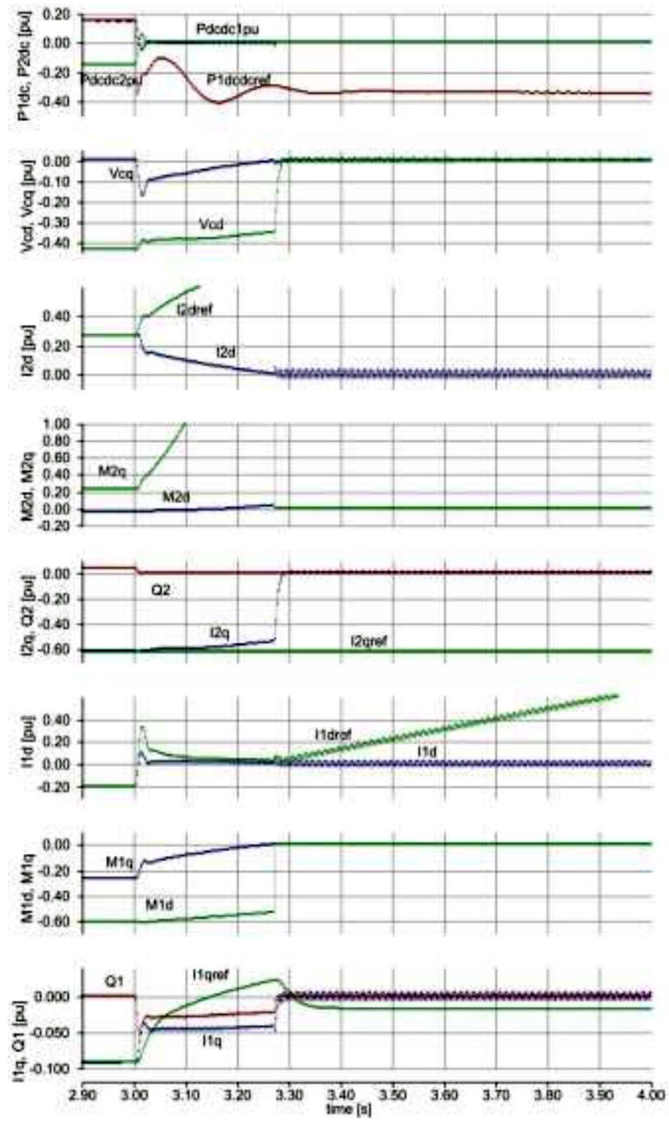

Fig. 13. Fault on dcdc cable. Internal dc/dc converter variables.

C. DC Fault on the Interconnecting Cable

Figs. 11–13 show the system responses for a permanent pole–pole dc fault at dc bus 2 terminals of the interconnecting dcdc cable.

It is observed in Fig. 12 that dc CB dcdc has interrupting current of around 8.5 kA. This is slightly higher current than in case of fault on dc cable 4 since there is now fault current infeed from three VSC converters. It is also seen in the lower three graphs of Fig. 12 that dc CBs in grid 1 do not see large currents.

Fig. 11 shows that VSC1 and VSC2 are able to establish a stable post-fault power flow and that grid 2 dc voltage deviation are limited. It is also seen that grid 1 only sees gradual loss of dc/dc infeed which confirms that dc/dc converter will not transfer dc fault.

Fig. 13 shows the internal dc/dc converter variables which are of interest since this is worst-case fault at high-voltage dc/dc terminals. It is seen as below.

1) Before the fault dc/dc converter operate satisfactory with power at reference point, $V_{\mathrm{cq}} = 0$, and reactive powers at each port equal to zero.
2) During the fault (3–3.27 s) the converter naturally responds by reducing currents and there are no transient overcurrents. No special controls are required.

The permanent fault is detected by low dc voltage for a preset time interval (around 250 ms) and dc/dc converter is tripped by blocking IGBT pulses (at 3.27 s). This permanently isolates dcdc cable from the dc grid 1.

All the dc CBs employ 90 mH reactor which introduce lags and slows the system dynamics, comparing with conventional VSC HVDC. The authors did not see need for special controls in the test system, however, in case of very large systems further dynamic studies will be required.

V. Conclusion

This paper presents a dc grid building methodology which ensures robust and accurate protection with moderate costs and simple controls. It is concluded that radial dc systems are well suited for limited-size local dc grids. Radial topologies fully exploit the advantages of fast hybrid dc CBs. On the downside, a dc cable fault will imply loss of one VSC converter. The back-up protection is also simple with radial systems.

It is proposed to interconnect radial local system using dc cables with dc/dc converters. DC/dc converters enable inherent isolation of dc faults and provide firewall between radial dc grids. It is essential to keep the number of dc/dc converters to minimum.

A full simulation model of 2 + 4 terminal dc grid with two-star points is presented. The PSCAD simulation results confirm advantages of the proposed topology for a range of dc faults. In particular, the robustness of protection system is demonstrated for worst case dc faults. The proposed grid control is found to respond excellent to grid contingencies.

Appendix

TABLE II
DC/DC Converter Data

Power P_{dcdc}	*1000MW*
DC Voltage V_{dc1}	*±250kV*
DC Voltage V_{dc2}	*±320kV*
Operating frequency *f*	*1.0kHz*
Number of phases	*4*
Filter capacitance C_{dc1}, C_{dc2}	*10μF*
Rated Power per phase (*1100MW* design)	*275MW*
Rated capacitor voltage *Vc [RMS]*	*380kV*
Capacitance *C*	*67.29μF*
Inductance L_1	*39.94mH*
Inductance L_2	*41.4mH*

TABLE III
VSC Converter Data

	VSC 1-3	*VSC 4-6*
Power P_{vsc}	*1000MW*	*1000MW*
DC Voltage V_{dc1}	*±320kV*	*±250kV*
DC Capacitance	*68μF*	*112μF*
Series resistance	*0.235Ω*	*0.235Ω*
Transformer	*1400MVA*	*1400MVA*
Transformer Xt	*0.15pu*	*0.15pu*
Series reactor	*0.1pu*	*0.1pu*

TABLE IV
AC System Data

	AC 1-2	*AC 4-5*
Voltage	*400kV*	*400kV*
Rac	*0.399Ω*	*0.399Ω*
Xac	*3.99Ω*	*3.99Ω*

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