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Advanced Fault Ride for VSC- HVDC Connecting Off-Shore Wind Farms

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Abstract:
This paper proposes a novel configuration and transient management scheme for Voltage Source Converter- High Voltage Direct Current (VSC-HVDC) connecting Large Scale Wind Farm (LSWF). The proposed configuration aims to fully utilize the HVDC converters with shunt and series reconfiguration during steady state and fault conditions respectively. Thus, it targets the employment of the available converters controls capabilities to enhance the Fault Ride-Through (FRT) performance of the VSC-HVDC and achieve smooth power evacuation to the electric grid. The control strategy is built in such a way to guarantee three factors: 1) Enhancing the voltage profile of the electrical grid during symmetrical and asymmetrical grid faults.
Keywords: *Fault Ride, VSC-HVDC, Off Shore Wind Farm, Fault Ride-Through, WIND FARMS, HVDC Transmission, HVDC System*

I. Introduction

Background

The offshore WFs are becoming increasingly popular due to several advantages over the currently predominant onshore wind farms. By 2030, Europe plans to have an installation of 120 GW offshore wind power out of the expected 300GW total wind power installation [1]. For the transmission distances over 100 km, the VSC based HVDC systems are considered to be the best solution to transfer offshore wind power to the main onshore grid [2], [3]. One of the most important aspects of the VSC-HVDC connected offshore WF system operation is the wind power evacuation during onshore AC grid faults. During such faults, the whole power supplied by the WF cannot be injected into the grid as the voltage in the onshore converter terminal experiences dip. The wind power, which is still being delivered to the DC link by the offshore converter, is being accumulated in the DC capacitors. This causes the voltage across those capacitors to rise. If the DC overvoltage exceeds certain threshold (usually 5-10 %), the converter and other equipment can be significantly damaged.

Due to the increment in electricity demand and the increased concern for the environ –mental impact of the conventional fossil fuel sources, a number of new generation technology, such as wind power, solar photovoltaic, tidal power, wave power, and biomass, have been developed. Among these renewable energy sources, wind energy is high-lighted because of its fast development in the last 25 years. The total wind power installed around the world has reached 369.557 GW at the end of 2014 [1]. Only in European Union (EU) annual installations of wind power have increased over the last 14 years, from 3.2 GW in 2000 to 11.8 GW in 2014 at a compound annual growth rate of 9.8% shown in Figure 1. The majority of the wind turbines have been installed onshore, but the large-scale expansion of onshore wind is limited by factors such as the land use and visual impact [2]. Therefore, offshore wind farms (OWFs) have shown a rapid development. Moreover, the offshore mean wind speed is higher than that in onshore sites and the turbulence is much lower[3]. All these factors have made offshore wind installation rise significantly through the years. Figure 2 shows the growth of offshore wind power from 2000, and it is projected till 2030.OWFs are usually located far from load centres. Therefore, long transmission cables are required. Moreover, the capacity of these wind farms becomes larger and larger. For such offshore network, where large power will be transmitted over long distance, application of high-voltage alternating-current transmission (HVAC) technology may not be feasible [6]. The reason behind is that with increasing transmission distance, the reactive power flow will be higher due to line capacitances, which will result in large line losses [7].

Thus, an alternative is to use high-voltage direct-current transmission (HVDC) technology. There are two HVDC technologies, i.e. current source converter (CSC) HVDC and voltage source converter (VSC) HVDC. CSC uses line-commutated switching device, which has some limitations, for example it needs reactive power compensation devices resulting in a bulk converter station. Modern HVDC transmission systems use VSC, which is self-commutated device. This means that in VSC, the current can be made lag or lead the ac voltage, so the converter can consume or supply reactive power to the connected ac network eliminating the reactive power compensation devices [8]. It can also make it possible to control the active power and reactive power independently. Furthermore, 1 to 2 kHz high switch frequency of pulse-width modulation (PWM) reduces the filtering requirements and power flow can be reversed without the need to reverse the dc-link voltage. All these advantages show VSC is good option for HVDC transmission.

Problem Description

When an OWF is connected to main grid through VSC-based HVDC, the HVD Cvoltage is controlled by the onshore HVDC converter which transfers the power to the onshore ac network. When a fault occurs at the ac grid, the onshore converter is unable to transmit all the active power to the ac grid, but OWF still inject active power to offshore converter, which will result in power imbalance between onshore converter and offshore converter shown in Figure 3. The resulting power imbalance will charge the capacitance in the dc-link. Without any actions, this will result in a fast increase of the dc voltage, which may damage the HVDC equipment. Therefore some strategies should be taken to regulate the power imbalance. LSWF connected via VSC-HVDC to electric grid faces many challenges during FRT operation such as DC link overvoltage, great reduction of power delivery, mechanical stresses on offshore wind turbines, and severe DC link oscillations in case of unbalance grid operation. The afore mentioned challenges can fully or partially exist depending on the deployed FRT scheme and control strategies in VSC-HVDC.

WIND FARMS

A "wind farm" is a group of wind turbines in the same location used for production of electric power. Individual turbines are interconnected with a medium voltage power collection system. At a substation, this medium-voltage electrical current is increased in voltage with a transformer for connection to the high voltage transmission system. A large wind farm may consist of a few dozen to several hundred individual wind turbines, and cover an extended area of hundreds of square mile (square kilometres), but the land between the turbines maybe used for agricultural or other purposes.

TYPES OF WIND FARMS

* On-Shore * Off-Shore * Near-Shore * Air borne

Figure 1: Types of Wind Farm

OFF-SHORE WIND FARM

Off shore wind farms is also called as floating wind parks. Floating wind parks are wind farms that site several floating wind turbines closely together to take advantage of common infrastructure such as power transmission facilities. A floating wind turbine is an offshore wind turbine mounted on a floating structure that allow the turbine to generate electricity.

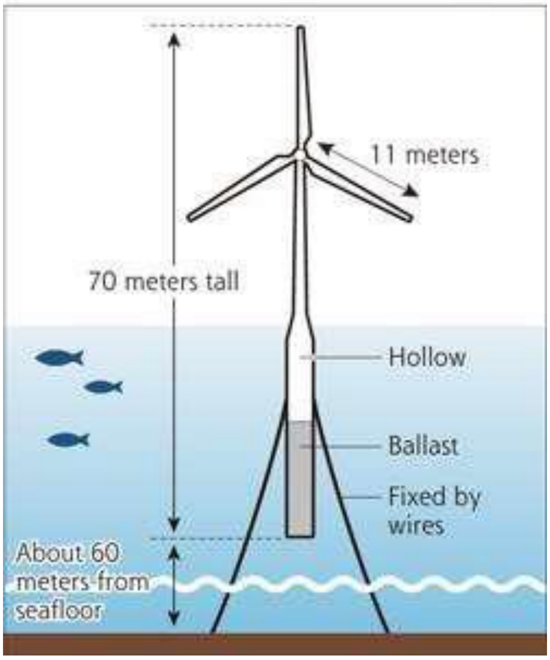

Figure 2: OFF-SHORE WIND FARM

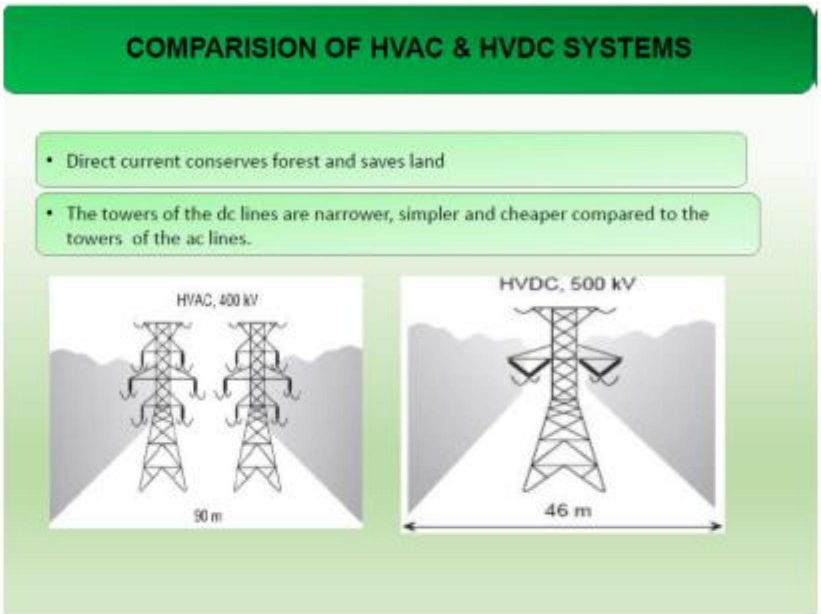

Figure 3: Comparison of HVAC & HVDC System

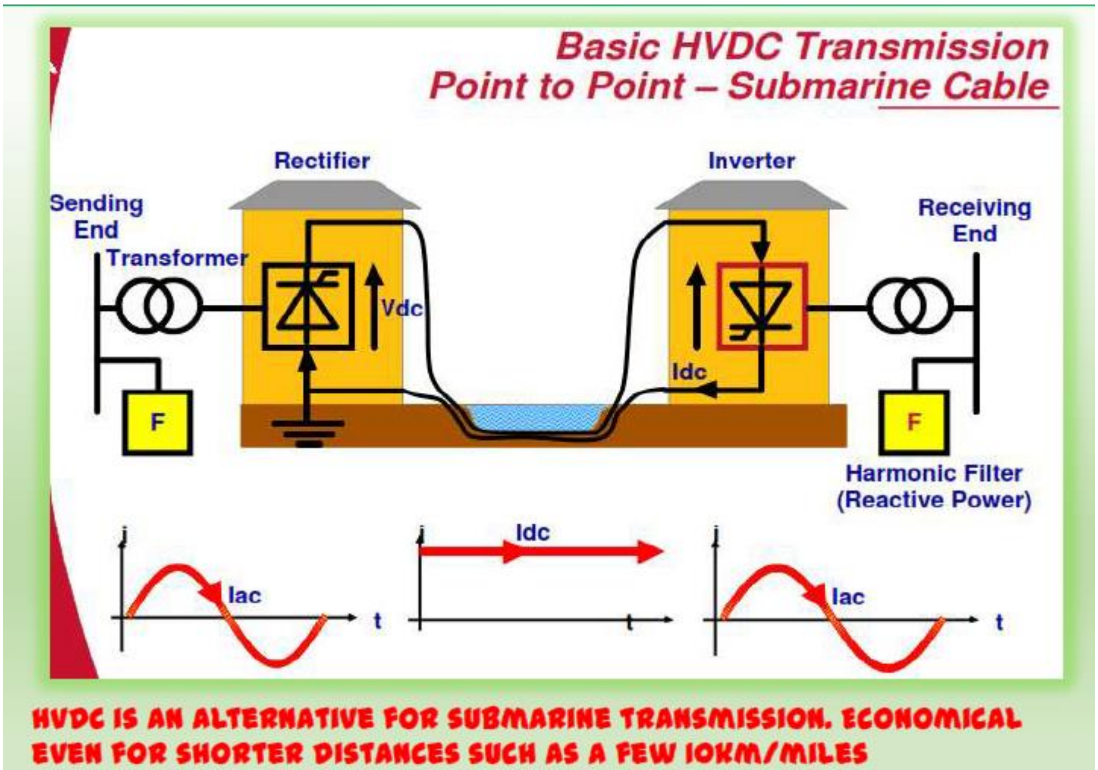

Figure 4: HVDC Transmission Point to Point- Submarine Cable

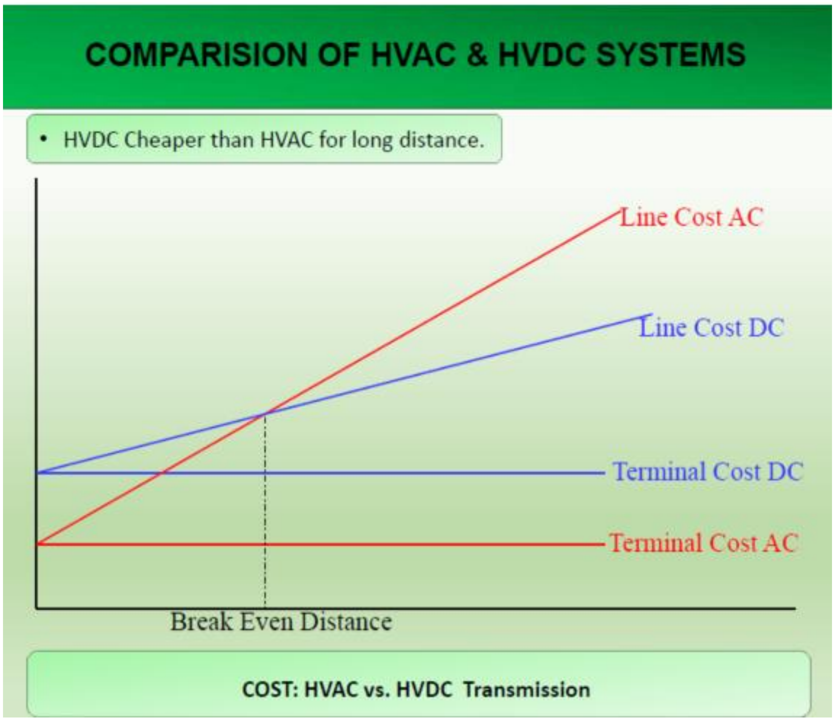

Figure 5: Comparison of HVAC & HVDC System

Characteristics and Advantages of VSC

Current source converter (CSC) uses thyristors. Thyristors can only be turned on by control action, and rely on the external ac system to provide turn-off action. This limits the usefulness of HVDC in some circumstances because it means that the ac system to which the HVDC converter is connected must have synchronous machine in order to provide the commutating voltage [9].Other types of semiconductor devices, such as insulated-gate bipolar transistor(IGBT) and gate turn-off thyristor (GTO), can be both turned on and turned off by control action. As a result, IGBT can be used to make self-commutated converters, which is also called VSC.

More and more HVDC systems adopt VSC. Compared with classical HVDC, which uses CSC, VSC based HVDC has many advantages [10].•With PWM technology, VSC can control the magnitude and phase angle of ac side voltage. This allows VSC-HVDC system to independently control both active power and reactive power flow within the operating range of VSCHVDC system.

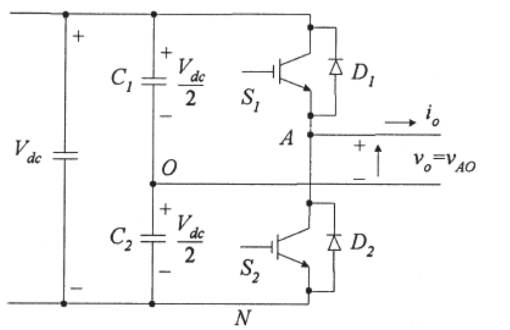

Figure 6: single-phase half bridge VSC circuit

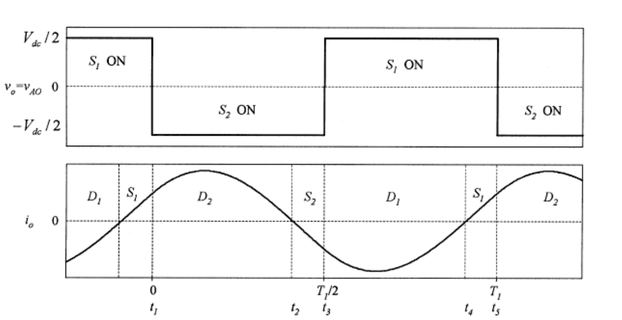

Figure 7 : Waveform of Single phase half bridge VSC circuit operation

There are two distinct modes of operation associated with the transfer of power from the dc to the ac side. When the power flows from the dc bus to the ac side, the converter operates as an inverter. In the case that the power is negative which means power is returned back to the dc bus from the ac side, the converter operates as a rectifier [11].

Figure 6 shows single-phase half bridge VSC circuit, but the work principle of three-phase six-step VSC is the same. In three-phase six-step VSC, there are six switches *S*1-*S*6 and six antiparallel diodes *D*1-*D*6 organized in three legs. The number of the switches indicates their order of being turned on. Each of the switch remains on for 180◦and every 60◦a new switch is turned on and the one in the same leg is turned off.

SYSTEM CONFIGURATION FOR OFFSHORE WPP
CONNECTED THROUGH VSC-HVDC

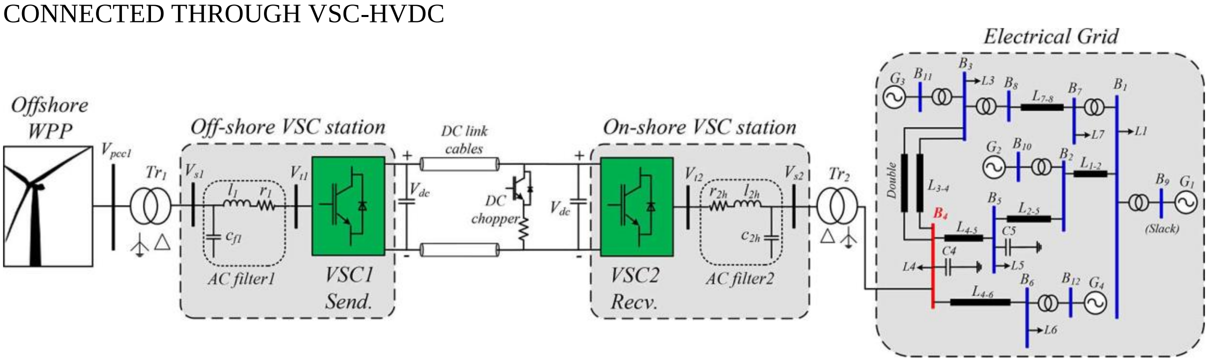

Figure 8: Configuration of a conventional VSC-HVDC system connected to IEEE-12 Bus system.

The conventional system configuration is demonstrated in Fig. 8, to illustrate the interconnection of LSWF through the VSC-HVDC transmission system. The wind power is converted from AC to DC by the offshore VSC station and transmitted to the onshore VSC station through the HVDC link, which is Equipped with DC chopper. Without losing generality, a standard IEEE 12-bus system is employed to represent the electric grid, where the bus; B4 is considered as the point of common coupling (PCC). The shunt transformer; Tr2 is the link between the onshore VSC station and the PCC. From the PCC, the power is dispatched into the grid through the lines, L3-4, L4-5 and L4-6 shall be capable to handle the rated power that is delivered from the onshore VSC station.

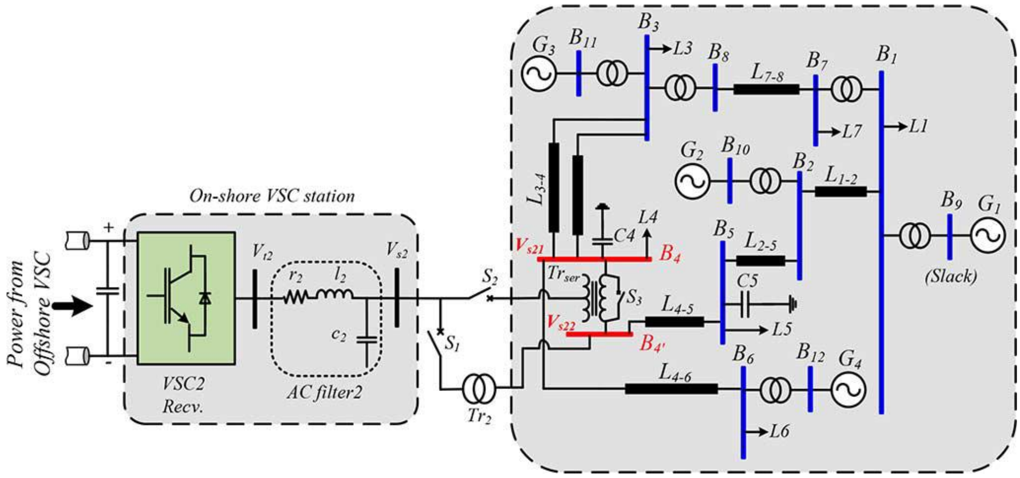

Figure 9: The new configuration of U-VSC-HVDC system.

Figure 9 shows the proposed configuration, which includes both series and shunt interfaces to the grid. In this case the DC Chopper is removed from the HVDC system. The power that is transmitted from the LSWF is also dispatched into the electric grid through the lines, L3-4, L4-5 andL4-6. Hence, the new adopted configuration illustrates a practical solution that neither significantly changes the original network, nor implements additional converter. The components that are added to the new config -uration include the series transformer (Tr ser) , and three electronic switches, S1,S2 and S3 , which provide the path for series injection during fault conditions. The shunt connection is activated during normal operation through the path of S1 and Tr2, which is linked to Vs22 and also selectively connected to the grid through to S3 ,to Vs21as shown in Fig. 9. In normal operations, the series Trans -former is disconnected by opening the switch S2 and closingS3. To illustrate the normal and fault operation of the proposed configuration. Fig. 3 demonstrates the states of power flow from the connection point of Vs2 into the electrical grid during steady state and fault conditions. The recon -figuration can be achieved by the combination of opening and closing of the three switches S1,S2 and S3. [12-15]

Control Structure of the Shunt Connection of the Onshore And /Or Offshore VSC Station

Shows the control diagram of the onshore and/or offshore VSC station. These detailed control loops are shown for the onshore VSC; however they can be applied for the offshore VSC as well. The measured voltages and currents are filtered out before controlling them, and they are used to determine the reference for positive sequence controller and – for the negative sequence controller. The positive and negative PLL angles are used to extract the positive and negative dq components, respectively. In this controller, the onshore VSC is used to regulate the PCC and DC link voltages; however the offshore VSC is utilized to control the offshore grid voltage and to inject wind farm active power. During fault conditions, the main goals for the onshore VSC station are as follow: a) supporting the PCC voltage of the electrical grid during steady state and transient conditions; b) mitigating the oscillatory active powers and DC voltage ripples caused by asymmetrical grid faults, c) providing smooth power delivery from the HVDC system to the electrical network. During asymmetrical faults, negative sequence components are produced. These components generate oscillatory powers and may cause severe DC voltage ripples that can trigger the DC overvoltage protection. To minimize these power oscillations and the corresponding DC link voltage ripples, the reference direct and quadrature components of the negative sequence currents required to mitigate DC link and power oscillations. [16]

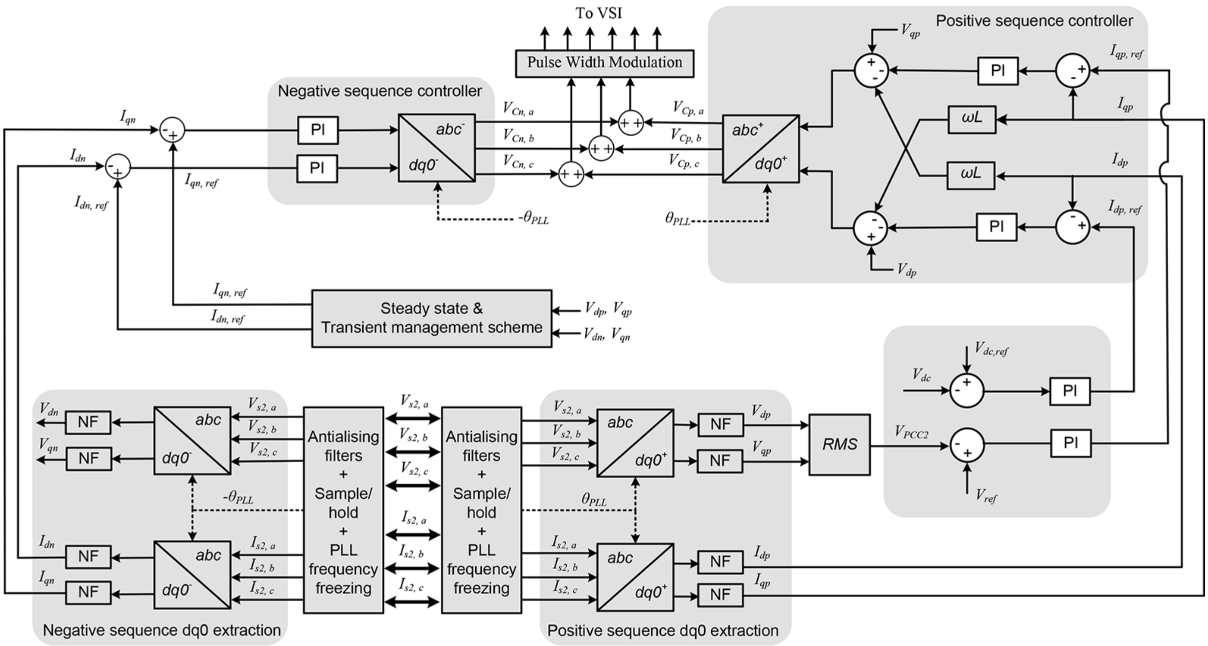

Figure 10: Positive and negative sequence controllers for the shunt connection operation during steady state and fault conditions.

Experimental Setup:

An experimental setup is constructed to verify the systemfeasibility and transient management capability of the proposedshunt-series reconfiguration and FRT control scheme.The VSC-HVDC system is simplified and scaled down, whichcan be tested in the low voltage research lab. Fig. 19 illustratesthe block diagram of the experimental system, whichcomprises the simulators of the on-shore VSC station andtwo grids. The electrical grid is represented by two VSCseach with rating 2 kW, and some parallel R-L loads. Theconverters are of brand ST [17]. The system parameters aregiven in Table II, Appendix I. The three-phase AC switches,, and are designed and built as fast IGBTs switches,which can be electronically controlled to operate shunt-seriesreconfigurations.Shown in Fig. 11, the shunt connection is built through thethree-phase inductor and operated by the AC switch, . Theseries path is made by the three-phase transformer andthe inductor and controlled by to support the seriesvoltage build-up function. The switch is used to bypass thetransformer for the shunt connection. Both electrical grid simulatorscan be controlled to emulate voltage dips. The systemis digitally controlled by one microcontroller, TMS320F28035,

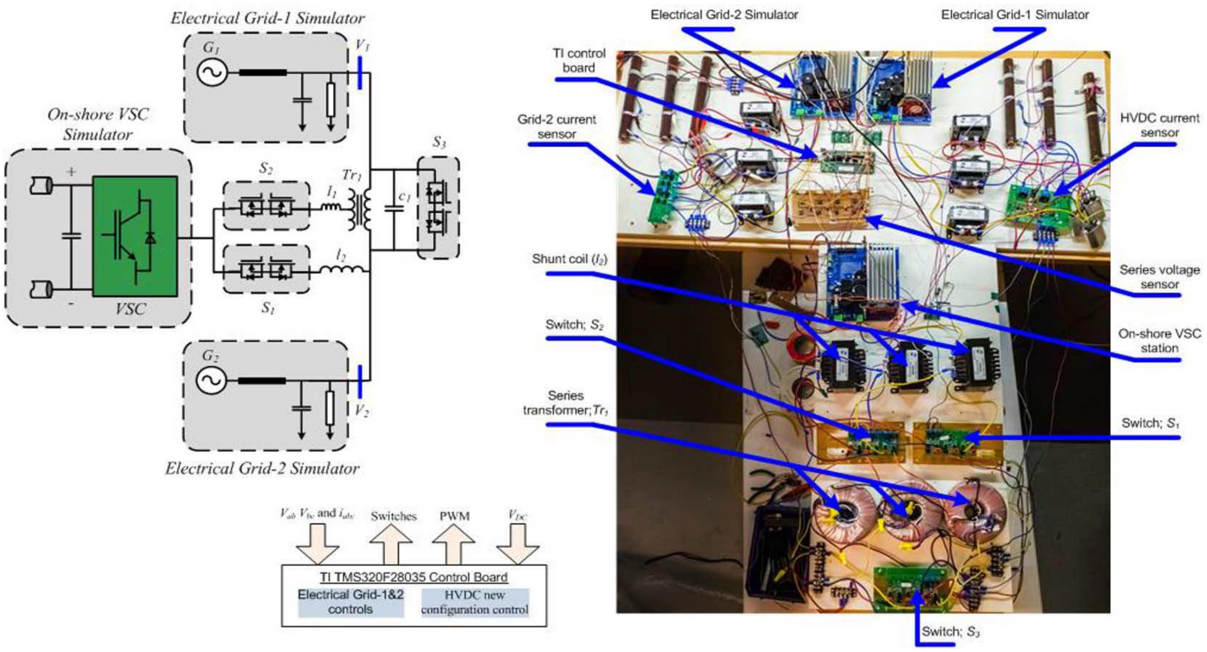

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Figure 11. Diagram and photograph of the experimental setup.

Table I Simulation Parameters

Onshore VSC station			
Shunt connection		**Series connection**	
Rated power	500 MW @ 0.9 pf	Rated power	500 MW @ 0.9 pf
Transformer rating	600 MVA	Transformer rating	600 MVA
Transformer Tr_{shn} voltage ratio	250/250	Transformer Tr_{ser} voltage ratio	250/250
Transformer Tr_{shn} leakage reactance	0.12 pu	Transformer Tr_{ser} leakage reactance	0.025 pu
AC filter2 shunt: l_{2h}	72 mH	AC filter2 series: l_{2s}	72 mH
AC filter2 shunt: c_{2h}	62 uF	AC filter2 series: c_{2s}	62 uF
DC link			
DC voltage		600 kV	
DC capacitance		300 uF	
DC cables resistance		0.015 Ω/km	
DC cables capacitances		0.52 uF/km	

Table II Experimental Parameters

Grid Emulator		Series connection	
L-L RMS voltage	70 V	Filter inductor	2.5 mH
Coupling resistor	0.2 ohm	Filter capacitor	3 uF
Filter inductor	5 mH	Series Transformer	1:1
Filter capacitor	3 uF	Series transformer leakage reactance	1.6 mH
Frequency	50 Hz	Rated voltage	220V
Load 1	108W	Rated current	2A

System Evaluation

This section involves a detailed validation studies to illustrate the effectiveness of the proposed configuration in enhancing the total performance of the electric grid during severe fault conditions within the onshore AC grid. [18-20]

A. *Fault Ride-Through Simulation Studies* The fault at bus; (Fig. 2), is applied at the instant; and lasts for *300 msec*.

B. \ Different fault types and scenarios are simulated for this evaluation as follows:

1- *Double line-to-ground Fault* is applied with and without the proposed configuration.

2- *Single line-to-ground fault* is applied with the proposed configuration.

3- *Three phase fault* with the proposed configuration.

1) Performance in Response to Double Line-to-Ground Fault (With and Without the Proposed Configuration):

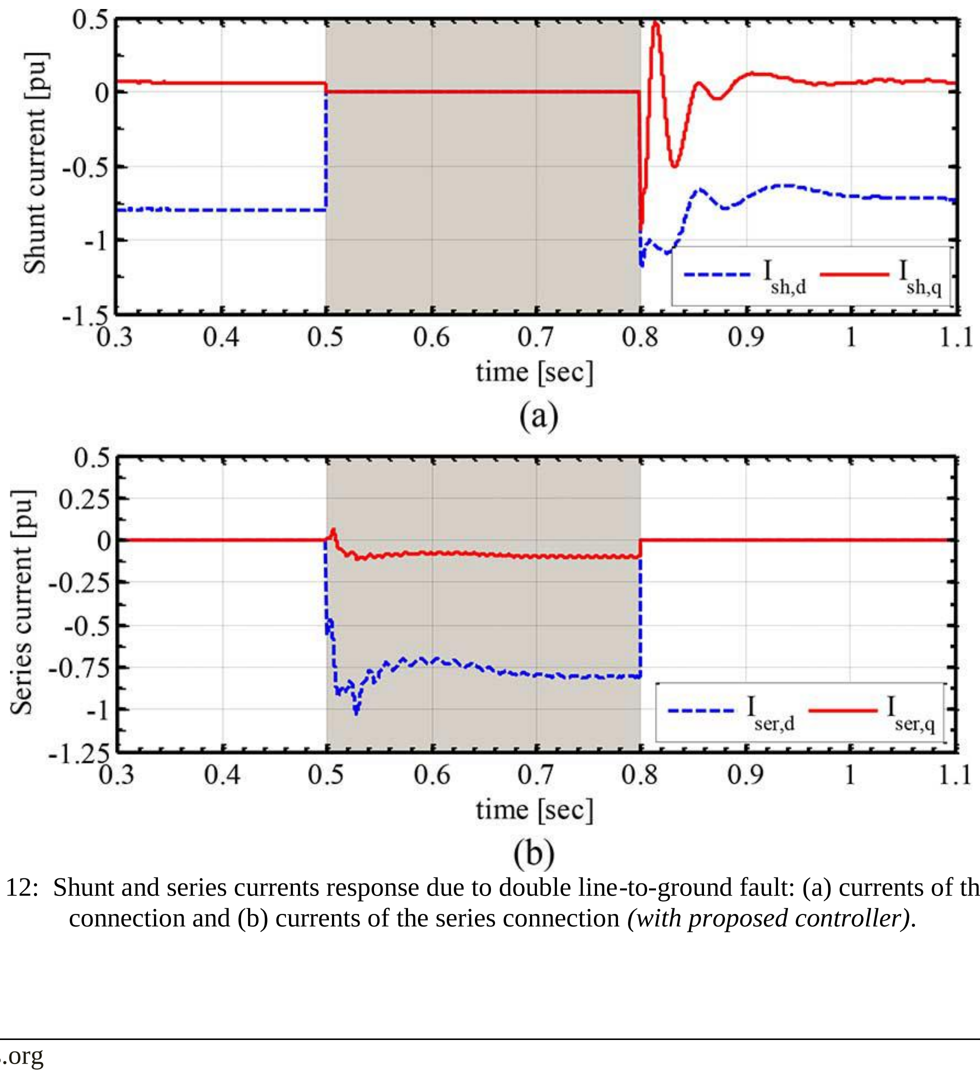

Figure 12: Shunt and series currents response due to double line-to-ground fault: (a) currents of the shunt connection and (b) currents of the series connection *(with proposed controller)*.

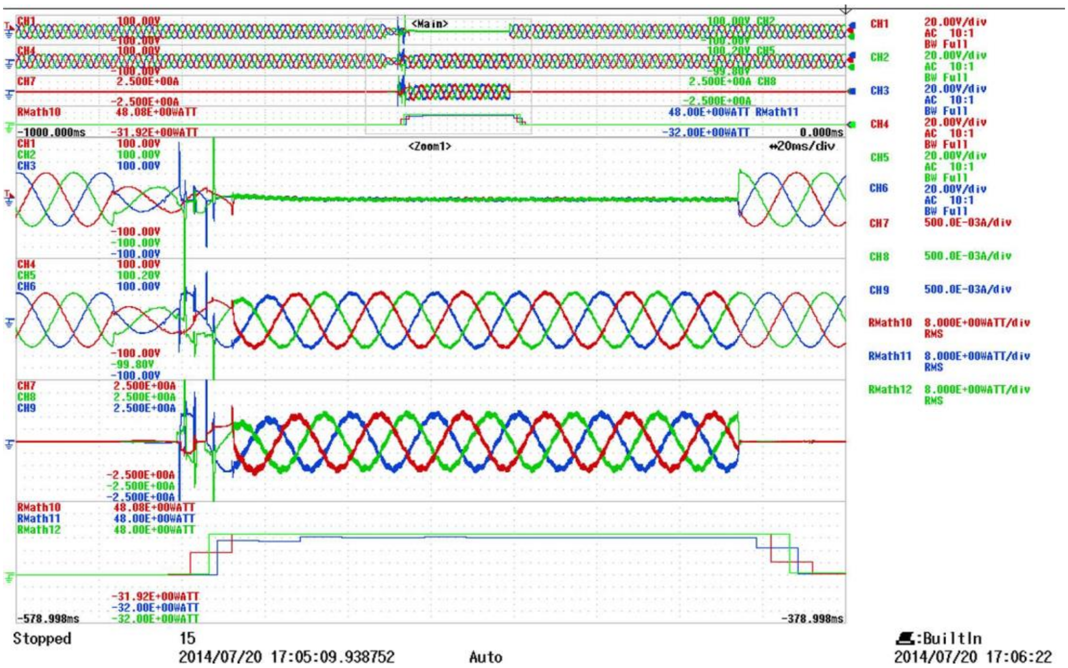

Figure 13: Experimental system response due to three phase to ground fault.

II. Conclusion

A single-ended universal power flow controller is designed for controlling VSC-HVDC system in connecting with LSWFs. The configuration is realized at the onshore VSC station to achieve multi functions during different fault types. The states of operations for the new configuration are presented and realized to allow for smooth power transfer from wind farm during faults in any of the AC power system networks. This reduces the possibilities of severe power network propagations that may occur due to sudden power reduction or generator oscillations. The controllers for the series and shunt connections are designed in such a way to minimize the DC link oscillations associated with asymmetrical faults. Finally, the comprehensive simulation studies and the experimental validation verified the concept and demonstrated the advantages of the proposed configuration.

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