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DC Voltage Performance Analysis of a Hybrid Multiterminal HVDC Grid Under Abnormal Conditions with Topological Investigation on Hybrid Scheme

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***Abstract*—.** Hybrid Multiterminal High Voltage DC system is a reliable technology capable of integrating multiple energy resources more efficiently and without compromising on the flexibility for integrating new power sources and loads to the grid. This paper provides a detailed analysis focused on improving the performance of DC side voltage of a Hybrid Multiterminal HVDC grid. The impacts of different parameters such as AC and DC voltage sags, connection topologies, interconnection of multiple DC grids and DC sources using DC-DC converters are studied. Operation of the test system is analyzed and compared through PSCAD/EMTDC simulations.

***Keywords*—**Hybrid Multiterminal DC (HMTDC), Line Commutated Converters (LCC),Voltage Source Converter (VSC) Multi Modular Converter (MMC), Multiterminal DC (MTDC).

I. INTRODUCTION

Nowadays with the development in HVDC technology, the HVDC transmission interconnections are increasing due to the fact that they provide a more reliable and robust transmission of power with the capability of interconnecting different types of AC and DC power resources to the grid with higher efficiency, flexibility and less line losses [1]. Thus the HVDC systems provide a good alternative to conventional AC grids.

An HMTDC is composed of different types of HVDC converters, the most common technology deployed today is the Line Commutated Converter (LCC)-type HVDC converter system [2] as it can achieve highest voltage levels while transmitting bulk power from far remote areas to the main grids. On the other hand, to interconnect offshore renewable sources and remote area loads, Voltage Source Converter (VSC)-type HVDC converter system [3] provides an efficient and flexible solution. An advanced type of VSC technology is the Multilevel Modular Converter (MMC) technology [4] which provides more advantages than its counterpart such as low harmonics and switching losses with higher reliability and stability with improved protection.

With combining the benefits of these technologies a hybrid LCC-MMC MTDC [5] provides a great solution for the applications such as intercontinental grids, super grids and other AC and DC grid interconnections. Therefore, multiple research studies related to the control and operation of HMTDC grids and its performance during abnormal conditions have been conducted so far. [6], [7]. However, the complexity in designing the control strategies for the requirements of interconnecting different AC and DC systems is laborious, therefore further research is required to investigate and analyze the system behavior under different circumstances. To improve overall system performance a ±5% tolerance limit of DC side voltage as a stability evaluation criteria is considered [8]. Connecting LCC grid with MMC grid requires state of the art research as both technologies are different, for this purpose using a DC-DC converter is a viable option.

Research has been undertaken to understand the response of the DC system during balanced voltage sags in the AC sides of the converters but research is rarely conducted during unbalanced voltage sags as they introduce different harmonics into the system which decreases the quality of the DC side voltage. Also it is of utter importance that the DC grid quickly energizes and reach a steady state.

II. SYSTEM DESCRIPTION

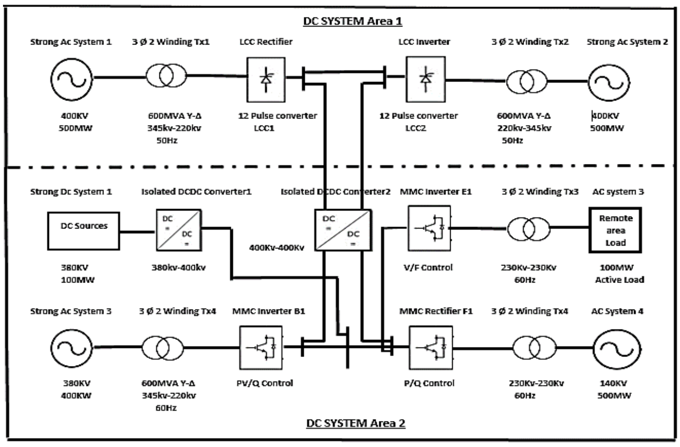


Fig.1. Block diagram of proposed five terminal Hybrid MTDC with remote AC load and a DC source integrated via DCDC converter.

The HMTDC is composed of two LCC converters and three MMC converters interconnected via a 400kV to 400kV DC-DC converter, thus forms two different network systems. The control and operation of both networks are based on CIGRE benchmark models [9], [10]. The DC system in area 1 is transferring 500 MW power from a strong AC grid 1 to a strong AC grid 2. In DC2 a large MMC rectifier is connected to an offshore AC system 3, and the large MMC inverter is connected to a strong onshore AC system 4 whereas another small MMC inverter supplies power to a remote area load. The DC system area 1 is connected to DC system area 2 via a DCDC converter to gain some important advantages such as the stability of the DC voltage under abnormal conditions like startup scheme, balanced and unbalanced AC voltage sags and DC voltage sags. To reduce the simulation time a simple average model DCDC converter (400kV to 400kV) with limited control that is a tap changer is utilized. The DCDC converter is an isolated type converter. To further improve the quality of the DC link voltage and maintaining balance in the system, the DC sources are integrated to specific locations shown in Fig.1.

III. HYBRID GRID CONVERTERS

A. *LCC converters*

It is the most developed and deployed technology in HVDC systems. Basic converter configuration depends upon Graetz bridge conversion system. From this both rectifier and inverter controls are designed separately based on the equation of dc current using two terminal LCC HVDC system.

$$I_d = \frac{\mathrm{VdorCos}\alpha - \mathrm{VdoiCos}\gamma}{\mathrm{Rcr + RL - Rci}} \qquad (1)$$

Rectifier controller is constructed using the alpha mode (line A-B) and constant current (line B-L) of rectifier whereas inverter controller is based on gamma mode (line D-E) and constant current (line D-K) of the inverter. Additional controllers (line F-G and H-I) are further designed in order to protect the system under unusual circumstances. The v_d and I_d characteristics for steady state operation are shown in Fig.2. A margin is also set if both the rectifier and inverters are in constant current mode that is I_{margin}. The controllers are designed in such a way that the characteristics of both inverter and rectifier match at only a single value.

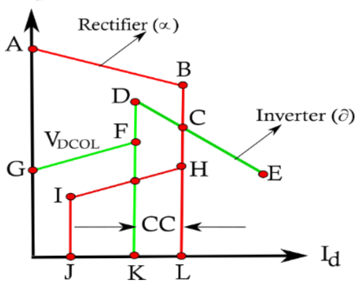


Fig.2. I-V characteristic curve.

B. *MMC Converters*

The multimodular converters are made from multilevel voltage source converters based on IGBT switching technology. The MMC converters used in the Hybrid HVDC grids are becoming popular with new switching techniques. The converter model used for this research is the average arm model [11. For simplified model of AAM is also shown in Fig.3 below.

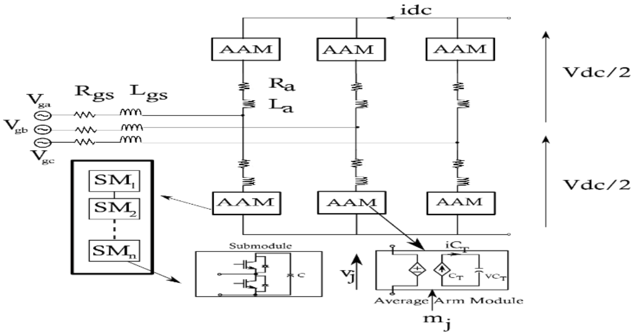


Fig.3.Average Arm Model (AAM) of MMC Converter.

From the AAM the equation are derived to introduce the control circuit of MMC. The primary control design of MMC is the same as VSC with an additional inner and outer control loop using the equations (5, 6). The inner controller controls the active and reactive powers independently using dq0 reference currents. The DC side dynamic equation [11] (7) is also used to design the DC current controller alongside the d and q axis current control loops as shown in Fig.4.

$$v^*_{m,d} = \mathrm{C(s)}\ (i^*_{g,d} - i_{g,d}) + \ v_{g,d} - w_{PLL} L_r i_{g,q} \qquad (5)$$

$$v^*_{m,q} = \mathrm{C(s)}\ (i^*_{g,q} - i_{g,q}) + \ v_{g,q} + w_{PLL} L_r i_{g,d} \qquad (6)$$

$$V^*_{mdc} = \ v_{dc} - C(s)(i^*_{dc} - \ i_{dc}) \qquad (7)$$

The outer control loops are also designed. These are capable of feeding the reference current to inner control system. Four control loops are deigned such that, DC voltage or active power loop and AC voltage or reactive power loop is used to provide the reference d and q axis currents. Another control loop is also made to feed the dc current inner vector controller using the energy based control of MMC AAM model as shown in Fig.4.

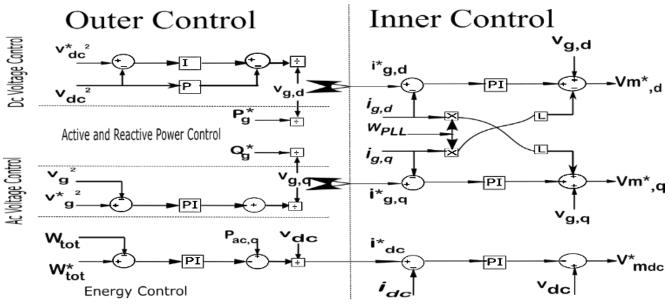


Fig.4. Inner and Outer Control loop Design of MMC Converter.

C. DC-DC Converters

A simple average model of isolated type DC-DC converter is used to integrate DC sources. Firstly this can provide initial current so that the startup DC voltage can be ramped up quickly and secondly if there are more DC sources integrated to the system using DC-DC converters the effects of voltage sags on DC link voltage can be reduced and thus the system is less dependent on high cost DC circuit breakers.

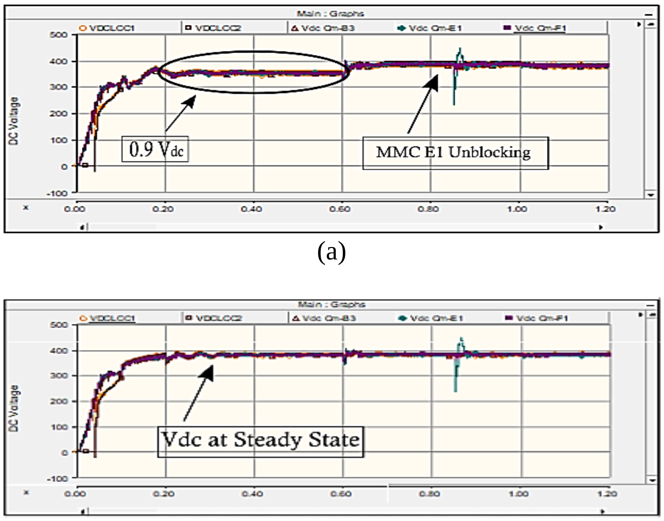
IV. SIMULATION AND ANALYSIS:

The simulations were conducted to investigate the reliability, flexibility and stability of the Hybrid system mainly focusing on the stability and quality of the DC link Voltage.

A. Startup Scheme

Fig. 5 shows the startup graphs of the hybrid HVDC grid. In Fig. 5(a), the DC voltage ramps up to 90% of the rated value at t = 0.2s. At t = 0.6s the rectifier MMC F1 is unblocked, raising the dc voltage to its nominal value. Meanwhile at 0.86s MMC E1 is unblocked, generating a notch for a 0.1s which is balanced at the same time.

Fig.5 (b) shows the system response when DC1 is connected to DC2 via a DC-DC converter which is rated at 400 kV-400 kV so this provides a reference to the Hybrid System due to which system ramps up and reaches its nominal voltage level at t = 0.2s, thus providing quick energization for the hybrid grid.



(a)

(b)

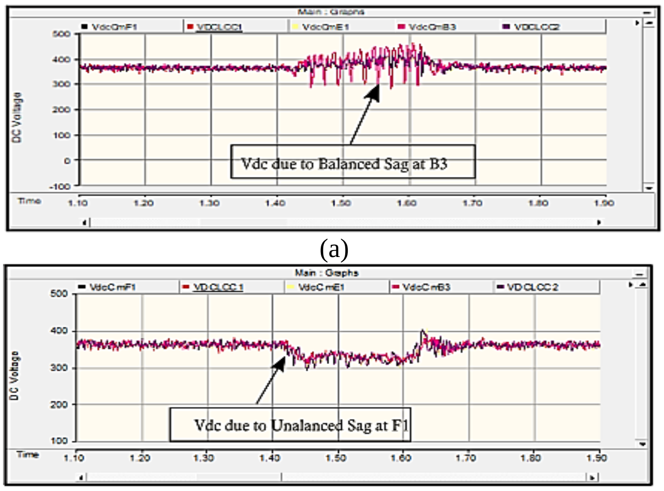
Time (sec)

Fig. 5. DC voltage response during start-up: (a) without inertia (b) with inertia provided by the dc sources.

B. AC Voltage sags

i. AC Voltage Sags at MMC B3 and MMC F1

Fig. 6 illustrates the behavior of the DC voltage during two types of AC faults at MCC inverter B3 and MMC rectifier F1. Two types of AC faults are unbalanced and balanced sags. Fig. 6(a) shows the DC voltage during a balanced sag generated by a three phase to ground fault at AC side of the MMC B3 inverter. The DC voltage sags are strong in strength and average voltage disturbance is 20%. Whereas Fig. 6(b) shows the DC voltage response during a two phase to ground fault that is 70% sag of unbalanced nature in the AC voltage.



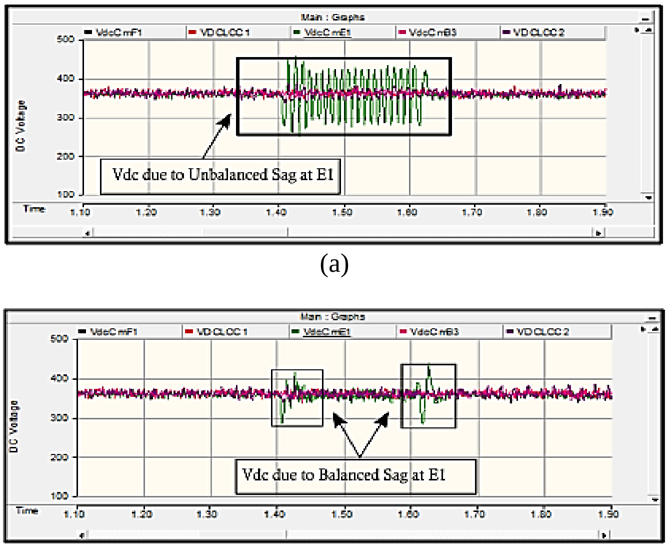
(a)

(b)

Fig. 6. DC Voltage measured at DC2 during (a) 100% AC Voltage sag due to L-L-L-G fault at inverter B3, (b) 70% AC Voltage Sag due to L-L-G Fault at inverter B3,

ii. AC Voltage Sags at Offshore Inverter MMC E1 Connected to a remote Load

Fig. 7 shows the response of the DC voltage during unbalanced and balanced AC faults (sags) at inverter MMC E1. The faults were applied at the AC side of E1 inverter. Fig. 7(a) shows the DC voltage during an unbalanced 70% AC sag, the response of the dc voltage measured at E1 inverter side is severely affected approximately by ±25% distortion, which is very critical for the grid. In comparison with the distortion due to unbalanced fault the effects of balanced ac sag are under limit and quickly stabilized as shown in Fig. 7 (b).



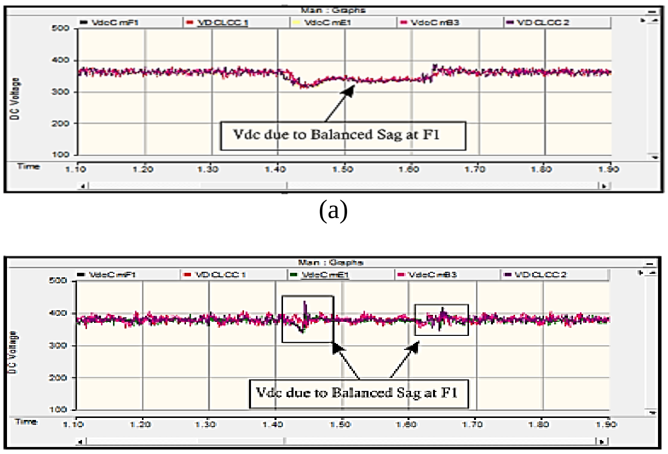
(a)

(b)

Fig. 7. DC Voltage measured during (a) 70% ACs Voltage Sag due to L-L-G Fault, (b) 100% AC Voltage Sag due to L-L-L-G Fault at Load Inverter E1

C. DC Source Integration:

Fig. 8 shows the performance of the DC link voltages at five converters during a balanced AC voltage sag at converter MMC F1, under the impacts of integration of a DC source using a DC-DC converter. Fig. 8 (a) shows the response of the DC voltage during a balanced AC voltage sag at rectifier MMC F1 with no dc source integrated to the hybrid grid. Here dc voltage drops to 20% of the rated value until the fault is cleared and rectifier F1 is unblocked again. Whereas in Fig. 8 (b), due to the inertia delivered by the dc source the dc voltage at converter MMC F1 is less affected.



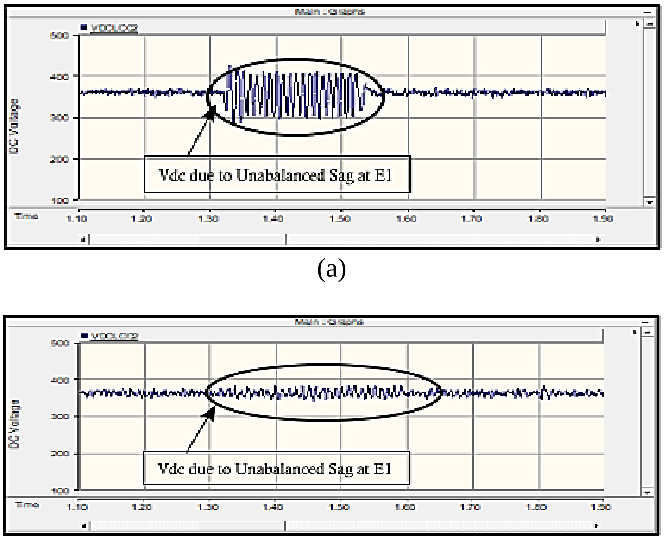
(a)

(b)

Fig. 8. DC Voltages measured (a) during balanced AC voltage sag near F1, (b) during balanced AC voltage sag near F1 with DC source integration,

D. Hybrid Connection Topology

Fig. 9 (a) shows the DC voltage response when inverter LCC is connected to inverter MMC E1 which is supplying power to a load of 100MW. The DC voltage is highly unstable during the sag as compared to the DC voltage response shown in Fig. 9 (b) where inverter LCC is connected to rectifier MMC F1. So it is undesirable to make a hybrid connection using a converter connected to a remote load.



(a)

(b)

Fig. 9. DC Voltages measured (a) Hybrid Connected via Remote area Load Inverter E1, (b) Hybrid Connected via offshore Rectifier F1

V. CONCLUSION

In the startup performance the dc voltage was restored to 100% rated value and quickly energizes the grid. In comparison with the case of impacts of unbalanced two phase AC voltage sags v/s the balanced three phase AC voltage sags on DC voltages at different converters are clearly observed and verified. A DC source was connected to DC system area 2 using DC-DC converter to investigate the performance of the Hybrid system during balanced and unbalanced AC voltage sags. The results therefore concluded that using an inertia source, usually provides a solution to improve not only the stability and reliability of the hybrid system but also reduces harmonics which can be discussed in the future work. A connection topology was also been investigated to improve system reliability under abnormal conditions and simulations reviled that LCC inverter should not be connected to MMC converter E1 connected to a remote area load, as it transmit severe disturbances to the inverter LCC during faults which are responsible for commutation failure.

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