Study of Inertial Frequency Response Control in Offshore Wind Farm with 5-level VSC based HVDC Transmission System

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ABSTRACT

In recent years the penetration of renewable energy power sources in many countries has increased; this, raises a significant issue with power system stability, particularly on frequency response. During large disturbances on power system network such as blackouts and tripping of power generating sources, the grid must maintain a balance between power generation and load demand to maintain frequency stability. Test models are developed in MATLAB/ Simulink with 75 doubly-fed induction generators (DFIG) with inertial response control system. The velocity of the wind is assumed to be 12 m/sec in test models to represent offshore wind farm. The Voltage Source Converter based HVDC transmission system connects the offshore wind power generating plant to the power grid. Two test models are developed based on 3-level and 5-level voltage source converter. Detail simulations were analyzed, to study the transient functioning of the power system when the wind turbines are required to exhibit inertial response. The impact of inertial response on power system stability and total harmonic distortion levels in two tests are discussed in this paper.

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ABSTRACT

In recent years the penetration of renewable energy power sources in many countries has been increased, So, raises a significant issue with power system stability, particularly on frequency response. During large disturbances on power system network such as blackouts and tripping of power generating sources, the grid must maintain a balance between power generation and load demand to maintain frequency stability. Test models are developed in MATLAB/ Simulink with 75 doubly-fed induction generators (DFIG) with inertial response control system. A velocity of the wind is assumed to be 12 m/sec in test models to represent offshore wind farm. The Voltage Source Converter based HVDC transmission system connects the offshore wind power generating plant to the power grid through. Two test models are developed based on 3-level and 5-level voltage source converter. Detail simulations were analyzed, to study the transient functioning of the power system when the wind turbines are requested to exhibit inertial response. The impact of inertial response on power system stability and total harmonic distortion levels in two tests discussed in this paper.

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I. INTRODUCTION

Using fossil fuels had a significant impact on global warming due to the release of greenhouse gases into the atmosphere. In the process of mitigating this effect, wind energy became a potential alternative power generation source adopted by many countries whose energy objective is to produce clean energy. Over a period of more than a thousand, wind energy is the sustainable energy source. Across the globe, the utilization of wind energy is becoming more and more prevalent. But only during the last decade its use on a large scale is planned and implemented. This development has come because of advances and improvements in wind turbine designs and its corresponding control systems [1]. Power generation from wind energy is the leading element in the power industry with a growth rate of more than 40 %. However, this massive growth brings new challenges. The area which suits for harnessing wind energy is usually located away from the load demand. And intermittency of wind is a significant factor which requires attention. At present, rapidly growing technology in renewable power generation sources is Offshore wind energy. Unlike the wind farms on land, these wind farms are constructed in water bodies (i.e. on oceans and sea's), where the average value of wind speed is higher when compared to the terrain.

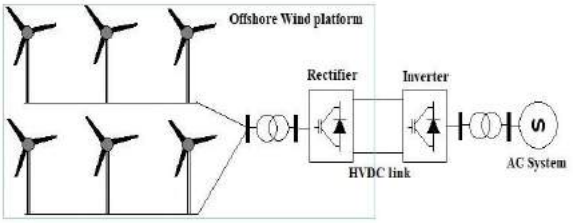

Figure 1: Schematic of off-shore wind energy system [2]

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II. INERTIAL FREQUENCY RESPONSE AND ITS IMPACT ON THE POWER GRID:

Frequency response has a notable influence on the power grid to maintain the overall power system stability. The original aspect of operating power grid reliably is, the system should be balanced always, (i.e. power generation, and load demand must be equal). If in case the generator produces extra power than the load demands the frequency will tend to increase, and if the generator produces less power than the loads demand the frequency will tend to fail. Hence there is a necessity of balancing the generation and load demand and operate the grid with reliability with the help frequency response. Frequency response is classified into three types [3].

i) Inertial Response - Supports to stabilize the initial frequency decline for few seconds. The inertial response is a turbine level frequency response control method which extracts the rotational inertia stored in the turbine to reduce the variation in frequency and support the power system initially for a few seconds during contingencies.

ii) Governor response or Primary response is delivered to supports to stabilize frequency decline within 10 seconds.

iii) Automatic Generation control (AGC) or Secondary response - Automatic generator control can take from minutes to hours to set back the scheduled frequency (i.e. 60Hz in the United States), to stabilize it, deploy the generators located at other power plants which deliver reserve power.

In recent years the installed of a wind generator is rapidly increasing, and it had made a significant impact on the grid integration. Since wind power plants are a sustainable power generating sources, to power dispatch it's preferred compared to other conventional power generating sources during off-peak load demand periods. Due to the high penetration of renewable energy sources, the possible frequency response can be extreme during the off-peak periods [4]. Hence there is a necessity to maintain an inertial response [5]. But due intermittences of wind, the wind power plants tend disturbances on the system different from that of conventional synchronous generators and are uncontrollable. The wind turbines do not exhibit inertia response because they are not directly coupled to the grid (i.e. coupled through the back-to-back converters). However modern wind turbine can display inertial response by designing the control systems in wind turbine [5]. But the drawback is the inertial response control is asymmetric. Inertial response control systems respond to only small frequency changes, Active power control is another control technique design in such a way that it responds to big events like under frequency load shedding [6].

Usually, after the loss of large power generation, the grid is undersupplied which results in a drop of the grid frequency. These frequency variations are resisted by the natural and instant response from traditional power generation sources. The momentum of turbines dominates the frequency dynamics (i.e. withstand deceleration by releasing its kinetic energy).

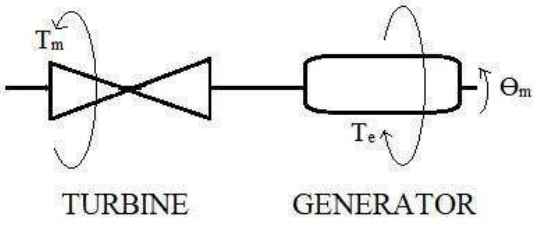

Figure 2: Electrical and mechanical torques

Generally, in electrical terms we consider two types of torques, one is mechanical torque (T_m), and the other is electrical torque (T_e) as shown in the above figure 12. In steady state, both the torques must be balanced. In case if the Te is greater than Tm, the rotation speed decreases extracting the stored kinetic energy (moment of inertia) from the turbine rotor. The developed inertia response control will increase the electric power in the range of 5-10 % of rated wind turbine power when it senses an imbalance between the load and power generation initially for few seconds to mitigate the frequency imbalance [6,7]. As we know that power is a multiplication of

torque and speed when torque is increased power will also increase correspondingly.

The detailed model of the active power control in a doubly-fed induction generator with an inertial response control system is shown in figure 3 [1]. Mechanical power extracted from the wind turbine is calculate by the tip-speed ratio of the wind turbine blades and pitch angle control. The rotor speed and turbine speed are calculated from the rotor model with inputs as mechanical power from the turbine and generator output power and derive a reference speed of the rotor. The rotor speed reference derived from the rotor model actuates the pitch angle control and rotor control mechanism. The torque order signal and the measured rotor speed form the rotor block derives the real power order (P_{ord}) to the converter circuit. The error signal generated from the power order limits block is given as input to the pitch compensation block. This block derives a pitch angle signal by comparing the actual power order and rated power [1].

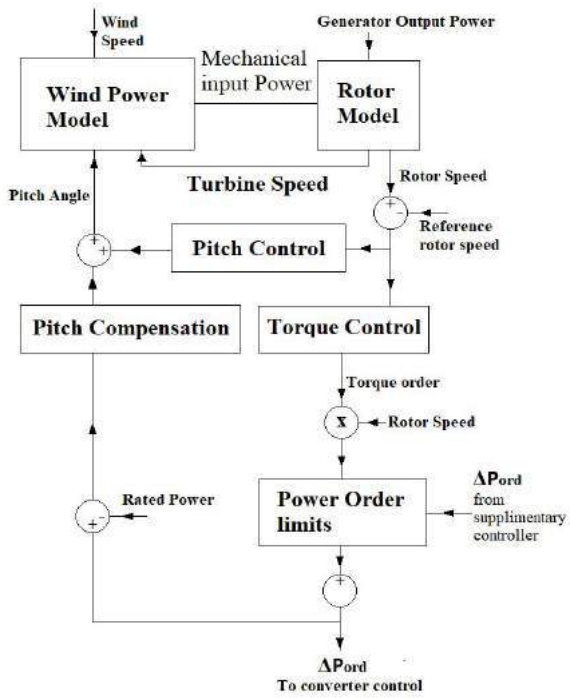

Figure 3: Active power control of Wind Turbine Generator

The measured frequency from the grid is compared with the reference frequency and the deviation is given to the frequency dead-band block as shown in figure 4. The frequency dead-band will not respond to the smaller deviations in the system frequency Since inertial control response should respond to the fault which eventually cause under-frequency load shedding.

If the measured deviation reaches the threshold value can pass through the block and passed through other low pass filters to scale the deviations approximately. The power order from the rate limiter is given to the active power control of wind turbine generators converter to deliver the increased torque power to decelerate the rotor by releasing its stored kinetic energy. During this process power increase to increase the frequency. After extracting the inertial energy, to reaccelerate the rotor the electrical power will drop allowing to recover the energy [6].

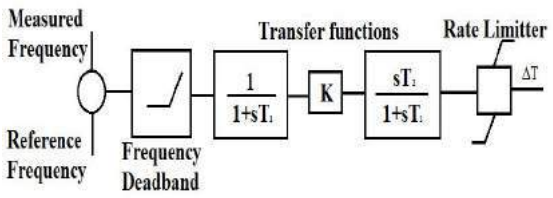

Figure 4: Schematic of the inertial response control model

Table 1: Parameters of the Inertia Control System

Parameter	Value
Frequency dead-band (p.u)	0.0025
Inertia controller gain	10
Time constant T1 in seconds	1
Time constant T2 in seconds	5.5
Rate limits, p.u/second	0.1;-0.1

The parameters used to produce the power order P_{ord} are select in such a way that the inertial response control system output is limited to only 10% of the rated value of wind turbine to reduce the impact of aero-mechanical stress on turbine [1].

III. VOLTAGE SOURCE CONVERTER

Off-shore wind energy transmission system implies long distances and extreme submarine

conditions. Therefore, High Voltage Direct Current transmission system (HVDC) is suitable; it is the advanced transmission system with low power losses. Since it uses direct current transmission, it allows asynchronous interconnections. The VSC configuration is very reliable for HVDC transmission system because of the following advantages:

- The use of reactive power compensation techniques is eliminated because both real and reactive power control can be obtained.
- There is no possibility of commutation failures in the bridge circuit.
- To change the direction of power, changing the polarity of converter stations is not necessary.
- Capable of operating in the system from islanded mode and black-out mode.
- Can be functioned with remote power generation sources to transfer power in bulk and local power generation as well with low power.

The following schematic figure 5 represents the back-to-back VSC based HVDC system.

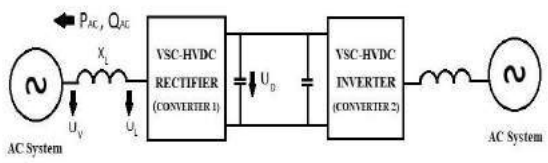

Figure 5: Schematic of VSC-HVDC system

The real and reactive power-angle control equations for the system are given by

$$P = U_D.I_D = \frac{U_L.U_{V(R)}}{X_L} \sin\delta \qquad (1)$$

$$Q = U_D.I_D = \frac{U_L.U_{V(R)}}{X_L} \cos\delta \qquad (2)$$

Where, P is the real power, the reactive power, $U_{V(R)}$ is the voltage on rectifier side, U_D is the voltage on DC side, XL is the reactance, δ is the voltage phase angle difference. $U_{V(R)}$ is proportional to the DC voltage = KuU_D (Where K_U is constant)

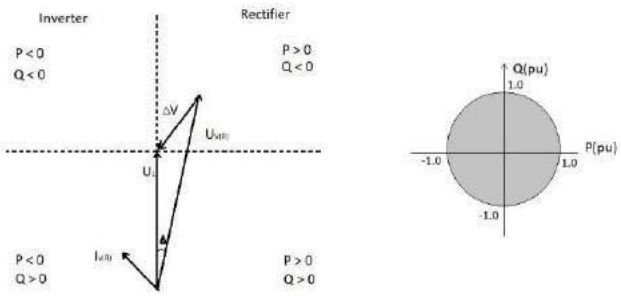

Figure 6: Phasor representation of real and reactive power

When the power is flowing from AC, the system towards a converter station the real power and reactive power are considered as positive. From the power angle equation, it's clear that both active and reactive power can have controlled by using the voltage source converter. The Pulse width modulation used in this Converter Stations Generates (VSC) the gate pulses from 3-phase sine wave (i.e. AC supply, which are then fed to the IGBT's in the rectifier and an inverter circuit). The schematic model of the five-level converter is shown in Figure 7, and Figure 8 illustrates the 5-level output voltage signals.

The calculations for designing the 5-level diode clamped converter for both rectifier and inverter design is as follows:

The number of DC bus capacitors is given by (n-1).

i.e. (5 – 1) = 4 (where n = level of converter).

Number of switches =2(n-1) =2(5-1) =2(4) = 8 switches (IGBT's)

Number of Clamping diodes = (n-1)* (n-2) = (5-1) * (5-2) = 12 clamping diodes.

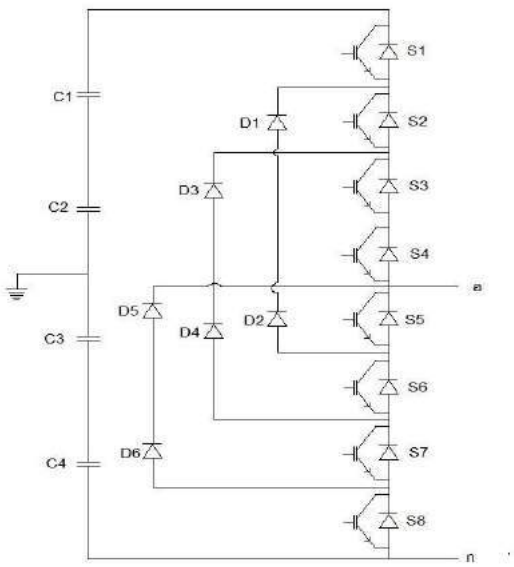

Figure 7: Schematic model of 5-level diode-clamped converter

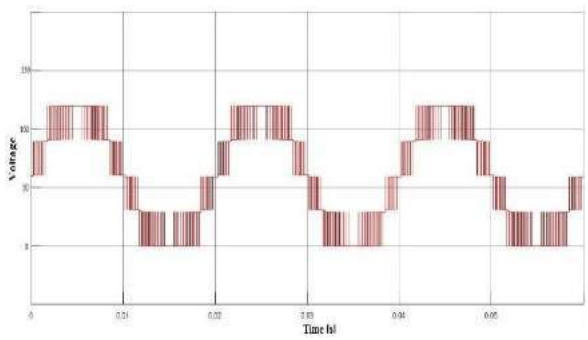

Figure 8: Five-level switching pulses

The pulse width modulation of the 5-level converter generates the gate pulses for the 8 IGBT's in the following sequence shown in table 2, where 1 and 0 indicate turn-on and turn-off state respectively.

Table 2: Switching Mechanism in a 5-level Converter [8]

Switching States	Voltage	D1 S1	D2 S2	D3 S3	D4 S4	D5 S5	D6 S6	D7 S7	D8 S8
+1	$V_{dc}/2$	1	1	1	1	0	0	0	0
+2	$V_{dc}/4$	0	1	1	1	1	0	0	0
0	0	0	0	1	1	1	1	0	0
-2	$-V_{dc}/4$	0	0	0	1	1	1	1	0
-1	$-V_{dc}/2$	0	0	0	0	1	1	1	1

IV. SIMULATION AND RESULTS

The test model designed in Simulink is operating with 230 KV voltage, 60 Hz frequency equivalent of 2000 MVA rated AC system, and it's connected to a back-to-back VSC based HVDC transmission system. Three phase three-level neutral point clamped converter system with insulated gate bipolar transistor are used at each end of the 46 miles HVDC transmission line. The gate pulses are generated from the voltage source converters (VSC) for the rectifier and inverter stations separately. In the study system, 75 double-fed induction generators (DFIG) with an output power of 2 Mega-Watts each are used [10] to represent an offshore wind with a capacity of 150 Mega-watts. This offshore wind farm is connected to a power system equivalent to 2500MVA, 230 kV 60Hz frequency through a 75 kilometers long High voltage DC system [7,9]. The wind speed throughout the test was assumed to be constant (i.e. 12 m/sec) as the average values of wind speeds are higher in offshore areas. The wind turbine model derived from [7] is used in this paper.

1 Simulation test 1

In the first case, the inertial response has been requested at t = 25 seconds, which will generate a P_{ord} pulse at this instant. The generated pulse is given to the power electronic controller of the wind turbine generator as discussed in chapter II. The following simulations show the transient behavior of the 3-level voltage source based HVDC transmission system. Figure 11 represents the rotating speed of the doubly-fed induction generator. It has been observed that when the P_{ord} is applied to the converter at t = 25 sec., the rotational speed is decreased. And the electromagnetic torque in the doubly-fed induction generator is higher than the aero-mechanical power. Figures 13 and 14 show the HVDC link voltage and current waveforms. It is noticed that at the instant P_{ord} is applied the HVDC link delivers more power to follow the inertial response behavior.

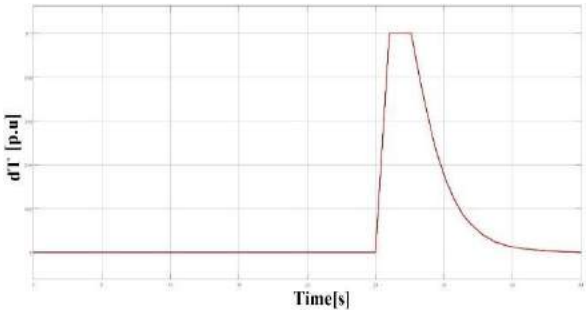

Figure 9: δT Torque pulse applied

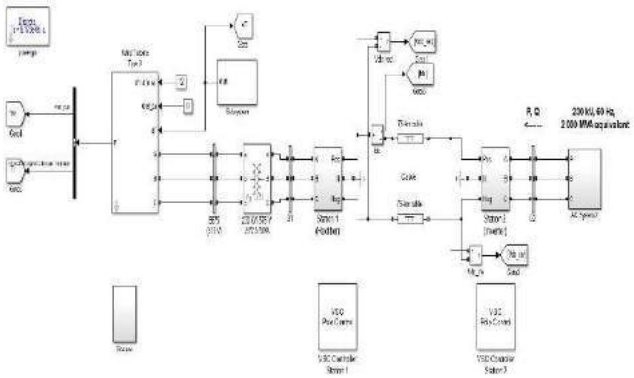

Figure 10: Simulink model of an offshore wind farm with VSC based HVDC system

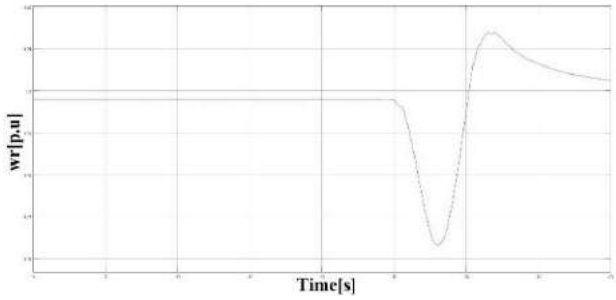

Figure 11: DFIG rotating speed in test 1

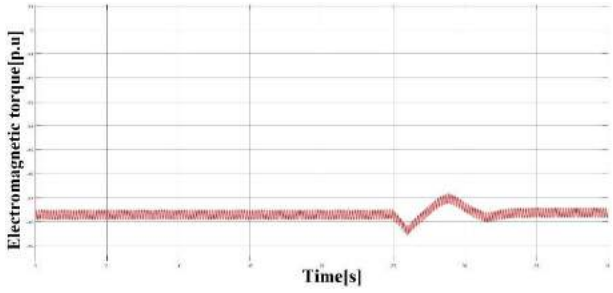

Figure 12: DFIG electromagnetic torque in test 1

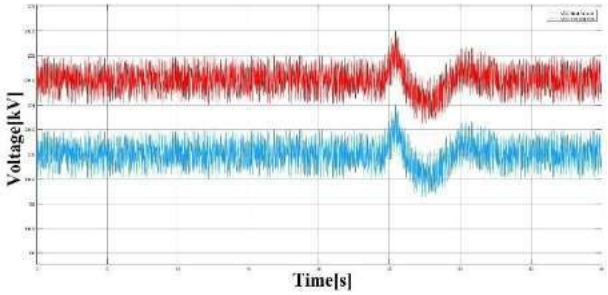

Figure 13: HVDC link voltage in test 1

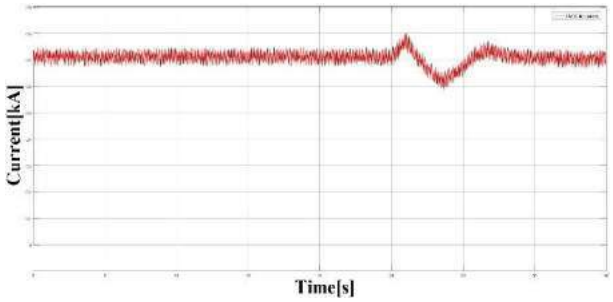

Figure 14: HVDC link current in test 1

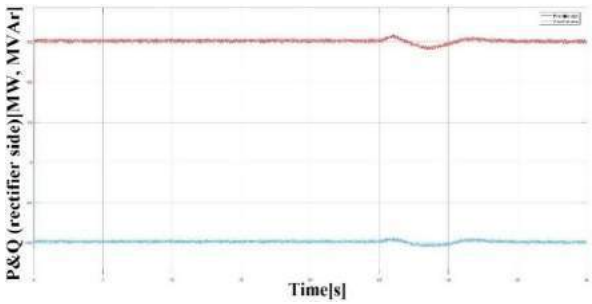

Figure 15: Active and Reactive Power (rectifier) in test 1

Figures 15 and 16 represent the real and reactive power, it's has observed during the normal operation, where the inverter output power supplied to the power grid is 124 MW. Some extra power is generated to overcome the transmission line losses, and when the inertial response is requested at t = 25 sec. the power changes to approximately 136 MW are delivering the extra power exhibiting inertial response.

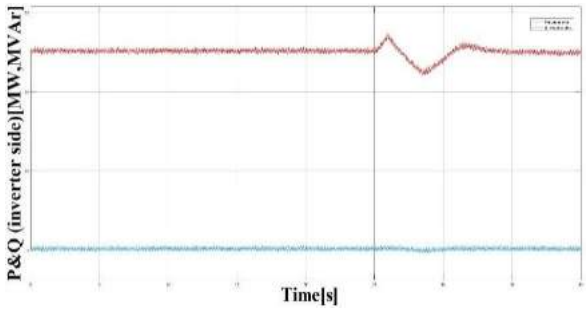

Figure 16: Active and Reactive Power (Inverter) in test 1

A generated power is proportional to the frequency when the power has increased the frequency also increase to reduce the variations in frequency during fault conditions.

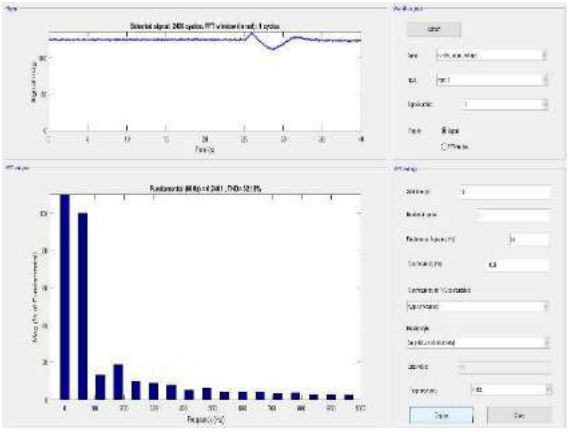

Figure 17: Analysis of Total Harmonic Distortion in three level converter

The AC voltage output from the 3-level converter is analyzed, and it showed 32.19% of Total harmonic distortion.

2 Simulation test 2

Most of the simulation test parameters are the same as the simulation test 1, but instead of three-level converters, this test is having been simulated with the 5-level converter. The flowing figures are the observed results from the test system.

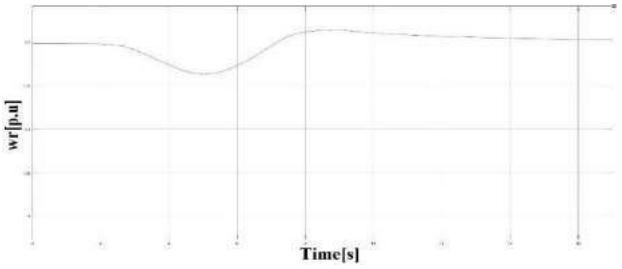

Figure 18: Rotating speed

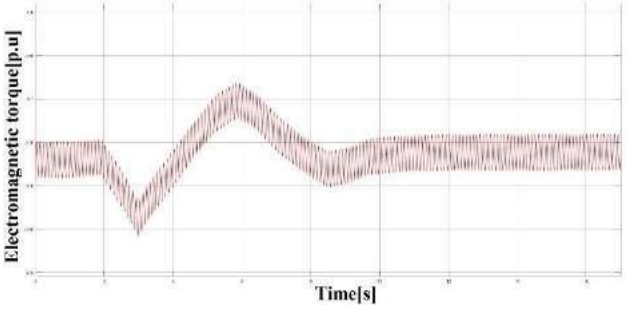

Figure 19: Electromagnetic torque

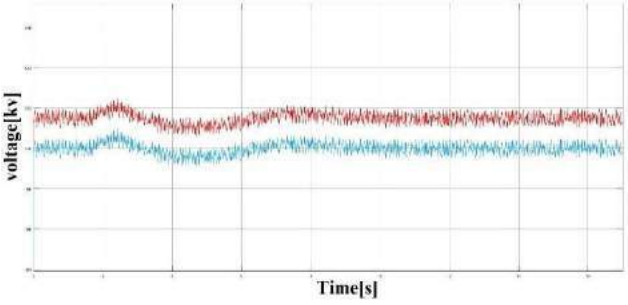

Figure 20: HVDC link voltage

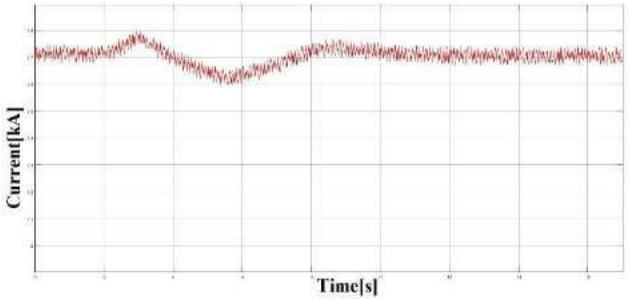

Figure 21: HVDC link currently

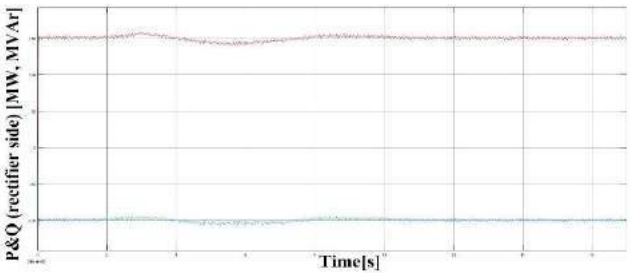

Figure 22: Active and Reactive Power (Rectifier) in test 2

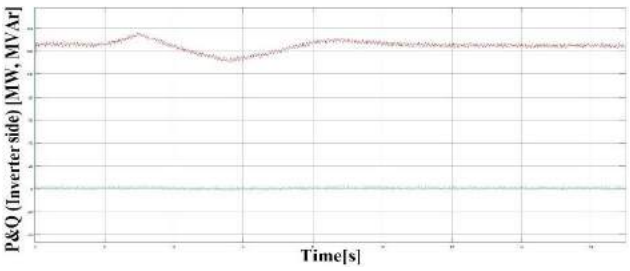

Figure 23: Active and Reactive Power (Inverter) in test 2

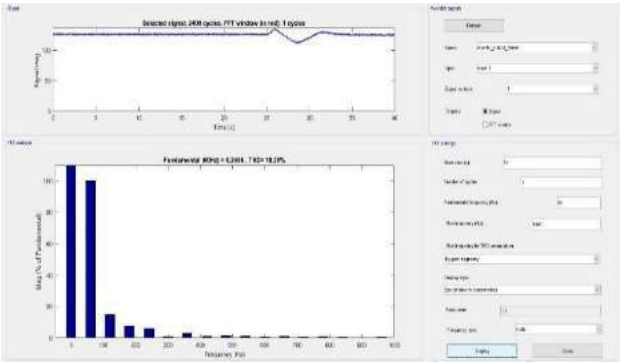

Figure 24: Analysis of Total Harmonic Distortion in five level converter

By considering the waveforms of rotating speed, electromagnetic torque, active and reactive power from rectifier and inverter side it's clear that the system is exhibiting inertial response behavior by increasing the power when the inertial response has been requested at t = 2 sec. The total harmonic distortion (THD) can be analyzed by inbuilt tool Fast Fourier Transform (FFT) analysis in Simulink. The AC voltage output from the inverter is analyzed, and it showed 18.29% of THD in the three phases 5-level converter, which is less than the value obtained in simulation test 1.

V. CONCLUSION

This opportunity was taken to study the transient behavior of the power system with inertia response control and its influence on power system stability. It has been observing that the HVDC link current increases when P_{ord} or δT pulse is agreed to the doubly-fed induction generator (DFIG) converter, the active power delivered by the HVDC system is increased from its nominal rating 150 MW to approximately 160MW to reduce the frequency variations. Both the simulation test models (i.e. Offshore wind farms delivering power through HVDC link with the configurations of three and five-level voltage source converter exhibit inertial response). This study describes the considerable impact of high wind penetration in power systems and its contribution to frequency response. It was observed that total harmonic distortion in five level converters is less compared to three level converter configurations, concluding that it is a reliable and efficient method to use multilevel converters high voltage transmission circuits.

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