OFFSHORE WIND FARMS DC GRID INERTIAL RESPONSE

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ABSTRACT – Inertial response from remote offshore wind farms (WFs) connected through point-to-point DC links relies on emulation of the onshore AC system frequency variation at each offshore wind turbine generator (WTG). This is not straight forward for a DC grid interconnecting WFs to multiple onshore AC systems. To address this problem, this paper builds up on a communication-less approach previously reported for provision of frequency services from offshore WFs connected through a DC grid. A weighted frequency scheme is adopted which relies on the fiber optic link embedded within the sub-sea cables for fast communication of onshore frequency variations up to the offshore converters. The effectiveness of the proposed approach is shown analytically and also through a case study on a 4-terminal DC grid interconnecting an offshore wind farm and two onshore AC systems.

1.Introduction:

1.1 Wind Energy

Wind energy is a renewable energy source, i.e. a clean source, which does not pollute or increase green house gases. Moreover, wind resources are plentiful and wind will not run out. Wind turbines generate no CO2, NOx or SOx during operation, and very little energy is required for manufacturing, maintaining and scrapping the plant. In fact, with moderate wind onshore sites, a wind turbine will recover all the energy spent in its manufacture, installation and maintenance in less than three months

1.1.1 Wind Turbines

Wind turbines are used to capture wind power. The standard wind power turbine of today consists of a turbine, which has three blades and the wind upwards, so the tubular steel or concrete tower is behind the turbine. The rotor captures the wind energy at the low-speed shaft. Since most generators are designed for high speed, a gear box is used and the energy is then transferred to the high-speed shaft and then to the generator. The generator is connected to a transformer to increase the voltage level to a suitable transmission level. The power in the wind of the area A, perpendicular to the wind direction, is given by the formula:

$$P = ½AV$$

where P is the power, ½ is the air density and V is the wind speed. The fraction of the energy captured by a wind turbine is given by a factor Cp, called the power coefficient.

1.2 Wind Farms

To increase the electricity produced and to keep the used land area at a minimum, wind turbines should be put together in a group, a so-called wind farm or wind park. A wind turbine always casts a wind shade in the downwind direction. In fact, there is a wake behind the turbine, i.e. a long trail of wind that is quite turbulent and slowed down, in comparison with the wind arriving in front of the turbine. As a rule of thumb, turbines in wind parks are usually spaced somewhere between 5 and 9 rotor diameters apart in the prevailing wind direction, and between 3 and 5 diameters apart in the direction perpendicular to the prevailing winds.

1.3 Offshore Wind Farms

At sea, periods of complete calm are generally extremely rare, and quite short-lived. Thus, the effective use of wind turbine generating capacity is higher at sea than on land. One of the primary reasons for moving wind farm development offshore is the lack of suitable wind turbine sites on land. Equally important, however, is the fact that wind speeds are often significantly higher offshore than onshore. An increase of some 20% at some distance from the shore is not uncommon. Given the fact that the energy content of wind increases with the cube of wind speed, the energy yield may be some 73% higher than on land. Economically optimized turbines, subsequently, will probably yield some 50% more energy at sea than at nearby land locations. Another argument in favor of offshore wind power is the generally smooth surface of water. Thus, wind speeds do not increase as much with the height above sea level as they do on land. This implies that it may be economic to use lower (and thus cheaper) towers for wind turbines located offshore. The temperature difference between the sea surface and the air above is far less than the corresponding difference on land, particularly during the daytime. Thus, the wind is less turbulent at sea than on land. This, in turn, results in lower mechanical fatigue loads and, thus, a longer lifetime for turbines located at sea. It is most economical to wash cables into the seabed (using high-pressure water jets) rather than digging or ploughing cables into the bottom of the sea. Cables have a high electrical capacitance, which may cause problems depending on the precise grid configuration and the distance to the shore. If the distance to the transmission grid on land is substantial, i.e. greater than approximately 100 km, an interesting alternative can be to connect the farms to the land using high voltage direct current connections (HVDC).

1.4 Wind power

WIND power is likely to replace a significant proportion of fossil-fuel based generation in countries like the U.K. where around 17 GWs of offshore wind power capacity are planned to be installed by 2020. Unlike conventional synchronous power plants, wind farms (WFs) do not naturally contribute to system inertia. Replacement of a significant amount of synchronous machines with wind generation would therefore cause a drastic reduction in the effective inertia of future power systems. This would result in large frequency excursions and high rates of change of frequency (RoCoF) after an event like the loss of a generating unit, impacting the system security and stability. In the future, WFs are likely to be connected to more than one onshore AC systems through a DC grid based on voltage source converter (VSC) technology to increase the flexibility in operation and security of supply. For example, a North-Sea grid and an European Supergrid are envisaged to allow effective sharing of intermittent renewable energy sources between the European countries. Emulation of onshore grid frequencies at each WTG (required to provide inertial support) is not straightforward for offshore WFs connected to multiple onshore AC systems through a DC grid. The challenge is to deal with multiple frequency variations in different AC systems which could have opposite trends. Onshore converters within a DC grid can be controlled to allow exchange of frequency support among the host onshore AC systems. Use of frequency-voltage (-) droop control together with existing power-voltage (-) droop control for autonomous power sharing has been proposed. An alternative scheme using direct communication between the AC areas is reported in. However, there is hardly any paper on the frequency support provision from offshore WFs connected through DC grids.

1.5 Dc Grid Converter Control

A. Control of Onshore Converter

As a natural extension to point-to-point HVDC links, all but one converters in a DC grid can be controlled to maintain their respective reference power while the remaining converter controls the DC link voltage, acting as a slack converter. In case of a converter outage, only the slack converter will take up the entire share of the resulting power imbalance. Moreover, the outage of the slack converter will lead to the shut down of the DC grid. For this reason use of power-voltage (P - V) droop in each converter is recommended as it allows all the converters to operate in DC link voltage control mode in order to achieve autonomous power sharing. The value of the droop constant influences the sharing of the power imbalance between the converters.

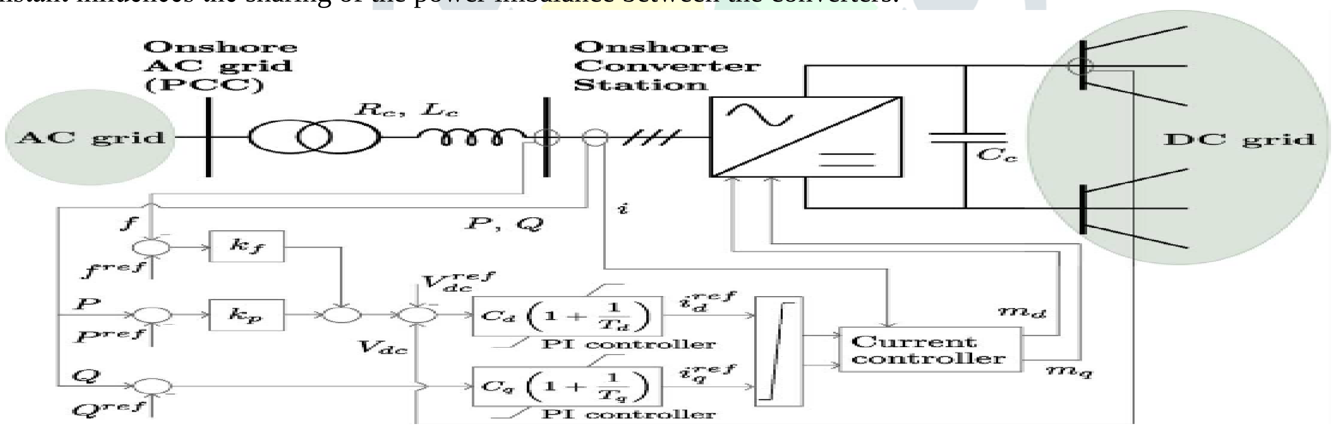


Fig 1.1: Control of Onshore converter

B. Control of Offshore Converters

The offshore converters connecting the offshore wind farms to the DC grid are required to be controlled to transfer all the offshore converters act as stiff AC voltage sources which tightly regulate the offshore AC voltage (V_{ac}) at a given frequency. The offshore frequency can be altered without significantly affecting the operation of the WF: as it is unlikely that loads will be connected directly to the offshore grid, variable frequency operation of the system is possible.

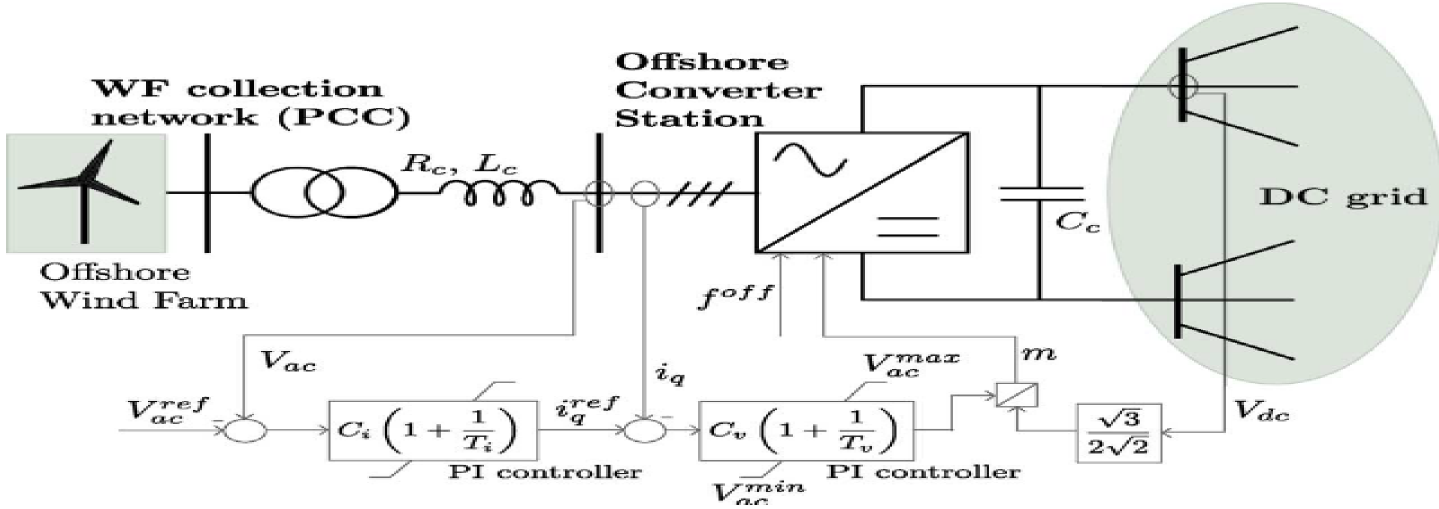


Fig1. 2: Control of Offshore converter

2.1 Basic Control

Variable speed wind turbines with fully rated converter (FRC) and permanent magnet synchronous generator are considered in this study. The control strategy for the FRC WTGs is shown in Fig. 3. This includes the control loops for each converter, maximum power point tracking (MPPT) and pitch angle control to regulate the power extracted from the wind extracting the maximum power from the wind. The pitch angle is kept to 0, which corresponds to the maximum power coefficients. Alternatively, for wind speeds above the rated one, the turbine operates in the rated regime with an increased pitch angle ( ) to limit the turbine speed and output power at their rated values.

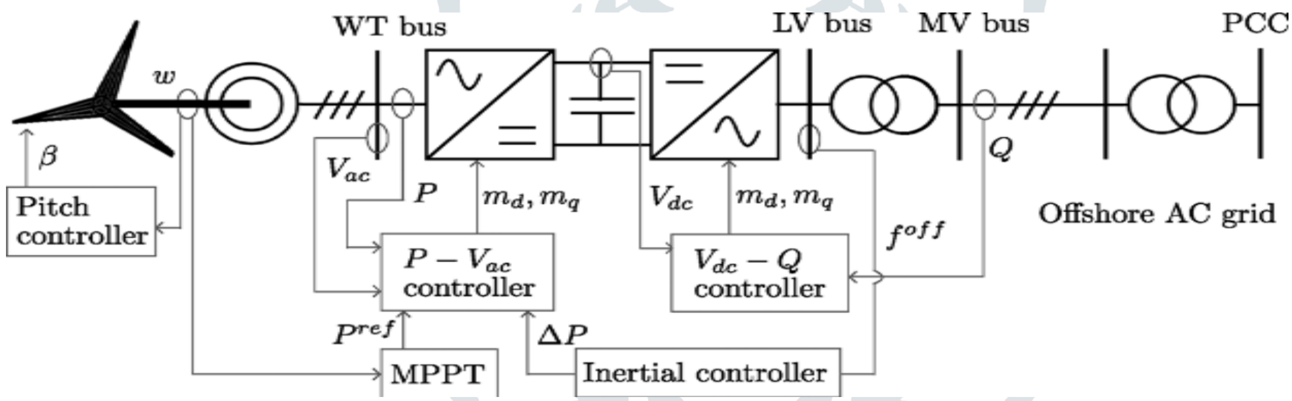


Fig 2.1: Wind turbine generator control

2.2 Inertial Control:

The WFs can provide frequency support in two ways. A possibility is to operate according to a de-loaded optimum power extracting curve. Alternatively, temporary overproduction can be achieved through the release of the kinetic energy stored in the turbine blades by slowing the speed of the turbine or pitching the blades. In this paper we consider that the inertial response of the wind farm does not depend on de-loaded operation.There are several mechanism for extracting inertial response from WTGs. Here we employ the derivative of the frequency variations to modify the power generated from the WTGs.

This particular work focuses specifically on inertial response from offshore WFs connected through DC grids. However, the proposed framework is general and also applies to primary frequency support from WFs with power reserve margin.

2.3 Emulation of onshore frequency variations at offshore wind turbine generators (WTGS)

In this section, two approaches for emulating the onshore frequency variations at the individual offshore WTGs across a DC grid are presented.

A. Communication-Less Scheme (CLS)

In order to allow WFs connected through a point-to-point DC link to participate in frequency control, communication less schemes have been proposed. The onshore converter produces a change in DC link voltage proportional to the onshore frequency variation using a frequency-voltage (f - V) droop. Using a similar f-V droop, the offshore converter sets the frequency of the corresponding offshore WF collection network in proportion to the sensed DC voltage variation at the s a proportional term. This results in perfect emulation of onshore frequency at each WTG, if the droop constants are chosen appropriately. A similar scheme was proposed in the context of offshore WFs connected to multiple onshore AC systems through a DC grid, henceforth referred to as Communication-Less Scheme (CLS). The CLS changes the frequency of the offshore WF. However, as a DC grid can have different topologies and several droop controllers, it is difficult to properly emulate the onshore frequency variations at each WF collection network. This can be explained from the expression for DC voltage at the offshore converter as derived next.

B. Weighted Frequency Scheme (WFS)

Building up on the CLS, an alternative strategy that relies on fast communication of the onshore frequency variations up to the offshore converters is proposed in this paper. The existing high speed fibre optic link embedded within a sub-sea DC cable is used for communication without any extra investment. The offshore frequency is set to follow the weighted sum of the onshore AC system frequencies which is eventually reflected in the individual WTGs through the WF collection network. Thus the onshore frequency variations are properly emulated at each WTG, triggering their inertial response. Note that presence of fibre optics communication in every cable of the DC grid is not required, but there should exist at least one communication path from each onshore AC system to each offshore WF to ensure proper emulation of the frequency event in the offshore grid. The frequency in the offshore grid is shown in Fig. 4 and can be expressed as

$$f^{off} = f^{ref} + \sum_{j=1}^{non} gj(fj - fj\,ref)$$

corresponding to the onshore converter stations. We consider that the usual practice for the wind turbines (WTs) is to provide inertial support by reducing the turbine speed, which releases the stored kinetic energy to compensate for the lack of available power and thus support a low frequency event in the AC grid. Accordingly, as WFs are meant to provide inertial response for the under-frequency events only, the weight is set to zero if the frequency variation in the th AC system ( ) is positive. Additionally, the weight coefficients are chosen such that. Situations in which the wind farm has to reduce its power output (i.e., WT speeding up and absorbing energy) that occur during fault-ride through (FRT) and periodic modulation of the WT power output for power oscillation damping are out of the scope of this study. A worst-case time delay is considered to model the latency in communication of onshore frequencies variations. In reality, this fiber optic communication delay would be much less (of the order of 1–10 ms) for most of the time.

2.4 Inertial Support Using Weighted Frequency Scheme (WFS)

An analytical formulation is presented in this section to show the effectiveness of WFS in reducing the negative frequency deviation in the onshore AC systems.We consider a generic framework in which each AC system is connected to the DC grid by ems caused by the frequency variation in system. Therefore, the proposed WFS improves the transient frequency deviation of the onshore AC systems.

In case of a DC side frequency event in converter connected to the onshore system , an opposite trend in the frequency variation of this system with respect to the rest of onshore systems is expected, as seen in the last two terms on the right hand side. As mentioned before, the elements in over-frequency events, which means that the inertia contribution from the offshore WFs would have an opposite effect in this system as compared to the rest of AC systems. Depending on the outaged converter operating mode (rectifier/inverter) the benefit in minimizing the frequency fall is obtained by either increasing the system inertia or reducing the coupling between onshore systems. Note that the above analysis is not dependant on the DC grid configuration and shows the benefit of WFS in a general framework. The simulation results shown later in Section VII are in agreement with this formulation.

2.5 Load Change in AC Systems

To demonstrate the effectiveness of inertial response using the WFS, a 40% step increase in the load connected at bus 8 in System A was considered. For this event the system response was investigated separately under high (19 m/s) and moderate (10 m/s) wind speed conditions. From here onwards, all the simulation results include - droop control at the onshore converters.

1) High Wind Speed Condition: A constant 19 m/s wind speed is considered under which the WF operates in the rated regime producing 1350 MW.

2) Moderate Wind Speed Condition: The same load event of the previous section is considered here under a moderate wind speed of 10 m/s. The WF operates in sub-rated regime and produces 680 MW. The turbine is controlled to operate at maximum power coefficient using the WFS is evident both in terms of improved RoCoF and frequency nadir as shown in Fig. 10. However, due to the recovery phase of the wind turbines, the restoration of post-event steady state is slower with a slight decrease of frequency observed after the initial support.

2.6 Change of Converter Power Reference

In the previous section the effectiveness of inertial control using the WFS was illustrated for a load event within an onshore AC system. Here a disturbance within the DC grid is considered in the form of a step increase in the power reference at converter station #1, same as in Section VII-A. The WF is assumed to operate at the rated regime producing 1350 MW.

The inertial support provided by the WF (black traces) improves the frequency nadir in System B compared to the case where only - droop control is active on onshore converters, see subplot (b). However, the additional inertial power injected by the WF causes a slight increase in the frequency of System A which is expected due to exchange of frequency support enabled by the - droop control on onshore converters. In this case, the frequency variation in System B is emulated at the offshore WF with no contribution from the positive frequency variation.

2.7 Change of Wind Speed

A sudden change in the wind speed results in variations of onshore AC system frequencies which would subsequently trigger inertial response from the WFs. To validate the control performance and the system transient response, we consider step changes to vary the wind speed. Although wind speed variations might be slower, step response simulations are interesting as they significantly affect the frequency of the onshore systems.

The presence of the inertial control using the WFS (black traces) improves the RoCoF and frequency nadir (which is not clear due to relatively long time scale) for both AC systems (System A and B) after the wind speed changes.

3.1 Inertial Response from Wind farms

The impact of displacing conventional power plants with wind farms is shown in this section. Fig. 6 (a), (b) compares these cases for two load events (7% and 14% increase in system load). The impact of these two events can be observed in Fig. 6. Synchronous machines inherently contribute to system inertia, whilst without additional control, wind farms do not participate in primary frequency control. Due to the reduction in net system inertia with wind farms, the grid frequency deviates more (first several seconds) from its nominal values. This phenomena is due to the fact that synchronous machine turbines rotate at system frequency with nearly constant rotating speed, whereas wind turbines are not synchronized to the grid but are controlled to provide maximum active power. The wind turbines contribute to primary frequency control by releasing the kinetic energy stored in the rotating mass. The stored kinetic energy is larger at higher wind speeds. Once the stored energy is exhausted, the wind turbines would have to recover that by producing less than rated power which is termed the recovery phase. Offshore wind power can help to reduce energy imports, reduce air pollution and greenhouse gases (by displacing fossil-fuel power generation), meet renewable electricity standards, and create jobs and local business opportunities.[8] However, according to the US Energy Information Agency, offshore wind power is the most expensive energy generating technology being considered for large scale deployment".[2]

The advantage Improving wind performance models, including how design conditions and the wind resource are influenced by the presence of other wind farms.

- Reducing the weight of turbine materials
- Eliminating problematic gearboxes
- Turbine load-mitigation controls and strategies
- Turbine and rotor designs to minimize hurricane and typhoon damage
- Economic modeling and optimization of costs of the overall wind farm system, including installation, operations, and maintenance

The energy per sea area is roughly independent of turbine size. Necessary data includes water depth, currents, seabed, migration, and wave action, all of which drive mechanical and structural loading on potential turbine configurations. Other factors include marine growth, salinity, icing, and the geotechnical characteristics of the sea or lake bed. A number of things are necessary in order to attain the necessary information on these subjects. Existing hardware for these measurements includes Light Detection and Ranging (LIDAR), Sonic Detection and Ranging (SODAR), radar, autonomous underwater vehicles (AUV), and remote satellite sensing, although these technologies should be assessed and refined

3.2 Planning

Offshore turbines require different types of bases for stability, according to the depth of water. Today a number of different solutions exist:

- A monopole (single column) base, six meters in diameter, is used in waters up to 30 meters deep.
- Gravity Base Structures, for use at exposed sites in water 20– 80 m deep.
- Tripod piled structures, in water 20–80 metres deep.
- Tripod suction caisson structures, in water 20-80m deep.
- Conventional steel jacket structures, as used in the oil and gas industry, in water 20-80m deep.

Floating wind turbines are being developed for deeper water.

Turbines are much less accessible when offshore (requiring the use of a service vessel or helicopter for routine access, and a jackup rig for heavy service such as gearbox replacement), and thus reliability is more important than for an onshore turbine. Some wind farms located far from possible onshore bases have service teams living on site in offshore accommodation units.[79].

3.3 Environmental impact

While the offshore wind industry has grown dramatically over the last several decades, especially in Europe, there is still a great deal of uncertainty associated with how the construction and operation of these wind farms affect marine animals and the marine environment.

Common environmental concerns associated with offshore wind developments include:

- The risk of seabirds being struck by wind turbine blades or being displaced from critical habitats;

- The underwater noise associated with the installation process of driving monopile turbines into the seabed;
- The physical presence of offshore wind farms altering the behavior of marine mammals, fish, and seabirds with attraction or avoidance;
- The potential disruption of the nearfield and farfield marine environment from large offshore wind projects.

The key benefits of offshore wind are:

- The wind resource offshore is generally much greater, thus generating more energy from fewer turbines;
- Most of the world's largest cities are located near a coastline. Offshore wind is suitable for large scale development near the major demand centers, avoiding the need for long transmission lines;
- Building wind farms offshore makes sense in very densely populated coastal regions with high property values, because high property values makes onshore development is expensive sometimes leads to public opposition.

3.4 HVDC system

HVDC plays an important role in modern power systems. With the technical development of power electronics and the rapid growth of smart grid, more and more HVDC technologies are being applied in transmission and distribution fields of power systems. Power converter is the key ac/dc energy conversion equipment, and it is generally classified into two types: current source converter (CSC) and voltage source converter. Due to the high power and maturate manufacturing level, CSC is widely selected as the basic power conversion unit in the practical HVDC projects, especially in the fields of long distance and high-voltage transmission. However, the inherent nonlinear characteristic of CSC may make it consume a certain reactive power from ac grid, and generate abundant harmonics to ac grid. Thus, harmonic suppression and reactive compensation are necessary for CSC-HVDC system.

In practical HVDC projects, ac power filters and reactive power compensators are placed at the ac grid side. It can suppress main harmonic currents not to flow into ac grid, and guarantee the power quality (PQ) of the public networks. However, it cannot consider the effects of harmonic and reactive power on the HVDC converter station itself. All the harmonic currents and reactive power components flow freely in the converter station, but there is no effective method to suppress themRegarding to the research on the harmonic transfer characteristic of the HVDC system, the switching function model has been applied earlier to study the harmonic transfer characteristic of the HVDC converter. Furthermore, modulation theory has been introduced first in to study the harmonic generation characteristic of the HVDC converter under unbalance power supply condition. The harmonic voltage and current transfer, and ac- and dc-side impedances of the HVDC converter has been established.

3.5 Technical HVDC advantages

- The HVDC power flow is fully controllable, fast and accurate. The operator or automatic controller determines how much power flows via the link.
- An HVDC link is asynchronous and can adapt to any rated voltage and frequency at reception. The HVDC link can be used to assist the AC networks at each end of the link (e.g. power system damping)
- HVDC links do not increase the systems short circuit level and fault cannot transfer across HVDC interconnected systems.
- HVDC can transport economically and efficiently over longer distance than AC lines or cables and, in a fixed corridor, HVDC transmission systems provide increased capacity.
- Large HVDC schemes (5000 MW - 6400 MW) are used to access remote hydro power resources, hence renewable energy with no CO_2 emissions.
- HVDC is more economical than HVAC for schemes with transmission distances more than 700 km.
- The main characteristics of the voltage sourced converters are a compact design, four-quadrant operation capability and high losses.Siemens is offering voltage sourced converters for HVDC applications with ratings up to 250 MW under the trade name HVDC plus Power Link Universal Systems.This paper focuses upon HVDC transmission systems with high ratings, i.e. with line-commutated current sourced converters.The advantages of a DC link over an AC link are:ansmission between AC networks A DC link allows power trwith different frequencies or networks, which can not be synchronized, for other reasons.
- Inductive and capacitive parameters do not limit the transmission capacity or the maximum length of a DC overhead line or cable. The conductor cross section is fully utilized because there is no skin effect.

- For very long distances and in particular for very long sea cable transmissions, a return path with ground/sea electrodes will be the most feasible solution. In many cases, existing infrastructure or environmental constraints prevent the use of electrodes. In such cases, a metallic return path is used in spite of increased cost and losses.
- **4.1 SIMULATION MODEL&RESULTS:**

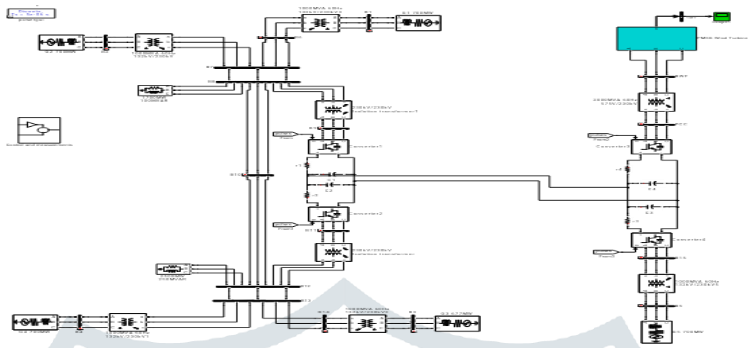
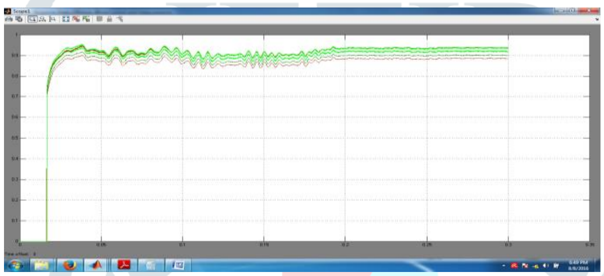
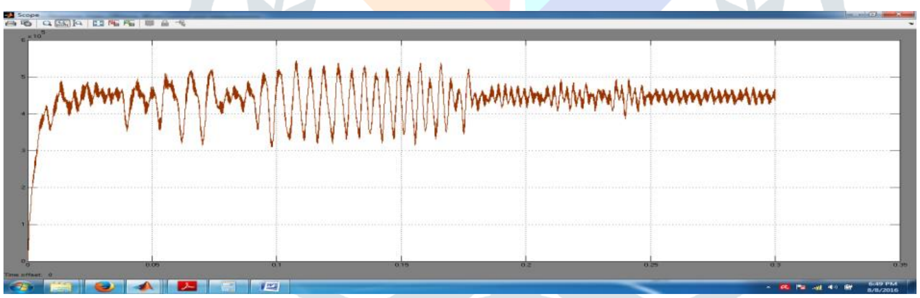
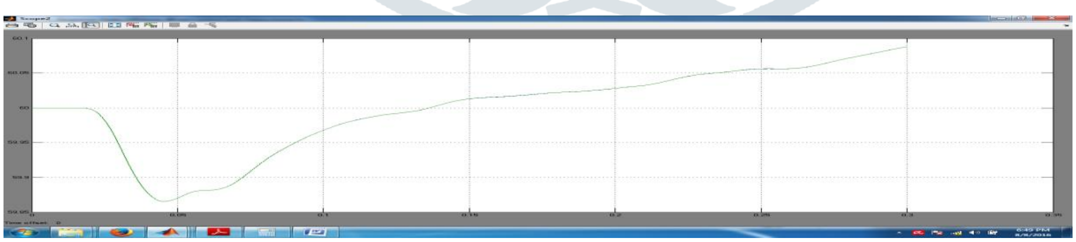
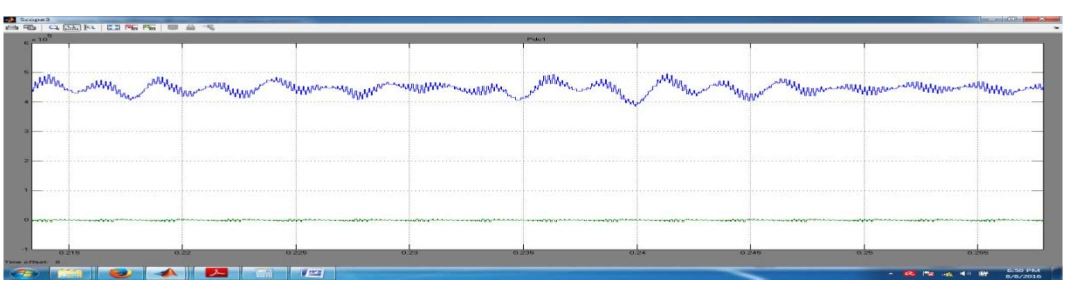


Fig 4.1: Matlab Simulink model









5. CONCLUSION

A methodology for providing inertial response from offshore wind farms connected through a DC grid is demonstrated. As an extension to a communication-less scheme reported in the literature, this paper adopts an approach where the variations in onshore system frequencies are communicated to the offshore converters using the fibre optic link embedded within the sub-sea DC cables. The analytical formulation presented in this paper shows the effective change in system inertia and frequency droop as a result of inertial support using the proposed WFS strategy. The case study on a 4-terminal DC grid connecting an offshore wind farm and two onshore AC systems also illustrates the inertial support from offshore WFs with the considered methodology. Different frequency events within the AC system and the DC grid were studied for varying wind speed conditions. It is shown that the proposed WFS approach can improve the transient frequency deviation in the AC systems experiencing under-frequency problems which is critical for secure operation of low inertia systems of the future.

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