IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE)
e-ISSN: 2278-1676,p-ISSN: 2320-3331, Volume 11, Issue 6 Ver. III (Nov. – Dec. 2016), PP 63-75
www.iosrjournals.org

Assessment of VSC-HVDC System for Transient Stability Improvement of a Power system with Large Wind Power Injection.

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Abstract: *This paper analyzes Power System Transient Stability Improvement through a Voltage Source Converter High Voltage Direct Current (VSC-HVDC) system with Large Wind power injection. The modern large wind farms and other renewable energy sources (RES) have no system inertia and are prone to system disturbances under fault. Though wind farms have little inertia, in the event of sudden loss of generation or a sudden loss of large load, the system frequency will start to decrease and may result into voltage collapse because the little inertia in the wind farm is not adequate to counter such large system disturbances. It is therefore crucial to analyze the existing conventional power networks before integrating large wind power into the grid. Global trend indicate that, countries are generating more and more wind power because it is a cheap source of energy and has less negative impact on environmental. In this study, one of the three synchronous generators of an IEEE 9 bus system is replaced by a wind farm of an equivalent generated power. Three scenarios investigated in this study includes a conventional generation alone, the convention generation injected with wind power and a conventional grid injected with wind power through a VSC-HVDC system. A short circuit fault to ground is initiated at 2s along the transmission line and cleared at 2.45s. Simulation results show that the inclusion of VSC-HVDC system improves system transient stability and allows large wind power injection into a conventional grid.*
Keywords: *Doubly-fed induction generator, Short-circuit fault, Power system transient stability, Wind power injection, VSC-HVDC Transmission.*

I. Introduction

Voltage source converter High voltage direct current (VSC-HVDC) transmission is the most efficient and economical modern mode of power transmission for long distance. Further, HVDC has the capacity to transmit bulk power in transmission networks [1, 2]. Globally, both developed and developing countries have adopted this relatively newer transmission technology based on its many advantages such as the ability to independently control the active power both under steady state and under fault. This ability has made this mode of transmission adorable globally by many power utilities. The modern HVDC system makes use of insulated gate bipolar transistors with high switching frequencies that allows the connection of weak or even passive networks [3].Due to the high switching frequencies of up to 1-5 KHz, the size of the filter and the Insulated Gate Bipolar Transistor (IGBT) valves reduces further as compared to thyristor valves in classical HVDC systems. The VSC acts like a synchronous machine and can generate AC voltages at required frequency. Compared to current source converters (CSC), VSC-HVDC system has better controllability characteristics because both active and reactive power can be independently controlled. Because of these characteristics, the performance of VSC based HVDC system with its controllers are connected with a wind farm and studied in this work. The VSC-HVDC system has two levels of controllers that work together to ensure system stability is maintained. The two are inner current controller (vector current controller) and the outer controllers. The latter is further classified into active and reactive power controllers, DC and AC voltage controllers and frequency controllers. The inner current controller loop is designed to ensure that it has a fast response than the outer controller loop. This feature is critical because the two controllers are interlinked and cannot work independently, thus they must operate at different response speeds. The VSC-HVDC system has the capacity to reduce carbon emission into the atmosphere because it has the capability to connect renewable energies such as wind farm that has been scientifically proven to be environmentally friendly. As rightly put in [4], VSC based HVDC technology driven by the growing installations of large-scale offshore wind farms as well as the dynamic evolution of power electronics expertise has gained wide acceptance. Many projects applying VSC-HVDC technology have been commissioned and others are at various stages of implementation. For example, the world's longest HVDC light project (Sweden Lithuania), commissioned in2015, shows the vital role of VSC-HVDC in the modern transmission era [5].

Although VSC-HVDC systems have been known to have many advantages as in [6, 7], there are also some setbacks. One of the major challenges for HVDC transmission systems is fault ride through (FRT) capability during different grid faults. Some researchers have identified other relevant drawbacks when vector current control is used in weak grid for instance in a Wind farm or a very weak grid [8-11].The first issue identified is the low frequency resonances that can interact with the vector current control during fault condition [12]. Second problem is due to the phase-locked loop (PLL) dynamics when the power converter is synchronized to a weak grid. PLL is used to synchronize the turning ON/OFF of the power devices by calculating and controlling the flow of active and reactive powers. When a converter with PLL is connected to a weak grid, it leads to further system instability and unless mitigation measures which are costly are put in place, the system stability will continue to dip. In [13], improvement measure like an alternative technique referred to as power synchronization control (PSC), which does not require synchronization with a PLL via emulating the behaviour of a synchronous machine was proposed. It is reported that PSC provides a good performance and fast dynamics for low short circuit ratio (SCR) values known for causing instabilities. However, the main obstacle of this topology is in dealing with faults in the AC grid. Normally, PSC switches to classic vector current control when the power converter current limit is reached [14]. Further, in [15] a control system for microgrids and railway electrical weak grid is presented for analysis of the system transient stability when subjected to faults. A reliability study in [16] analyzed the

Operational experiences of the first 660-kV HVDC link in the world rated as 4 GW.The analysis demonstrated the importance of keeping HVDC systems energized during fault disturbances to avoid bulk power interruption that may lead to huge stability problems. In order to address the above shortcomings, many solutions have been proposed such as in [17] where a new VSC-HVDC system is proposed based on a hybrid multilevel converter with ac-side cascaded H-bridge cells. The proposed configuration can handle grid faults and avoid line shutdown due to faults. However, the controller relies on reducing the power transmitted from the sending end converter, by reducing system reliability when connected with an offshore Wind power plant (WPP). Current grid codes stipulate an FRT capability of wind power plants down to zero voltage for fault durations up to 150 ms [18]. Therefore, despite the challenges facing VSC-HVDC system connected with a large wind farm, it still has better controllability than LCC-HVDC system or any other transmission system available. There are various combinations of strategies that can be selected for load flow analysis; these are PQ control, DC and AC control, frequency control, Vac-P control mode, Vdc-Q control mode, Vdc-phi control mode and Vac-phi control mode. The selection of any type of control mode depends on the application required. In this study, two control strategies are selected. The first control strategy involves control of active power and reactive power on the inverter side (VSC 2) and control of reactive power and DC voltage on VSC 1 side. The second strategy implemented in this study involves control of active and reactive power on VSC 2 side while VSC 1 side control the DC and AC voltages. The two strategies are good enough for this analysis since they explore all the possibilities for VSC -HVDC system control.

1.1. Vsc Control Strategies

VSC-HVDC controllers play a very critical role in ensuring that the transfer of power between the grids and the converter is well controlled. In addition, VSC-HVDC controller's allows independent control of the transmitted active and reactive power through the DC link while making sure that the power transmitted through the DC link is within the acceptable voltage levels through reactive power control. Active power
Flow direction reversal in VSC-HVDC is done by changing the polarity of the DC current unlike the classical HVDC which employs reversal of DC voltage polarity [19]. The reactive power is controlled by controlling the magnitude of the output voltage from the converter. Two power control strategies commonly used are the direct power control and vector current control [20]. The former involves controlling the phase-angle shift between the converter voltage and the AC system voltages while the reactive power is controlled by varying the converter output voltage magnitude with respect to system demand. Because of disadvantages likeVariable switching frequency and necessity of fast conversion and computation, the use of direct power control is not very common [21], thus not implemented in this study.The second and most commonly used technique for injecting power to an AC power system is vector dq-current control [22]. The vector current control is based on the control of two independent current components, d-axis and q-axis in the synchronous reference frame (SRF) while the synchronization is provided by a phase locked loop (PLL) [23]. This control technique permits an independent control of active and reactive Powers [24] with a fast dynamic response. In addition, it has the ability to control the DC voltage flow through the DC link through the control of reactive power in the converter. Vector control also has in built capability for overcurrent protection brought about by lightning and trees falling on the

transmission lines thus causing short-circuit. In a VSC-HVDC system, the input currents to the rectifier and the output currents from the inverter are measured and compared with the reference current values and the error signal is fed to the controllers to produce switching signal to the PWM converters. The converters play the role of power conversion either from AC to DC and vice versa.

1.2. Vector Control Principle

The vector control system is based on a simplified representation of three phase systems known as dq components transformation. Its control strategy is implemented on the vectors of currents as represented in a dq-rotating reference frame. In vector control strategy, the three phase quantities are first transformed to quantities in a two coordinate (a, b) Stationary system and then further transformed to quantities in a dq-rotational reference frame. This makes the transformed quantities appear as constant magnitude vectors (DC- vectors), since the reference frame is rotating at system frequency. Fig.1. shows the transformation of axes for vector control.The dq-transformation is the transformation of coordinates from the three phase stationary coordinate system to the dq rotating coordinate system. This transformation gives the advantage of analyzing DC quantities which is easier than analyzing AC equivalents. In addition, the comparison of the DC quantities results into static errors. These errors can be eliminated by applying simple PI controllers [25].Vector control strategy has a decoupled control ability that makes it possible to independently control the active and reactive powers. The decoupling of quantities allows the implementation of a cascaded control strategy which has improved dynamic performance.

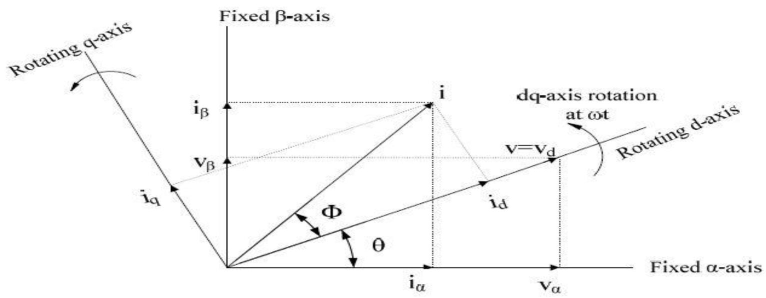

Fig 1. The transformation of axes for vector control

At least two converters are needed for power conversion though multiple converters can also be selected largely based on the reliability and flexibility desired. Each converter can only have one type of controller at any given time and the selection of the other converter largely depends on the desired application. The cascaded control scheme implemented in this study is shown in Fig.2.

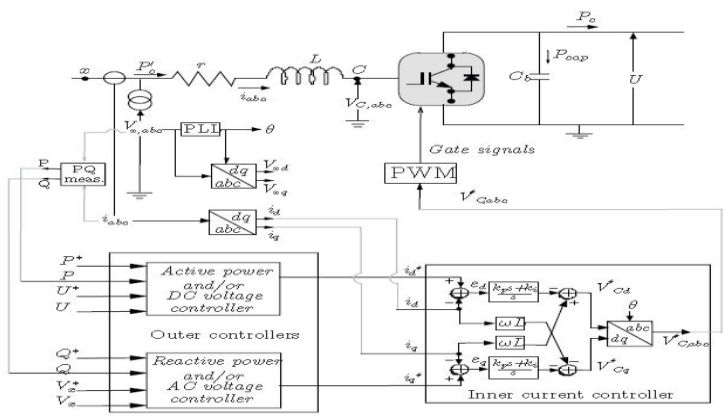

Fig.2. Complete diagram of VSC with inner and outer controller

II. Vsc-Hvdc System Modelling

Before discussing about modelling of the VSC-HVDC system, it is important to briefly highlight its constituents. Basically, a VSC-HVDC transmission system consists of converter valves, phase reactors, filters, power transformers and DC lines. Though all components are important, converters play the biggest role of converting AC to DC (rectifier) and DC to AC (inverter). The two converters can be connected either via a dc cable or an overhead line or in back-to back connection depending on the application. Normally, the converter valves are built with insulated gate bipolar transistor (IGBT) power semiconductors and are provided with R-C snubbers and series R-L elements to reduce dv/dt and di/dt stresses that occur during switching transitions. IGBTs operate at very high frequencies and thus the need for filter sizes reduces further. Phase reactors have large inductance and small resistances to enable regulation of active and reactive power to the AC grid and also protect the transformer against high frequency harmonics [26]. Transformers are used to convert voltages to values suitable for the converters while shunt filters are used to filter out the generated harmonics and prevent them from entering the AC system. The DC capacitor is for maintaining the DC voltage at constant value. The DC capacitor should be carefully selected to avoid large ripples in the DC voltage. The vector control strategy for VSC-HVDC starts from the mathematical modelling of VSC-HVDC system in dq-reference frame. The VSC can be represented by a controlled voltage source for the AC side as in Figure 3.0 (a) and a current source for the DC side as in Figure 3.0 (b). Therefore, we can represent the converter and grid interaction by the following equivalent circuit.

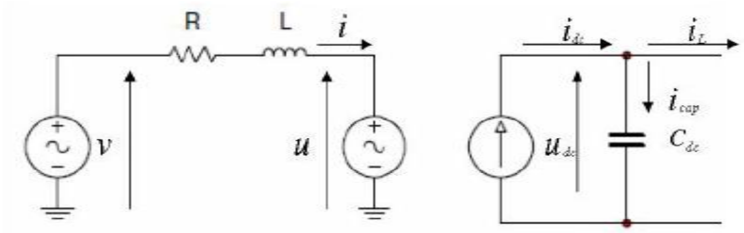

Fig 3. (a) Voltage source for the AC side; (b) Current source for DC side

According to Kirchhoff's Voltage Law (KVL), the algebraic sum of the voltages across any set of branches in a closed loop is zero. Therefore applying Kirchhoff's voltage low across the reactor (L) and the resistor (R) the following equation holds true:

$$L\frac{di_{abc}}{dt} = V_{abc} - U_{abc} - Ri_{abc} \quad (1)$$

Where V_{abc} - Grid AC voltage in abc reference frame
U_{abc} - Converter AC side output voltage in abc reference frame
i_{abc} - AC current through the reactor in abc reference frame
R - Reactor resistance
L - Reactor inductance
Then applying Clark transformation, the time varying three phase quantities are transformed to vectors in a two coordinate (α,β)system.

$$\begin{pmatrix} x_\alpha \\ x_\beta \end{pmatrix} = \frac{2}{3}\begin{pmatrix} 1 & cos\frac{2\pi}{3} & cos\frac{4\pi}{3} \\ 0 & sin\frac{2\pi}{3} & sin\frac{4\pi}{3} \end{pmatrix} \quad (2)$$

Hence, this results in equation 3 below:

$$L\frac{di_{\alpha\beta}}{dt} = V_{\alpha\beta} - U_{\alpha\beta} - RI_{\alpha\beta} \quad (3)$$

By using transformation angle from the system phase measurement at the PLL the electrical quantities are further transformed from the (α,β) stationary coordinate system quantities to a rotational dq-reference frame equivalent quantities by applying the following park transformation:

$$\begin{pmatrix} x_d \\ x_q \end{pmatrix} = \begin{pmatrix} cos\vartheta & sin\vartheta \\ -sin\vartheta & cos\vartheta \end{pmatrix}\begin{pmatrix} x_\alpha \\ x_\beta \end{pmatrix} \quad (4)$$

Hence, Equation 3 is transformed to a dq rotating reference frame equation given by

$$L\frac{di_{dq}}{dt} = V_{dq} - U_{dq} - (R + j\omega l)i_{dq} \quad (5)$$

Where the term $j_{\omega l}$ represent the time derivative of the rotating reference frame.Rearranging Equation 5 into two real and imaginary components gives Equation 6 and 7 that shows the relationship between the converter voltages and input currents in dq reference frame.

$$L\frac{di_d}{dt} = V_d - U_{dconv} - R_{id} + jwi_q \quad (6)$$

$$L\frac{di_q}{dt} = V_q - U_{qconv} - R_{iq} - jwi_d \quad (7)$$

Similarly, applying Kirchhoff's current law on the output side of the DC circuit in Fig. 3. Yield the following Equation;

$i_{dc} = C\frac{du_{dc}}{dt} + L$ (8)

Where

i_{dc} −Converter output DC current i_L- DC current through DC link

C_{dc}- DC capacitor capacitance. Thus Equations 6, 7 and 8 complete the mathematical modelling of VSC-HVDC system.

III. Modelling of the Inner Current Controllers

The inner current controller is placed between the outer controllers and the PWM generator and normally the inner current loop is also referred to as vector current control. Its response time is very fast compared to the outer controllers for system stability. In this study, the current loop is modelled considering constant dc bus voltage because the voltage control loop is much slower than the inner current control loop. According to [27], the inner current control is implemented in a dq-coordinate system. The phase locked loop (PLL), which provides the reference angle of the dq transform, normally enables the d-axis to be aligned with the voltage vector at the point of common coupling (PCC). In order to achieve an independent control of real and reactive power [28], the inner current control loop should have two PI regulators each for the d and q axis currents. These controllers transform the error current from the comparison to a voltage signal which is used by PWM generator for switching the converter. The inner current control loop is as shown in fig.4below. It consist of four parts [29] namely, PI controllers (regulator), decoupling factors (PWM converter), system model and the measurement terms for the system being analyzed. The regulator is the proportional and integral controllers (PI controllers) and basically they are the PQ controllers. As a result of the dq transformations produced by the DC vectors, the PI is able to reduce the steady state error signal to zero.

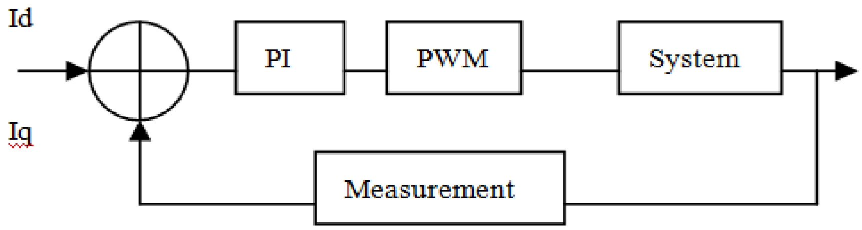

Fig. 4. The inner current control loop in dq axes.

The PI regulator is represented by the equation below

$K_P(1 + \frac{1}{S_{Ti}})$ (9)

The PWM produces the output voltage. In PWM the switching frequency is expected to be much larger than the system frequency. In this study, converter switching frequency of 5000Hz is chosen. The high frequency chosen reduces the size of the filters required to eliminate the harmonics generated.

3.1 Modelling Of The Vsc Outer Controllers

Normally, a VSC-HVDC system has four outer controllers. In this study case, only three outer controllers are discussed. These are the Active power controller, Reactive power controller and the DC voltage controllers. Generally, a two terminals-HVDC system has a rectifier and an inverter. The rectifier station operates as a power control mode to control active power drawn from the AC grid and at the same time controls the reactive power compensated to the grid. It also has the capability to control AC grid voltage directly. The inverter station has the responsibility of ensuring that the DC link voltage is maintained at the desired specific level otherwise the active power flow balance between the two converters may result into system being unstable. The outer controllers need to be properly tuned so that to damp the system oscillations and attain system stability. The outer controllers generate the reference d-component currents and q-component currents. In [30], all the outer controllers are implemented by a PI controller where the difference between the reference values and the actual value is fed into the controller as the d-q reference currents. The active and reactive power controllers and the DC voltage controllers are discussed in the next subsection.

3.2 Active And Reactive Power Controllers

The objective of PQ controllers is to regulate the active and reactive power exchange between the converters and the grid. The reactive power balance in a grid largely relies on the voltage levels on the grid and any deviation will lead to system instability. The active and reactive powers are calculated from the grid and compared with the reference values and the error signal is made to pass through PI regulator. The PI controllers create the reference d and q currents which are fed to the inner current controllers. The structure and transfer functions of active and reactive power control are as shown in fig. 5.

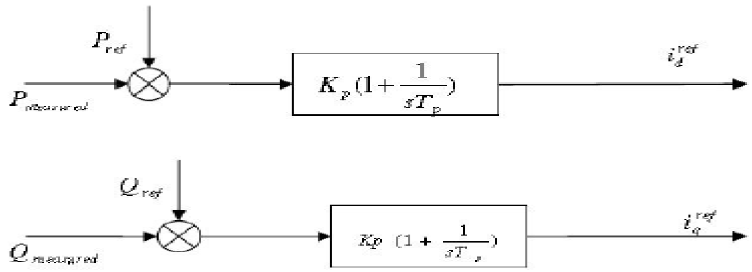

Fig 5. Active and reactive power controllers loop in dq axes

In a VSC-HVDC system, every converter can be selected to independently control its reactive power injection into the power system. Similarly, only one converter is selected at a time to independently control the active power and the DC voltage respectively. In [31], the converter selected to control the DC voltage is called the slack converter because it usually compensates the losses in the DC network and therefore has a similar function as a slack node in an AC grid. The outer control loop of the VSC converter controls the active and reactive power. The PI controller used for the active and reactive power controller has the same structure as the PI controller. [32], states that there is no general rule for tuning the controllers and therefore in this study, trial and error method was carried out to yield best responses. The selected parameters for the controllers are the KP=10 and the Ti=0.1respectively.

3.3. Dc Voltage Controller

DC voltage controller is responsible with controlling the active and reactive powers between the converters. In VSCHVDC -system, the DC voltage control is implemented through the integration of the inner current loop and the outer control loop. The two must work concurrently for power flow balance between the converters and subsequently between the grids.As previously mentioned, the inner current controller should be fast enough in order to get the best system response. Based on [22], the DC voltage controller has four parts, namely;

1. The PI controller $K_P(1+\frac{1}{S_{Ti}})$
2. The inner current controller, $(\frac{1}{1+T_{eqs}})$
3. The system, $\frac{3}{2}\frac{1}{C.S}\frac{Vd}{Vdc}$
4. The measurement circuit is the feedback loop$\frac{1}{1+T_S S}$

Where Ts is the sampling time of the inner current controller. In order to derive the DC voltage control loop, some assumptions were made. Assuming a lossless converter, the power into the converter is equal to the power output from the converter. Therefore, based on this assumption, the two equations below holds true:

$$P = \frac{3}{2}V_d i_d \tag{10}$$

$$Q = -\frac{3}{2}V_d i_Q \tag{11}$$

Equations 10 and 11 indicate that, the active power is dependent on d-axis current while the reactive power is dependent on q-axis current. Similarly, the DC Power is given by;

$$P_{dc} = V_{dc} i_{dc} \tag{12}$$

Equating the active power equation 10 with the DC power equation 12 yields

$$\frac{3}{2}V_d i_d = V_{dc} i_{dc} \tag{13}$$

Applying the Kirchhoff's current law at the node on the dc of fig. 2, yield the equation 14 below.

$$C_{dc}\frac{du}{dt}dc = i_{dc} - i_L \tag{14}$$

Where i_{dc}Converter output DC current, iL - DC current through DC link, C_{dc}- DC capacitor capacitance
Rearranging equation 14 becomes,

$$i_{dc} = i_L + C_{dc}\frac{du}{dt}dc \tag{15}$$

Substituting equation 15 to 13 yield;

$\frac{3}{2}V_d i_d = V_{dc}\left(i_L + C_{dc}\frac{du}{dt}dc\right)$ (16)

Using the basic Laplace transformation and solving for U_{dc}in eqn.16, we get
$V_{dc} = \frac{1}{C_s}\left(\frac{3}{2}\frac{V_d i_d}{V_{dc}} - i_L\right)$ (17)

The resulting block diagram of the dc voltage controller loop is illustrated in Fig. 6. The disturbance introduced by iL can be eliminated by introducing a compensation term $\left(\frac{2}{3}\frac{V_{dc}}{V_d}i_L\right)$before the converter.

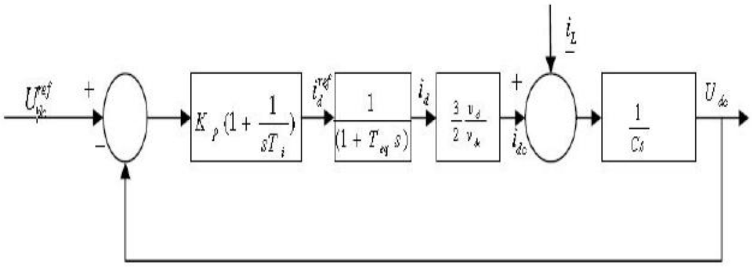

Fig 6. Dc voltage control loop in dq axes

3.4 Tuning The Dc Voltage Controller Using The Symmetrical Optimum Criterion

Tuning of the DC voltage control is a critical activity in maintaining the reactive power at desired levels otherwise a slight change in DC voltage would lead to system instability. The tuning of the DC voltage controller is based on symmetrical optimum tuning where the controlled system has one dominant time constant and other minor time constant. The PI controller can be tuned using the modulus optimum criteria however, when one of the poles is already near to the origin or at the origin itself, the pole shift does not change the situation significantly. The open loop transfer function of the voltage controller already has two poles at the origin. An alternative criterion to tune the controllers in this condition is given by the symmetrical optimum criteria. As in fig. 6, DC voltage controller loop has a pole at the origin and thus the optimum symmetrical tuning is used in this study to design the controller's parameters. Various research has been carried out concerning the tuning of the DC voltage controller based on optimum symmetrical tuning [33] and [34], as such, the equation below holds true;
$T_i = a^2 T_{eq}$ (18)
Ti is the proportional time constant. It is also recommended that a is between 2 and 4, thus, the equivalent time delay T_{eq} due to the current control loop is given as in equation 19 below.
$T_{eq} = aT_a = a\frac{Ts}{2} = a\frac{1}{2fs} = 2 \times \frac{1}{2\times5000} = 0.0002$ (19)
Where $fs$is the switching frequency,
$\mathbf{Ta} = \frac{\mathbf{1}}{\mathbf{2fs}}$ (20)
1/2fs is the inverse of the switching frequency.
If a=3 then,
$\mathbf{T_{eq}} = \mathbf{3} \times \frac{\mathbf{1}}{\mathbf{2\times5000}} = \mathbf{0.0003}$ (21)
$\mathbf{T_i} = \mathbf{3^2} \times \mathbf{0.0003} = \mathbf{0.0027}$
(22)
In this study, the parameters below were utilized based on the symmetrical optimum tuning and for a=2, the proportional gain becomes
$K_p = \frac{2}{3}\frac{V_{dc}}{aV_d T_{eq}} = 0.163$ (23)
From figure 6, K is given by:
$K = \frac{2}{3}\frac{K_P V_d}{Vdc} = 0.137$ (24)
Now using the PI controller parameters, the overall closed loop transfer function for fig. 6, become,

$G_{cl} = \frac{K+KT_i s}{K+KT_i s+TiCS^2+TiTeqCS^3}$ (25)

$G_{cl} = \frac{0.1347+1.078\times10^{-4}s}{0.1347+1.078\times10^{-4}\ s+4.315\times10^{-8}s^2+8.629\times10^{-12}s^3}$ (26)

3.5. Vsc-Hvdc System With Wind Power Injection

VSC-HVDC system is the most convenient and reliable mode of power transmission compared to LCC-HVDC and the HVAC system due to its inherent ability to independently control the active and reactive power through vector current control method. It also has better control of the DC voltage through regulation of the active and reactive power. Further, globally, many grids have been interlinked between member countries thus exerting pressure on the existing conventional transmission system during the export of the surplus energy. In addition, environmental pollution accelerated by the conventional generation has reached advanced levels that need to be curtailed by adopting renewable generation such as wind power. Wind energy is a clean source of power; however, integration of large scale wind power is a challenge because of the unpredictable nature of wind, and strict requirements of voltage and frequency grid codes, especially in the case of isolated and offshore power systems [35]. In this study, doubly fed induction generator (DFIG) based wind turbines are utilized due to their inherent ability to control voltage and reactive power. Further, DFIG operate over wide range of speed with excellent control of active and reactive power. However, most of the onshore and offshore wind farms are located far away from the load centres thus making the convention transmission method uneconomical and not feasible. In [36], wind power has emerged as one of the most dominant renewable sources of energy with immense growth potential across the globe. Actually, the global wind energy capacity has increased rapidly and is the fast growing renewable energy sources. The wind energy is largely harnessed from the offshore wind farms where wind is strong, large available sea areas, has high wind speed, and is less turbulent. Further, in the offshore, there is little human activity taking place and thus the noise produced by the wind turbines have no impact on human beings and unlike the onshore wind farms that produce some noise impacting negatively on the community living around. Wind power transmission cannot go unchallenged especially where underground cables in the sea get damaged, the cost and process of repair is expensive and time consuming compared to overhead transmission for the case of onshore wind farms. As previously mentioned in this study, transmission of wind energy using conventional system is cost effective for distances less than 100km [37]. However, for distance exceeding 100km, the conventional system (HVAC) lead to the problems as stated in [38]. These problems are overcome by VSC-HVDC system. The fig.7 shows a VSC-HVDC system connected to a wind farm.

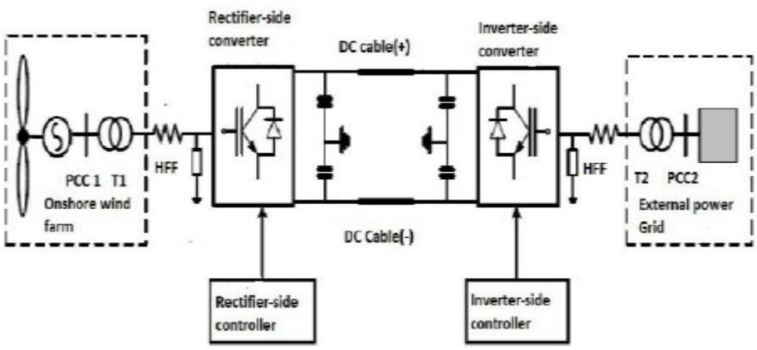

Fig 7. VSC-HVDC with wind farm

In addition to the ability of the DFIG to control the reactive power and voltage, VSC-HVDC system provides additional reliability and flexibility. VSC-HVDC system incorporate the vector current control method to provide additional independent control of active and reactive power at both sides of the grid, continuous control of voltage and frequency, blackstartingand quick reversal of active power flow thus making it possible for integration of wind power with VSC-HVDC system. As such, SC-HVDC links are designed to control active power in the sending end converter (rectifier) and dc voltage is controlled at the receiving end converter (inverter).Normally, reactive power at both sides of the converter is controlled in order to maintain the AC voltage and reactive power within desired levels [39]

IV. Methodology

In the preceding sections, much has been discussed about VSC-HVDC system integrated with wind farm due to its inherent ability to provide the very crucial control of active power and reactive power between the grids. Concerns have also been raised regarding how much wind power can be integrated into a conventional grid through a VSC-HVDC system of transmission. To respond to the issues raised, this study analyzes the effectiveness of the modelled VSC controllers with a standard IEEE 9 bus system connected to a wind farm through a VSC-HVDC transmission system. The user defined models of inner current and outer controllers are shown infig.8 and fig. 9 respectively. More wind power integration to the conventional grid is a possible reality with VSC-HVDC system. Fig.10 shows the overall arrangement of the system for this study.

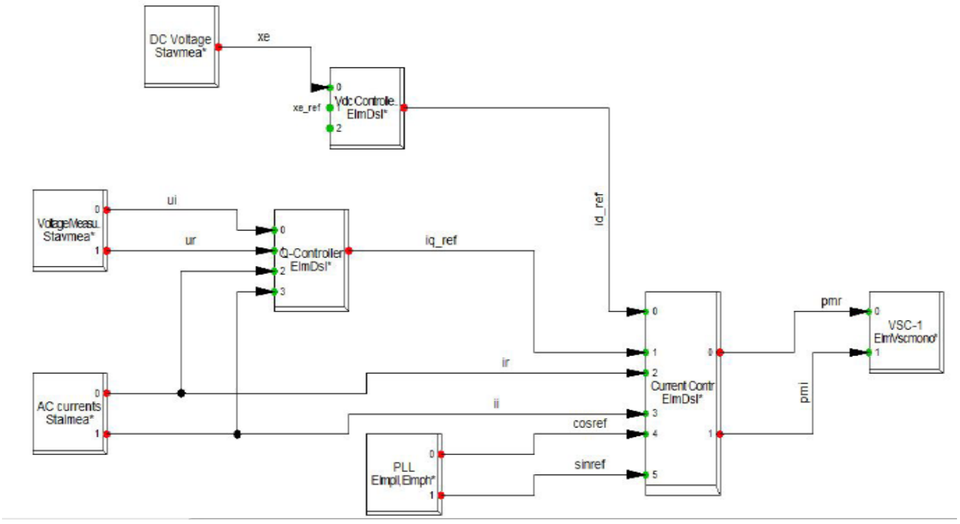

Fig 8.VSC 1 controller set up

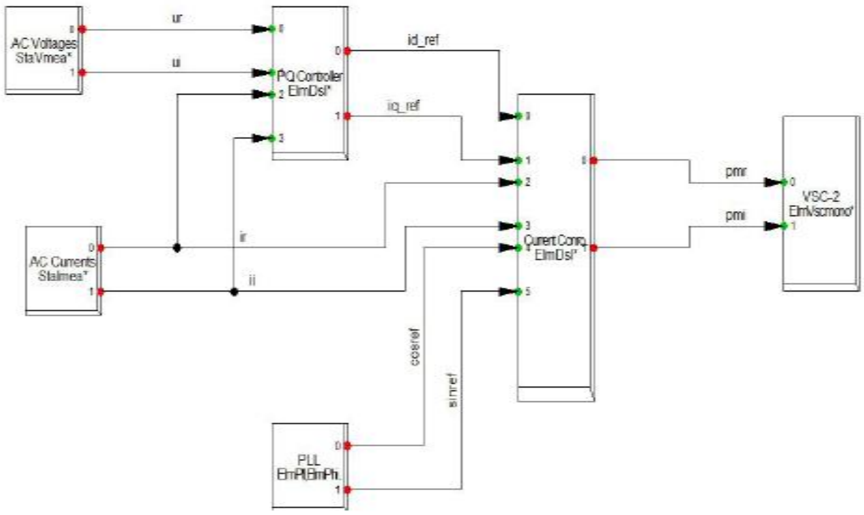

Fig. 9. VSC 2 system control set up

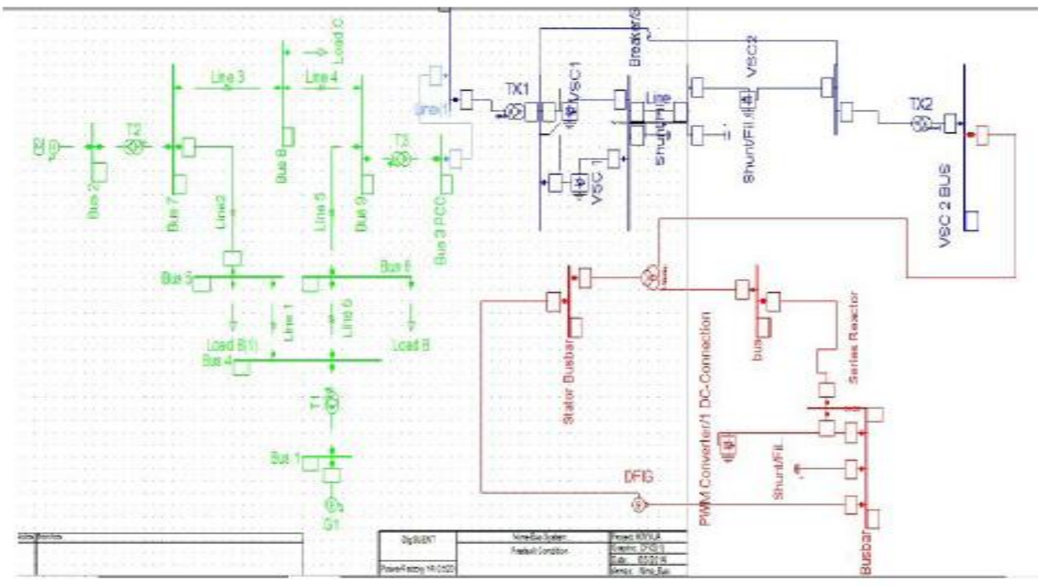

Fig. 10. VSC-HVDC with wind farm connected to 9 bus system

V. Simulation Results

The simulation results in this study was aimed at finding the critical clearing time for a conventional grid connected without wind farm, conventional grid with wind farm and a conventional grid connected with wind farm through a VSC-HVDC transmission system. A three phase to ground fault was initiated along the transmission line and cleared after the Preset time. Figure 10 was implemented in Digsilent software and Load flow was run and results were shown in figures 11-16respectively.

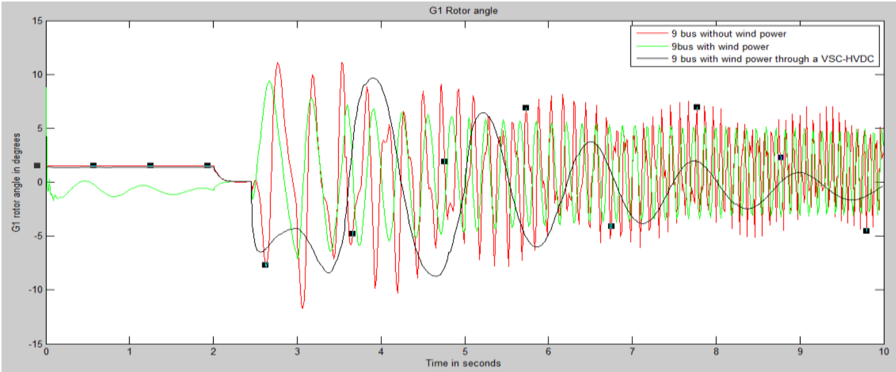

Fig. 11.G1 rotor angle for a fault 2s cleared at 2.45

Fig. 11 shows that a conventional grid connected with wind farm through a VSC-HVDC system is stable at a clearing time of 0.45 seconds while the other combinations were unstable. This indicates that transmission system based on VSC-HVDC has better controllability with large wind power integration.

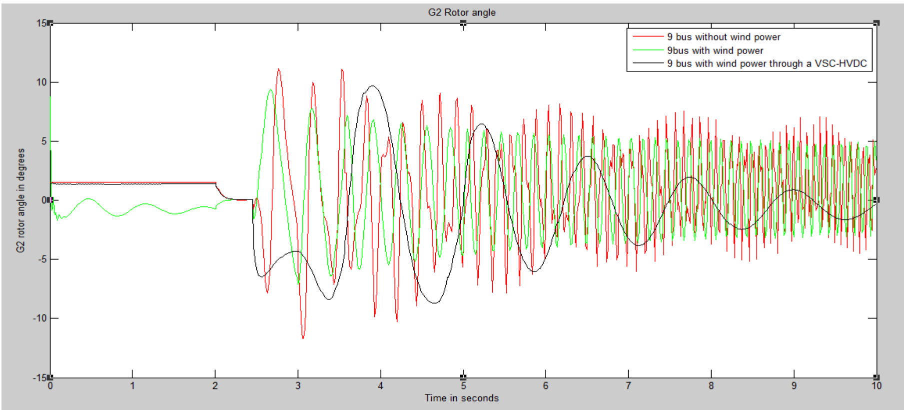

Fig 12. G2 rotor angle for a fault at 2s cleared at 2.45

Fig.12 indicates that for G2 with fault near bus 7, the rotor angle reached stability faster for the 9-bus connected with wind farm through a VSC-HVDC transmission system.

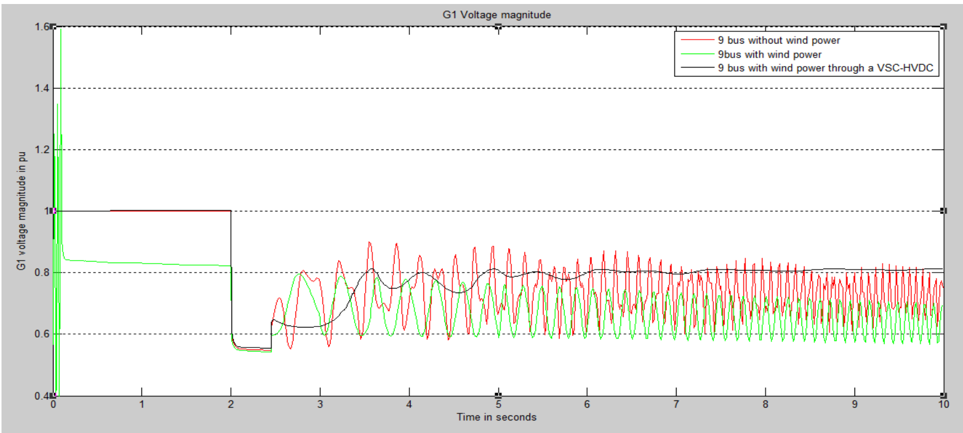

Fig. 13.G1 Voltage magnitude for a fault 2s cleared at 2.45

Similarly, fig.13 shows similar results of transient stability with regard to voltage magnitude for a conventional grid integrated with wind power through VSC-HVDC system.

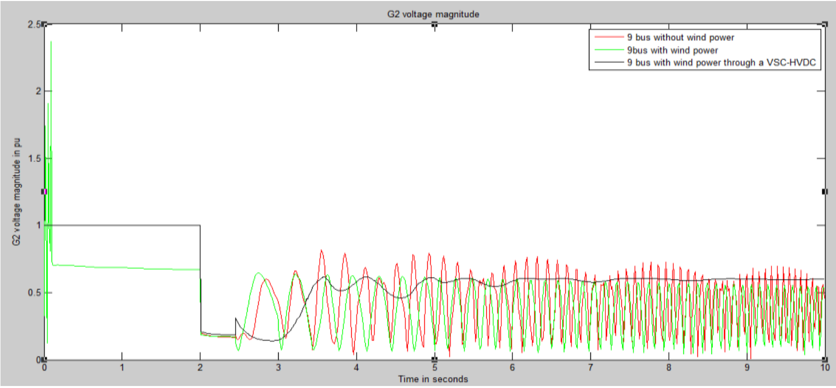

Fig. 14. G2 voltage magnitude for a fault at 2s cleared at 2.45

Fig 14 indicates transient stability for loads connected with a conventional grid, with a wind farm and with wind farm whose power is transmitted through a VSC-HVDC system. In this fig.14, it is apparent clear that the wind farm connected through a VSC-HVDC transmission system achieves transient stability faster as compared to the other two options.

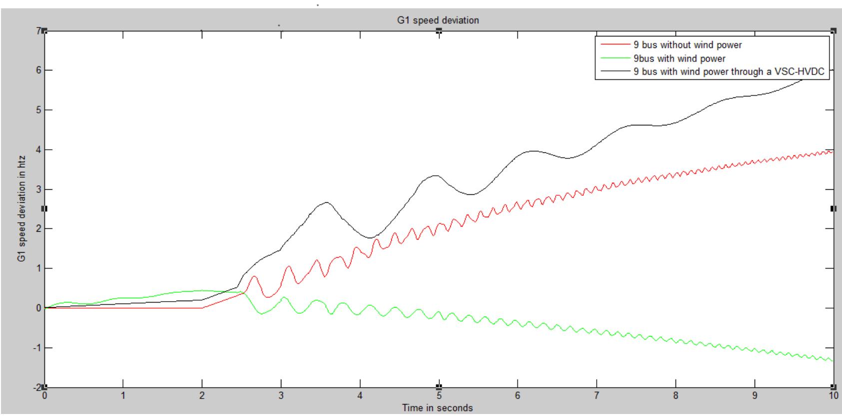

Fig. 15. G1 speed deviation for a fault 2s cleared at 2.45s

Fig. 15 shows that a system connected with a wind farm through a VSC-HVDC system achieved stability earlier than the other two combinations.

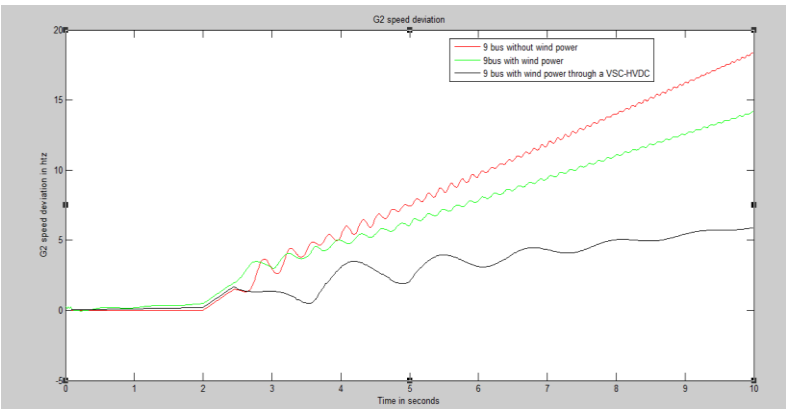

Fig. 16. G2 speed deviation for a fault at 2s cleared at 2.45

Fig. 16 shows that the speed for conventional grid and the one with wind power injection are most affected because G2 is nearer the fault than G1. Also, wind farm connected through a VSC-HVDC system has a clearing time of 0.45

VI. Discussion

In this paper, three scenarios were analyzed. The first one includes conventional 9 bus system connected without a wind farm, the second is a 9 bus conventional generation connected with a wind farm and the third one is a 9 bus system connected with a wind farm through a VSC-HVDC system. The figures 11-16 shows that a 9 bus system injected with wind power through a VSC-HVDC system demonstrated superior transient stability performance. Further, the speed deviation and the voltage magnitude shows decreasing amplitude oscillatory behaviour after fault is cleared an indication of good control of active and reactive power. The other two scenarios that consist of conventional grid without wind farm and the one injected with wind power indicate increasing amplitude characteristics after fault initiation at 2 s along the transmission line. The simulation results for the same two scenarios further shows that after the fault is cleared at 2.45s, the system oscillatory characteristics continues an indication of system instability.

VII. Conclusions

This paper has analyzed Power System transient stability improvement through A VSC-HVDC system with Large Wind Power injection. The generator 3 in a 9 bus IEEE system was replaced with an equivalent wind farm of 85MW (26.7%) of the total conventional generation). The analysis was based on three scenarios of which, the one with 9 bus connected with wind farm through a VSC-HVDC transmission system was found effective in control of Voltage, speed , active and reactive power. This is demonstrated in figures 11-16 where a three phase fault to ground initiated at 2.0 seconds was cleared at 2.45 seconds. It is therefore possible to inject large amount of wind power into a conventional grid through a VSC-HVDC system and sustain system stability.

References

[1]. M. P. Bahrman and B. K. Johnson, "the abcs of HVDC transmission Technologies," IEEE Power Energy Mag., vol. 5, no.2, pp. 32–44, 2007.

[2]. K. Kim, V. K. Sood, "HVDC transmission: Power conversion applications in power systems." in Hoboken,NJ, USA:Wiley, 2009.

[3]. V. A. N. Flourentzou and G. Demetriades, "VSC-based HVDC power Transmission systems: An overview," IEEE Trans. Power Electron, Vol. 24, no.3, pp. 592–602, 2009.

[4]. W. X. J. L. K. A. Moawwad, M. S. El Moursi, "Novel configuration and Transient management control strategy for VSC-HVDC," IEEE TRANSACTIONS ON POWER SYSTEMS, vol. 29, no. 5, pp. 2478– 2488, 2014.

[5]. ABB, "the world's longest HVDC light cable." tech. rep. available: http

[6]. W. J. Zhao, "the engineering technology of HVDC," China Electric Power Press, Beijing, 2004.

[7]. J. B. M. E. A.S. Elansari, S.J. Finney, "Frequency control capability of VSC-HVDC transmission system," AC and DC Power Transmission, 1th IET International Conference on, vol. 10, pp. 1–6, 2015.

[8]. "IEEE guide for planning dc links terminating at ac locations having low Short-circuit capacities," tech. rep., 1997.

[9]. H. W. A. Farag, M. Durrant and K. Abbott, "robust control of a VSC- HVDC terminal attached to a weak ac system," in Proc. IEEE Conf. Control Applications, vol. 1, 2003.

[10]. H. K. H. Konishi, C. Takahashi and H. Sato, "a consideration of stable Operating power limits in VSC-HVDC systems," in Proc. 7th Int. Conf. AC-DC Power Transmission, 2001.

[11]. L. Zhang, Modeling and control of VSC-HVDC links connected to weak AC systems, PhD thesis, Ph.D. dissertation, KTH, Stockholm, Sweden, 2010.

[12]. M. B. L. Harnefors and S. Lundberg, "input-admittance calculation and Shaping for controlled voltage-source converters," IEEE Trans. Ind.Electron., Vol. 54, pp. 3323–3334, 2007.

[13]. L. Z. P. Mitra and L. Harnefors, "offshore wind integration to a weak grid by VSC-HVDC links using power-synchronization control: A case study,l,"IEEE Trans. Power Del, vol. 29,no.1, pp. 453–461, Feb,2014.

[14]. L. H. Zhang and H.-P. Nee, "power-synchronization control of grid- connected voltage-source converters," EEE Trans. Power Syst,Vol. 25, no.2, pp. 809–820, May, 2010.

[15]. B. Bahrani, Advanced control strategies for voltage source converters in Microgrids and traction networks, PhD thesis, Ph.D. dissertation, Cole Polytechnique Fdrale de Lausanne, Lausanne, Switzerland, 2012.

[16]. Z. J. Guo. Q and N. L., "faults predictions and analysis on reliability of the 660 K.V. nngdong HVDC power transmission system," in Proc. 4th Int. Conf. Electric Utility Deregulation and Restructuring and Power Technol., pp. 99–103, 2011.

[17]. S. Adam, K. H. Ahmed and B. W. Williams, "new breed of network Fault-tolerant voltage-source-converter HVDC transmission system," IEEE Trans. Power Syst., vol. 28, pp. 335–346, 2013.

[18]. 'Requirements for offshore grid connections in the e.on netz network," In E.ON Netz GmbH, 2008.

[19]. P. Haugland, "it's time to connect: Technical description of HVDC light Technology,"(available at: http://library.abb.com), ABB, 2006.

[20]. O. M. W. Wang, A. Beddard M. Barnes, "Analysis of active power Control for VSC-HVDC," EEE Transactions on Power Delivery, vol. 29, issue 4, pp. 1978 – 1988, June, 2014.

[21]. J. S. Cole and R. Belmans, "Generalized dynamic VSC-MTDC model for Power system stability studies," IEEE Transactions on power. Systems, Vol. 25, no.3, pp. 1655–1662, 2010

[22]. G. Singh, "Controller design and stability analysis of VSC based HVDC Transmission system," International conference on power system and advanced control engineering (ICPACE), ISBN: 978-1-4799-8370-4, pp.344–349, 2015.

[23]. S.-K. Chung, "a phase tracking system for three phase utility interface. Inverters," IEEE Trans. Power Electron., vol. 15, no.3, pp. 431–438, 2000

[24]. A. J. Egea-Alvarez and O. Gomis-Bellmunt, "active and reactive Power control of grid connected distributed generation systems," Modelling and Control of Sustainable Power Systems, ser. Green Energy nd Technology, L. Wang, Ed. New York, NY, USA: Springer, pp. 47–81, Nov, 2012

[25]. J. B. Elansari, S.J. Finney and M. F. Edrah, "Frequency control capability of VSC-HVDC transmission system," AC and DC Power Transmission, 11th IET International Conference on, ISBN: 978-1-84919-982-7, Vol. 10, pp. 1–6, Feb, 2015

[26]. W. X. Moawwad, M. S. Moursi and J. L. Kirtley, "A. moawwad, "IEEE TRANSACTIONS ON POWER SYSTEMS, vol. 29, No.5, pp. 2478–2488, 2014.
[27]. M. B. . Wang, A. Beddard, "Analysis of active power control for VSC-HVDC," tech. rep., The University of Manchester, 2014.
[28]. C. Schauder and H. Mehta, "vector analysis and control of advanced, Static VAR compensators,"Proc. Inst. Elect. Eng., Gen. Transm. Distrib.,vol. 140, pp. 299–306, 1993
[29]. W. Liying and N. Ertugrul, "selection of pi compensator parameters for VSC-HVDC system using decoupled control strategy,"in Universities Power Engineering Conference (AUPEC), 20th Australasian, and pp.1– 7, 2010
[30]. J. S. Cole and R. Belmans, "Generalized dynamic VSC-MTDC model for power system stability studies," EEE Transactions on power Systems, Vol. 25, No.3, pp. 1655–1662, 2010.
[31]. J. B. Elansari, S.J. Finney and M. F. Edrah, "Frequency control capability of VSC-HVDC transmission system," AC and DC Power Transmission,11th IET International Conference on, ISBN: 978-1-84919-982-7, vol. 10, pp. 1–6, Feb, 2015
[32]. N. K. M.R. Hassan. L. Vanfretti, L. Wei, "Generic high level VSC- HVDC grid controls and test systems for offline and real time simulation, "Electric Power Quality and Supply Reliability Conference (PQ), ISBN: 978-1-4799-5020-1, pp. 57–64, 2014
[33]. S. Preitl and R. Precup, "an extension of tuning relations after Symmetrical Optimum method for pi and PID controllers," Automatica, Vol. 35, pp. 1731–736, 1999.
[34]. P. S. Aydin, A. Akdag and N. Hugo, "optimum controller design for a Multilevel AC-DC converter system," Proc. Of Twentieth Annual IEEE Applied Power Electronics Conference and Exposition, APEC, vol. 3, pp. 1660–1666, 2005.
[35]. M. Tsili and S. Papathanassiou, "a review of grid code technical requirements for wind farms," Renewable Power Generation, IET, Vol. 3, pp. 308–332, 2009.
[36]. Y. A. Kaplan, "overview of wind energy in the world and assessment of Current wind energy policies in turkey," Renew. Sustain. Energy Rev., Vol. 43, pp. 562–568, 2015.
[37]. L. Xu and L. Fan, "system identification based VSC-HVDC dc voltage Controller design, IEEE," 2012.
[38]. M. B. P. J. S. Gonzlez and J. R. Santos, "optimum design of transmissions Systems for offshore wind farms including decision making underrisk,"Renew energy, vol. 59, pp. 115–127, and 2013.
[39]. W. Liying and N. Ertugrul, "selection of pi compensator parameters for VSC-HVDC system using decoupled control strategy," Universities Power Engineering Conference (AUPEC), *Australasian, pp. 1–7, 2010*