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B4-131

CIGRE 2018

Design Aspects of MTDC Grids with Integration of Renewable Energy Sources

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SUMMARY

The growing concern about climate change has led to large scale integration of Renewable Energy Sources (RES) into power system networks. For integration of large RES, Voltage Source Converter (VSC) based High Voltage Direct Current (HVDC) systems offer the most attractive solution due to the advantages of independent control of active and reactive power, black start capability, lower losses and minimal environmental impact. There is growing interest to integrate of RES into Multi Terminal Direct Current (MTDC) grids rather than connecting by multiple point-to-point VSC HVDC links, for better utilization and enhanced power system security.

It is expected that the MTDC grids perform with same levels of reliability as AC grids and point to point HVDC links. Robust and reliable operation of MTDC grid in cooperation with RES requires that it must have the capability to sustain and ride through the transients due to faults and disturbances in AC/DC systems. Fast protection and control schemes in combination of VSC HVDC Modular Multilevel Converters (MMC) are needed to address this requirement. Half Bridge (HB) MMC together with Hybrid HVDC Breaker (HHB) provides the promising solution for secure DC grid operation for DC side faults. Another important requirement for MTDC grid is to provide Fault Ride Through (FRT) capability for RES such as wind farms in case of ac side faults. DC Chopper plays a crucial role in limiting the dc voltages in MTDC Grid and enables the wind farm to remain in operation during fault conditions.

This paper deals with large scale integration of RES employing VSC HVDC with HHB and DC Choppers to enable stable operation of MTDC grid. Functional aspects of DC breaker and DC chopper are described and their performance for various fault scenarios are analyzed by simulation studies on MTDC grid. Primary and backup protection scheme for HHBs and the application of DC Choppers for fault ride through of wind farms are presented. Further, it is shown that HHB can be utilized for DC line energization there by eliminating the need for Pre-Insertion Resistor (PIR).

KEYWORDS

VSC HVDC, Modular Multilevel Converter, Multi-terminal DC grid, Hybrid HVDC Breaker, DC Chopper, Fault ride through, DC Grid Protection

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1. Introduction

The growing concern about climate change has led to large scale integration of Renewable Energy Sources (RES) into power system networks. Voltage Source Converter (VSC) based High Voltage Direct Current (HVDC) systems has been successfully applied for integration of RES such as offshore windfarms as it is offers lower cost and higher efficiency compared to ac transmission systems but also because of the advantages offered by VSC HVDC technology such as independent control of active and reactive power, black start capability, support to weak ac systems [1]-[2]. Such large scale integrations of renewables using VSC HVDC are gaining interests in North Sea region [3] and China [4].The credibility achieved with point to point HVDC connections is encouraging for realisation of Multiterminal DC Grids (MTDC) in the near future. The added boost for the realisation of MTDC grids also comes with the technology breakthrough achieved with Hybrid HVDC Breaker (HHB) which enables fast interruption of fault current in case of dc faults [5]. For instance, Zhangbei HVDC Grid which is under development in China is planned as a multi terminal DC grid based on VSC HVDC converters, HHBs and RES. The largest converter station in this system is rated at ±500kV/3000MW [6].

It is expected that such MTDC grids perform with same levels of reliability and flexibility as existing AC grids and point to point HVDC links. Robust and reliable operation of a MTDC grid in cooperation with renewable energy sources requires that the MTDC grid must have the capability to sustain and ride through the transients due to faults and disturbances in AC/DC systems. Fast control and protection schemes in combination with DC Breakers such as HHB are needed to address this requirement [7]. Use of Current Limiting Reactors (CLR) helps to limit the rate of rise of fault current until the time the protection acts and sends the trip signal to HHB [8]. This is essential in order to reduce the rating and cost of HHB employed in MTDC grids. Besides providing fast interruption, HHB can also assist in auto reclosing of faulted line. Since majority of the faults in the transmission system with Overhead Lines (OHL) are temporary faults, it is desirable to re-energize the disconnected line automatically after the fault has been cleared to restore the power transmission as soon as possible. It is an important aspect for ensuring the reliable operation of MTDC grid. It is shown in [9] that HHB with such auto reclosing feature reduces the stress on the converter and minimizes the disturbance in the connected ac system. There is another important feature of HHB which has been studied in this paper is related to energization of line. The simulation results presented in section-3 illustrates that HHB can be utilized to perform line energisation in MTDC grid and there is no need of additional equipment such as Pre-Insertion Resistor (PIR) and bypass breaker to reduce the inrush current and overvoltage during energisation.

The protection strategy in MTDC grids plays a vital role in handling dc faults and is required to be fast enough that the disturbances are localised and isolated within short duration. The protection also has to be robust to handle the primary protection failure so that the backup protection is immediately available [10]. This can limit the widespread effect of disturbance in the MTDC grid. HHB with bidirectional current breaking capability is able to provide backup protection operation for fault current interruption in either direction. The backup protection operation using bidirectional HHB is studied and the simulation results are discussed in section-4 of this paper.

With integration of wind farms with large power ratings in MTDC grids, DC choppers are required to provide Fault ride-through (FRT) capability of wind farms in HVDC links [11]. As the planned connection capacities of wind farms are very large, the design of DC chopper at multiple locations in MTDC grid calls for appropriate control and coordination in their operation so as to achieve desired performance. An attempt in this regard is made and detailed simulation study is presented in section-5 of this paper.

2. Test system considered for the study

A typical four terminal bipole MTDC grid as shown in Figure 1 at transmission voltage of ±500 kV is considered for the purpose of study. The converters are of half bridge MMC topology. Rated power of converter S1, S2 is 3000 MW and converter S3, S4 is 1500 MW. The converter stations are connected by OHLs. Each transmission line is equipped with HHB on either end. The HHB considered in this study is proactive type of DC breaker proposed by ABB [5]. As described in [5] the main breaker section of HHB is composed of several modules that are connected in series to obtain the required transmission voltage level and has current breaking capability in both directions. Current limiting reactors (CLR) are placed on the line side of HHB, to limit the rate of rise of fault current for dc faults. This system is considered to have large integration of RES at the converter stations S1 and S3, whereas the converter stations S2 and S4 are connected to the ac grid. DC choppers are connected at the stations S1 and S3 to provide FRT capability to the wind farms. Detailed simulation studies are carried out on this test system in PSCAD and the results are discussed in the forthcoming sections of this paper.

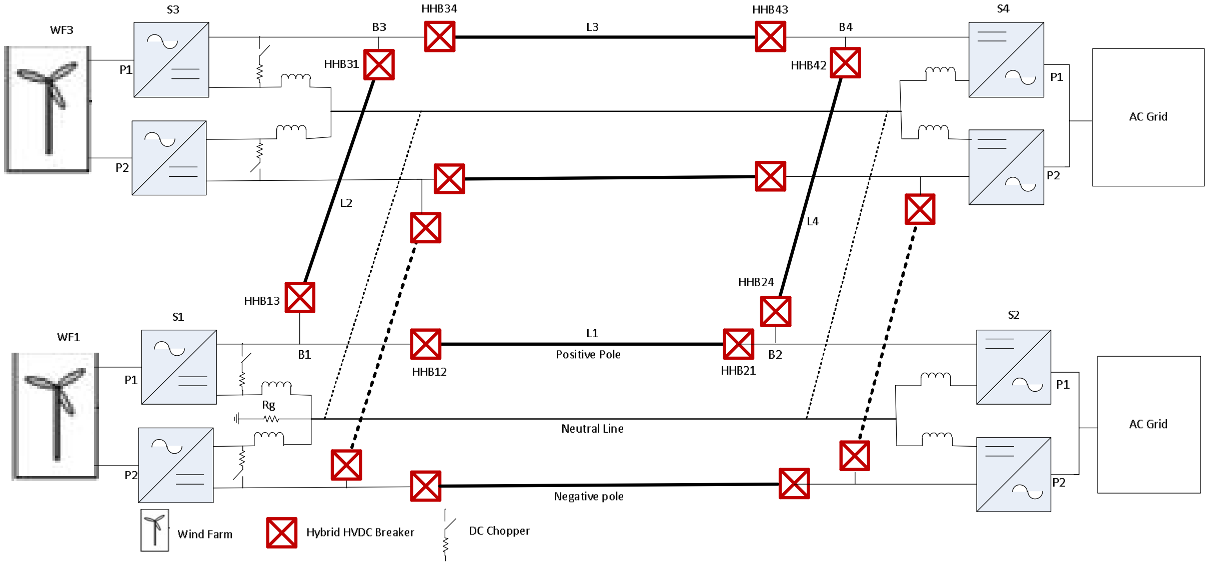


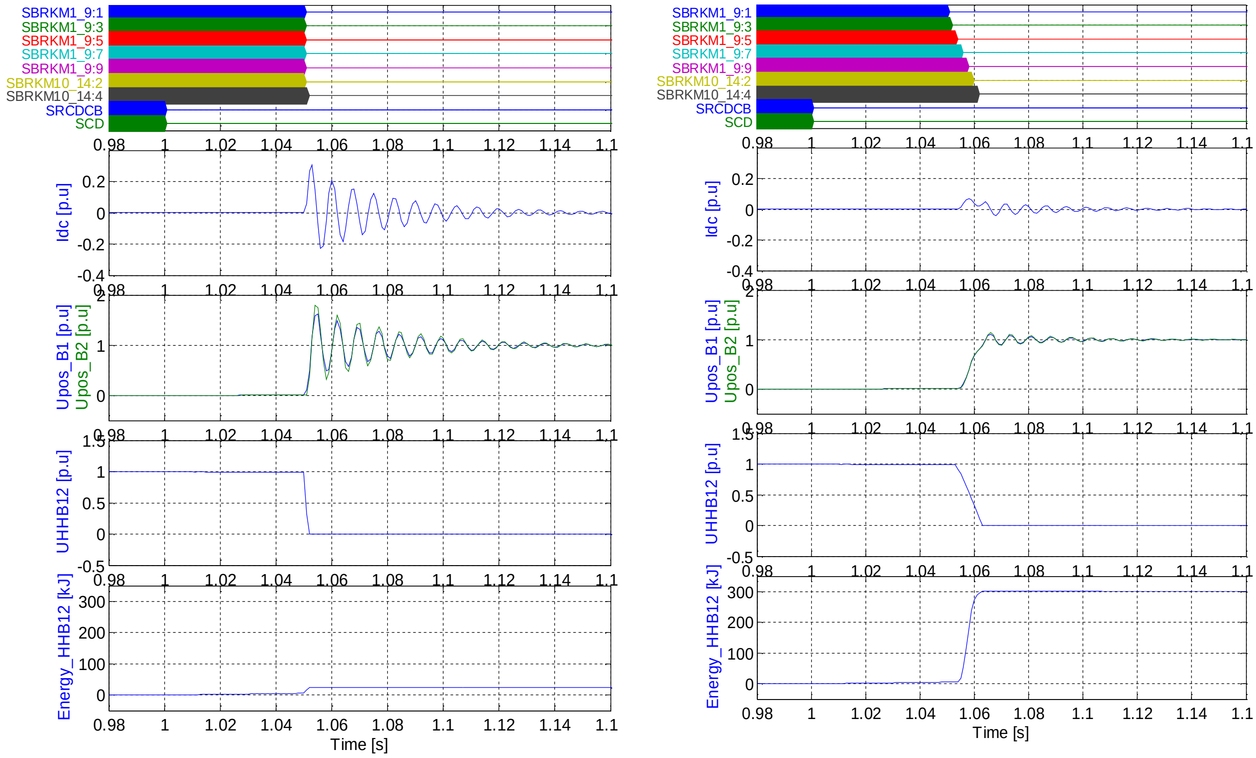
Figure 1 Four Terminal MTDC study system

3. DC Line Energisation

In this section the use of HHB for DC line energization is discussed. Considering the MTDC system shown in **Figure 1**, it is assumed that initially all the HHB modules in all the converter stations are in open condition and all the lines are in de-energized state. For the purpose of study, energization of the line L1 is considered by closing the dc breaker HHB12. As HHB has a modular structure, the main breaker modules can be closed in sequence with pre-defined time delay such that the inrush current through HHB can be minimized, there by the magnitude of overvoltage on the line being energised and the disturbance to the connected ac system is limited. The objective of this paper is to evaluate and propose an appropriate operating sequence of HHB modules, for line energisation and to show how HHB can eliminate the need for dc-side pre-insertion resistor.

First the converter S1 is deblocked in DC voltage control mode to bring the converter dc voltage to the rated value. Next the line disconnector of HHB12 is closed. Now the line is ready for energization by operating the dc breaker HHB12. By sequentially closing the main breaker modules with a specified time delay between two successive modules, the voltage over HHB is step-wise decreased which results in gradual build-up of dc voltage at the line-side. In this paper, line energization is studied with two different module closing delays of 100 µs and 1 ms and the simulation results so obtained are compared in **Figure 2**.

The simulation starts with closing of the disconnectors of HHB12 at t=1 s and 50 ms later the HHB modules starts closing with specified time delay between successive modules. It is observed that with smaller closing delay of 100 µs, the overvoltage at line termination reaches to about 1.80 p.u due to reflection at the open end, and the inrush current through HHB is around 0.30 p.u. whereas with a time delay of 1 ms between the closing of each of the modules of HHB, the overvoltage at line termination is around 1.14 p.u and the inrush current is around 0.07 p.u. However the arrestor energy dissipation is much higher in the latter case which is around 300 kJ as the arrester across the main breaker modules are inserted for longer period due to longer closing delay between the modules. Thus it is clear that with appropriate sequence design, HHB can be used to reduce inrush current through the converter valves and transient overvoltage at the line termination during OHL energisation.



(a) 100 µs time delay (b) 1 ms time delay

Figure 2: DC line Energisation by HHB12 with 100 µs and 1 ms delay between closing of each HHB module
*Plot1 : Main breaker module status (*SBRKM*) and disconnector status (*SCD, SRCDCB*) of HHB12*
Plot2 : DC current through HHB12 ; Plot3 : DC voltage in the positive pole at bus B1 and B2
Plot4 : Voltage across HHB12 ; Plot5 : Energy stress at the arrestor of HHB12

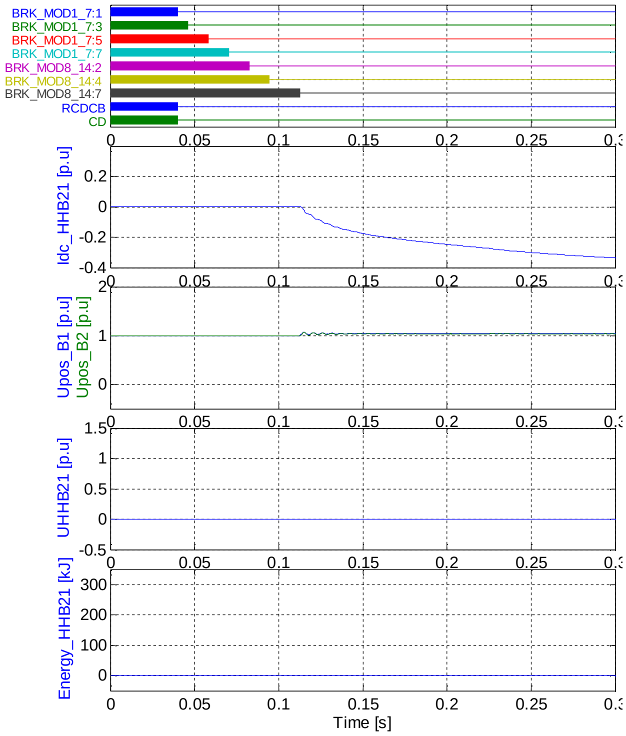


Figure 3 Station connection to an energised line
*Plot1 : Main breaker module status (*BRKM) *and disconnector status (*CD, RCDCB*) of HHB21*
Plot2 : DC current through HHB21 ; Plot3 : DC voltage in the positive pole at bus B1 and B2
Plot4 : Voltage across HHB21 ; Plot5 : Energy stress at the arrestor of HHB21

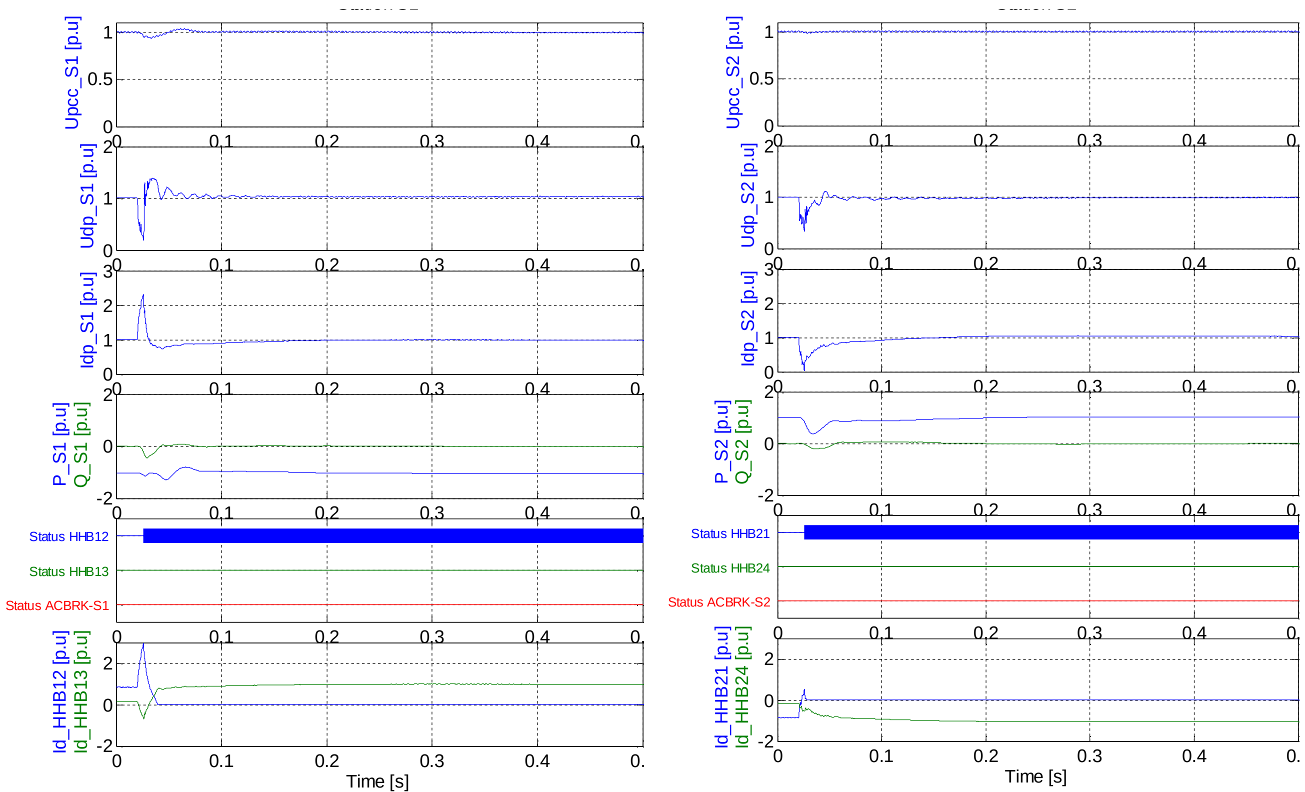
As next step, the energised line L1 is connected to the energised converter station S2 by closing the dc breaker HHB21 at 0.11s.The simulation results for this operation are presented in **Figure 3**. It may be noted that there are no significant transients observed in this case as the voltage across HHB21 is very less compared to energising to an open line. After all the modules of HHB21 are closed and based on the operating mode of converter in the MTDC grid, the power flow is established in the energised dc line L1. The above simulation results clearly demonstrates the importance of having an appropriate design sequence for HHB in reducing inrush current and overvoltage at the line termination during line energisation sequence. Further it can be understood that there is no need for additional equipment like Pre-Insertion Resistor (PIR) and bypass breaker, as HHB is able to perform line energisation satisfactorily, in MTDC grids.

4. Protection Design for DC Faults

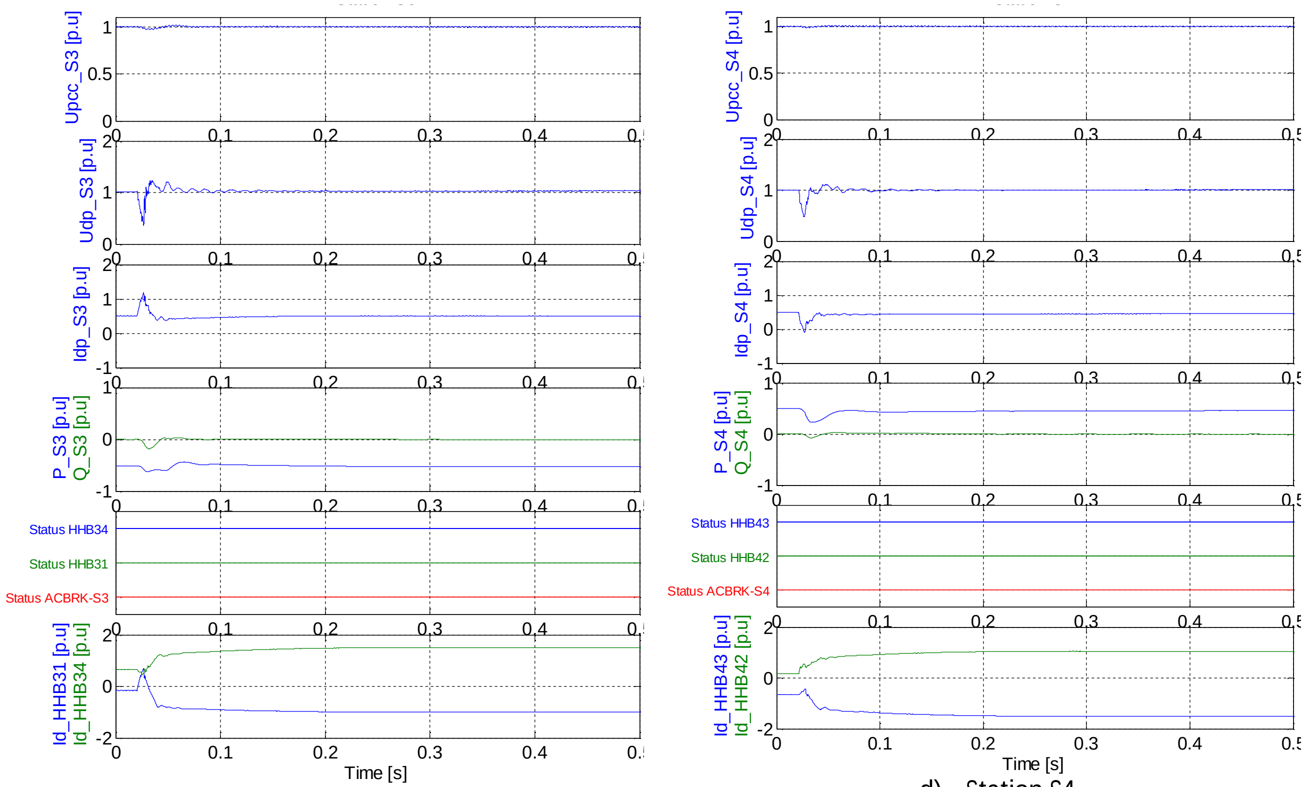
A fault in a DC Grid gives rise to significant overcurrents quickly due to low impedance in the DC network. Hence the faults should be detected and cleared in a very short time before it causes damage to the system or equipment due to excessive overcurrent. HHB plays a vital role in fast interruption of the fault currents and ensures reliable operation of MTDC grids. Besides current limiting reactor (CLR) of HHB, line protection design are also equally important for fault current limitation and fault detection respectively. Current limiting reactor has to be selected such that, the fault current is limited within the breaking capability of HHB for a given breaking time of the HHB. The primary line protection must also be supplemented with suitable backup protection scheme to ensure reliable and selective fault detection and isolation of faulted line. In the event of failure of primary protection or HHB failure the backup protection is activated to limit the spread of disturbance throughout the MTDC grid. In order to demonstrate the coordination of primary and backup protection and its impact on the system behavior, two scenarios of dc pole to neutral fault interruptions are studied and the results are discussed in this section.

Consider a dc positive pole to neutral fault initiated at t= 0.02 sec in the transmission line L1, close to the station S1. The primary protection at the respective stations S1 and S2 detect the fault and issue trip signal to the breakers HHB12 and HHB21. In this case the fault detection time by the primary protection depends on the distance to the fault location from the respective stations. On receiving the trip signal, HHB12 and HHB21 interrupt the fault current and isolate the faulted line L1 from rest of the system. Results for this case are presented in **Figure 4**. It can be observed that the MTDC system is subjected to disturbance for a short duration only until the HHBs isolate the faulted line. Slower the speed of protection and operation of DC breaker, longer will be the disturbance in the MTDC grid.

In another scenario, failure of primary protection namely, HHB12 is considered. When HHB12 fails to open, breaker failure alarm is generated. There after the protection system triggers the backup protection operation and sends trip signals simultaneously to the backup breakers HHB13 and AC breaker of station S1. Results for this case are presented in **Figure 5**. It can be observed that HHB13 opens to isolate the fault on the dc side. However the fault current continues to be fed from the ac side of S1 until the AC breaker opens. The dc voltage controlling station S4 now assists in restoring the power balance in the MTDC grid by changing its mode of operation from inverter to rectifier to cater to loss of station S1. It is observed that in this case station S1 experiences the disturbance on its connected ac network for the duration until its AC breaker is opened where as the extent of disturbance on MTDC network is minimized with the help of suitable backup protection design.



a) Station S1 b) Station S2



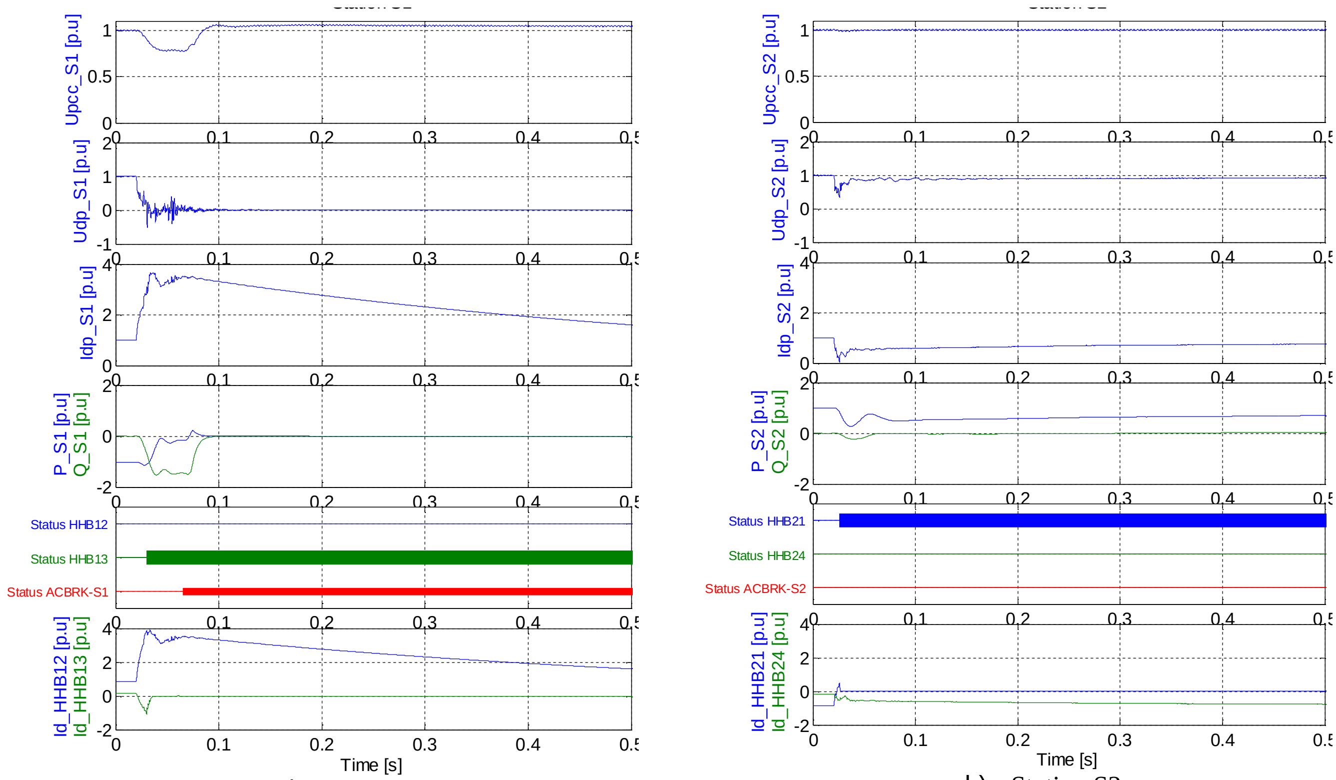
c) Station S3 d) Station S4

Figure 4 : Fault clearing by primary protection

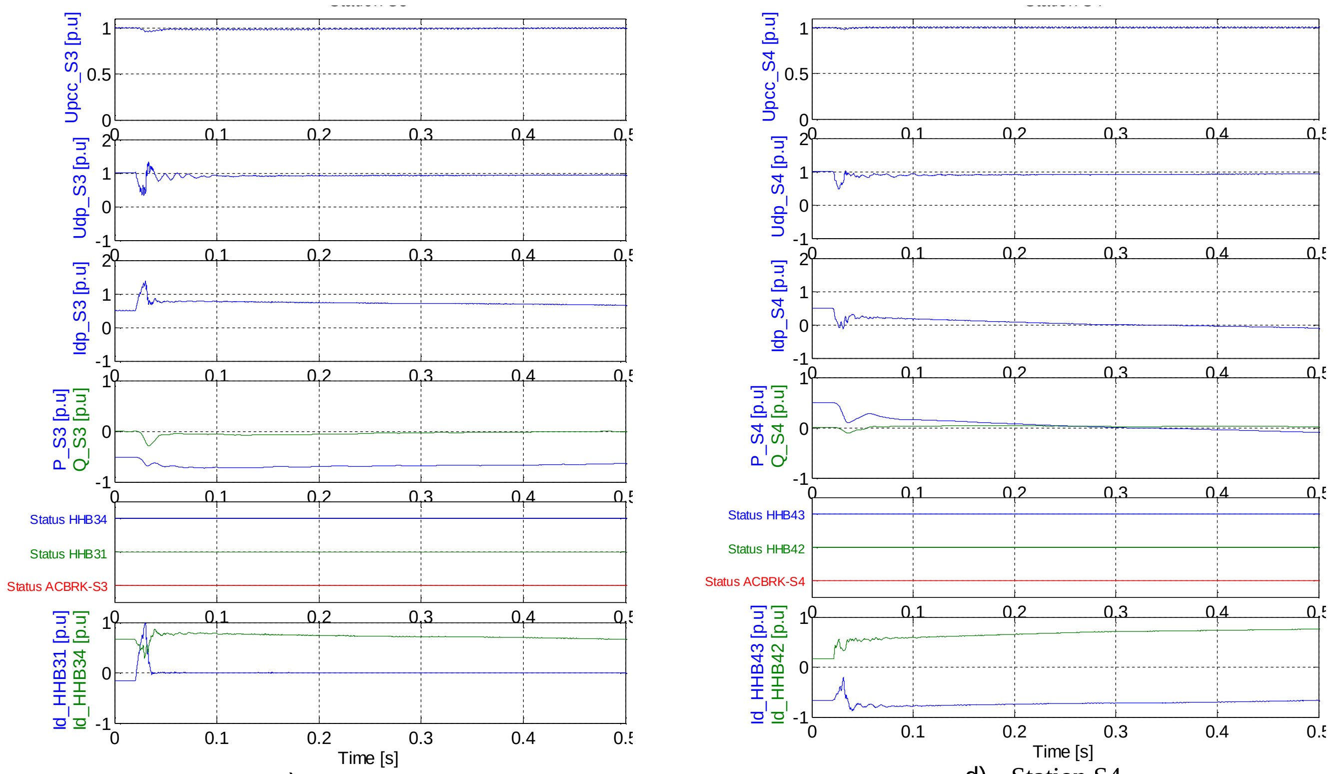
Plot1 : PCC voltage *Plot2 : DC positive pole voltage*

Plot3 : DC current in positive pole *Plot4 : Real and Reactive power exchange with the ac system*

Plot5 : Status of HHB and AC breaker *Plot6 : Current flow in HHB*



a) Station S1 b) Station S2



c) Station S3 d) Station S4

Figure 5 : Fault clearing by secondary protection

Plot1 : PCC voltage *Plot2 : DC positive pole voltage*

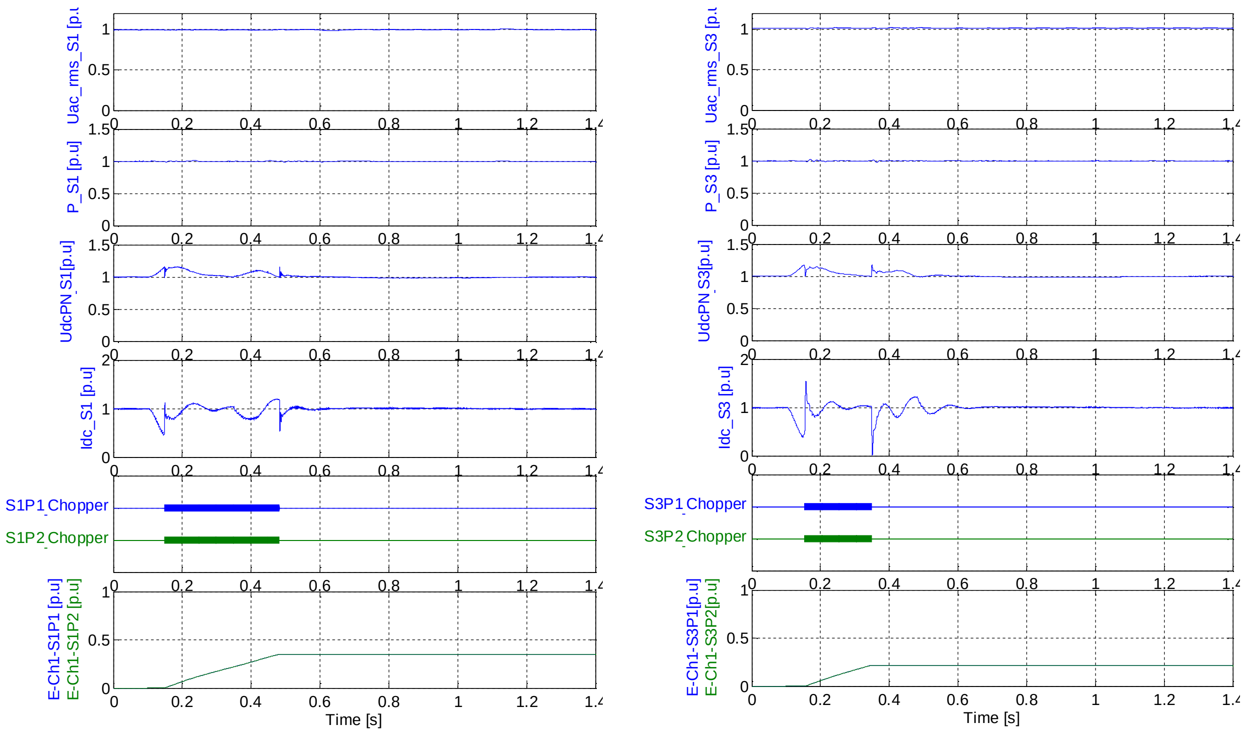
Plot3 : DC current in positive pole *Plot4 : Real and Reactive power exchange with the ac system*

Plot5 : Status of HHB and AC breaker *Plot6 : Current flow in HHB*

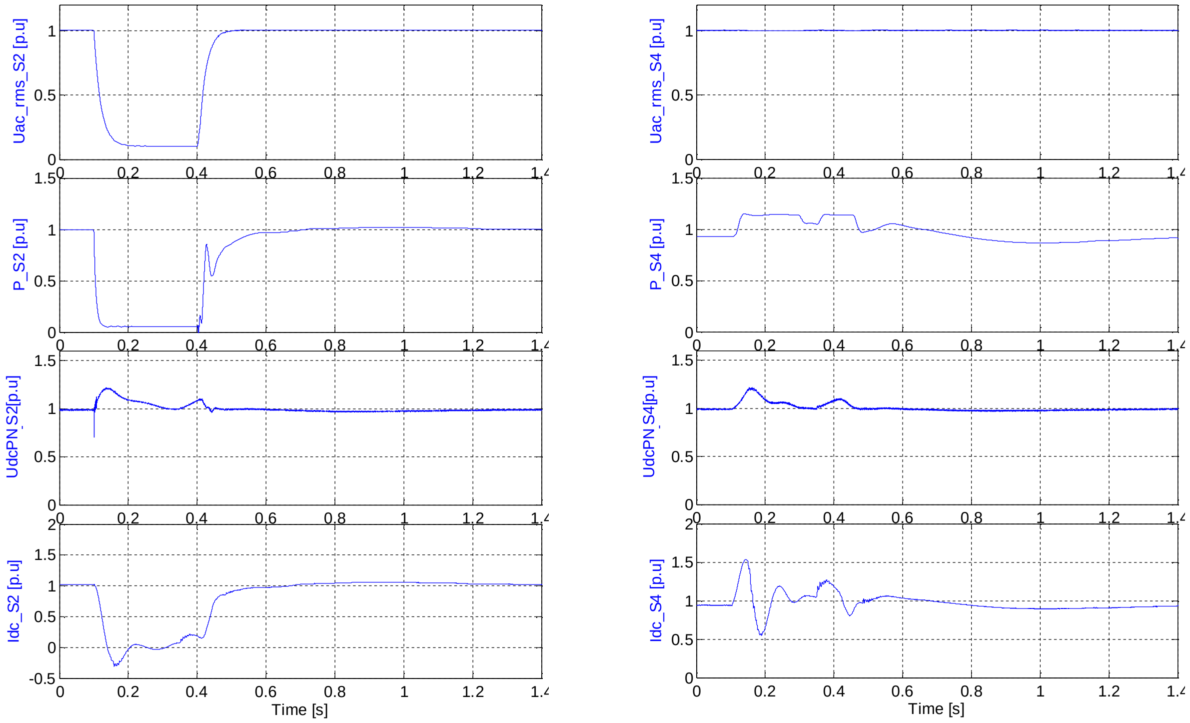
5. Fault Ride-Through (FRT) of wind farms in MTDC systems

An important aspect of MTDC grid integration with RES is that in the application of the wind power connection the VSC HVDC converter is responsible for controlling the voltage and frequency of the wind farm. Some situations arise when surplus power cannot be evacuated in time by the converter (for example power capability of one converter is reduced or completely lost due to external AC faults) and on the other hand power generated by the wind farm cannot be reduced instantaneously. This leads to accumulation of the excess energy in converter cell capacitances of rectifier station resulting in over voltages on the converter. In such case DC Chopper plays a crucial role in limiting the over voltage in MTDC Grid by dissipating the excess power in the chopper resistance for a short time before the control actions take over and reduce the power input to the rectifier station. DC Chopper is basically a resistor in series with IGBT switches connected pole to ground. This scheme is quite common in case of HVDC links connected to off-shore wind farms where DC Choppers are installed at the onshore / inverter station to provide FRT for ac side faults. Studies with single chopper have been dealt in the past for point to point HVDC configurations [12]-[13] and also MTDC grids [11]. In this paper rating and operation aspects of multiple choppers in MTDC grids are studied.

In point to point HVDC configurations, a chopper is rated equal to converter rating to dissipate the unbalance power during the fault. One advantage that can be leveraged through MTDC grid is that it is not required to design the chopper for full converter rating at each station. Choppers installed at different stations with combined rating equivalent to highest inverter station rating can be utilized since the maximum energy unbalance that can occur in the MTDC grid is the loss of highest rated inverter station for a fault in the AC grid. In the four terminal MTDC grid shown in Figure 1, DC choppers are connected at rectifier stations S1 and S3 with combined rating equal to station S2 which being the highest rated inverter station. Stations S1, S2 and S3 are operated in power control mode and S4 is in DC voltage control mode. **Figure 6** shows the results for a 3 phase to ground fault (initiated at t=0.1s for a duration of 300ms) at the ac side of station S2. From the plots it can be observed that the choppers at station S1 and S3 absorb the excess power and control the DC voltage within the acceptable limits. The disturbance at inverter station is not reflected on to rectifier stations, enabling the MTDC grid to ride through the ac fault which is the primary objective of deploying the choppers in the system. In addition to that, station S4 which is in DC voltage control mode also evacuates a portion of the excess power within its rated capacity. Once the fault is cleared, the DC choppers turn off based when the dc voltage goes below preset level and station S2 restores to its pre-fault power and entire MTDC grid resumes normal operation.



a) Station S1 b) Station S3



c) Station S2 d) Station S4

Figure 6 : DC Chopper operation in MTDC Grid for 3 phase to ground fault on AC side of inverter station S2
Plot1 : Uac_rms_sx : Grid side AC voltage for respective stations
Plot2 : P_Sx : Real power measured at station Sx
Plot3 : UdcPN_Sx : DC pole to neutral voltage
Plot4 : Idc_Sx : DC pole current
Plot5 : Sxpy_Chopper : Chopper status connected at station Sx on Pole y
Plot6 : E-Ch1-SxPy : chopper energy which is at station Sx connected to Pole y

6. Conclusion

Some of challenges in integrated operation of renewables with VSC HB MMC with HHB and DC chopper are discussed in this paper. The simulation results demonstrate that HHB is a key enabler in realization of MTDC grids. An appropriate sequence design for operation of HHB at line energization is essential to limit the overvoltage at the line termination and reduce inrush current in the converter valves. This can eliminate the need for installation of additional equipment like Pre-Insertion Resistor (PIR) and Bypass Breaker. It is also shown that with suitable design and coordination of DC chopper at different stations, for large integration of RES, can limit the overvoltage and will be effective in achieving successful fault ride through capability for wind farms connected to MTDC grids.

Further it is shown that with appropriate primary and backup protection design the disturbance in MTDC grid and connected ac system can be minimized. Thus it is demonstrated in this paper that a more flexible and reliable operation of MTDC grids with VSC MMC HB with HHB and DC Chopper is possible, even with large scale integration of RES, with appropriate design considerations.

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