Genetic Algorithm based Dynamic Stability Analysis of Offshore Wind Farm

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Abstract— **Wind energy is considered as a promising source among all the renewable energy sources, providing additional transmission capacity and maintains system reliability in better way. The simulink model of wind turbine driven doubly-fed induction generator (DFIG), which feeds ac power to the utility grid is presented in this paper. A novel genetic algorithm based optimization technique is proposed for wind energy system design. The doubly-fed induction generator (DFIG) is connected in between the rotor terminals and the utility grid via common dc link. The power flow between the direct current (DC) bus and the alternating current (AC) side is controlled by the grid side converter thereby allowing the system to be operated in stable power flow mode. The machine side converter provides proper rotor excitation. Offshore wind farm (OWF) driven doubly-fed induction generator connected to a power grid via high-voltage direct-current (HVDC) link is presented for stability improvement using Genetic Algorithm approach based PID controller. The PID controller containing two modules is used to provide the complete controllability of the offshore wind generation system. Genetic Algorithm provides gain parameters to the PID controller which will effectively mitigate the instability problem occurred in offshore wind generation system that shows further impact on stability of the power generation. The control algorithm intern achieves optimal tuning of PID controller parameters. The genetic algorithm based dynamic stability analysis is carried out in the MATLAB Simulink software.**

Keywords—Off-shore wind farm, Doubly-fed induction generator, PID controller, Genetic Algorithm

I. INTRODUCTION

The electric power generation using wind energy requires low cost among all the renewable energy sources. Wind electric power generation system is environmentally clean and safe renewable energy sources in the world. Research indicate that the global electric energy demand will almost reaches triple the present demand by the year 2050. Currently renewable energy sources supplying 15% to 20% of total world energy demand. According to the American wind energy association (AWEA), the installed capacity of wind grew at an average rate of 29% per year. At the end of 2014, the worldwide installed capacity of wind energy was over 368 GW. According to the report, the "moderate" scenario growth starts with 14 percent in 2014, which will tapering off gradually to 10 percent by 2020 and then down to 6 percent by 2030.

Offshore Wind Farms (OWFs) are located at a distance of less than 25 km away from seashore and May consists of several high-capacity parallel operated Wind Turbine Generators (WTGs). The use of several Doubly-Fed Induction Generators (DFIGs) directly connected to a power system is one of the simplest ways of running an Offshore Wind Farm due to the advantages of both higher operating efficiency and reactive power control of DFIGs.

The employment of an HVDC link for an Offshore Wind Form has the merits of, effective reactive-power compensation, fast active power modulation, less voltage drop on an onshore substation, etc. over conventional AC transmission lines.
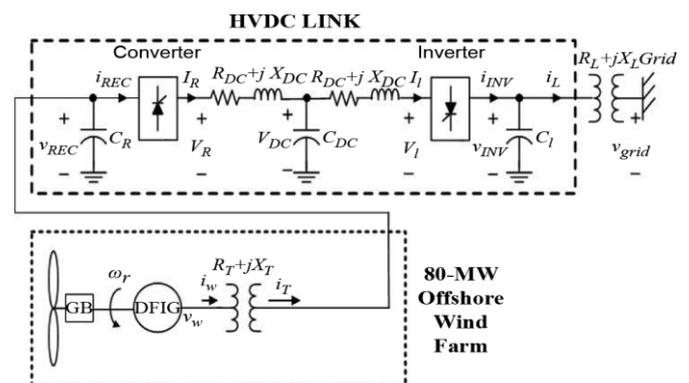
II. MODELING OF THE CONFIGURATION

Fig 1. Basic configuration of the offshore wind farm connected to an onshore power grid via line-commutated HVDC link

The basic configuration of an 80MW Offshore Wind Farm (OWF) connected to an onshore power grid via HVDC link is shown in Fig.1. The 80MW Offshore Wind Farm (OWF) is obtained by integrating forty 2MW DFIGs and is modelled by an equivalent 80MW Doubly Fed Induction Generator driven by an equivalent variable speed wind turbine through an equivalent Gear Box (GB) is presented. The output of the equivalent 80MW Doubly-Fed Induction Generator is connected to the AC input terminals of the HVDC link via step-up transformer and a connection cable.

The equivalent impedance of $R_T + j\, X_T$ represents the combined impedance of the step-up transformer and the connection cable whereas combined equivalent impedance of the AC transmission line and the step-down transformer is represented as $R_L + J\, X_L$ shown in Fig. 1. The HVDC link consists of a T-equivalent DC line, an AC-to-DC converter, and a DC-to-AC inverter. The high voltage direct current link delivers the generated power of the DFIG to the onshore power grid through a step-down transformer and an AC transmission line.

A. Doubly-Fed Induction Generator

A doubly-fed induction generator (DFIG) driven offshore wind farm consists of a wound rotor induction generator and an AC/DC/AC IGBT based Pulse Width Modulation (PWM) converter. The rotor is fed at variable frequency via AC/DC/AC converter, while the stator winding of Doubly Fed Induction Generator is directly connected to the 50 Hz power grid. The DFIG technology allows extracting maximum energy from lower wind speeds by increasing the turbine speed by minimizing mechanical stresses on the turbine during gusts of wind. The turbine speed producing maximum mechanical energy for a given wind speed is optimum and is proportional to the wind speed. The other advantage of the DFIG technology is the ability of power electronic converters to absorb or generate the required reactive power, thus eliminating the installation of capacitor banks as in the case of squirrel-cage induction generator.
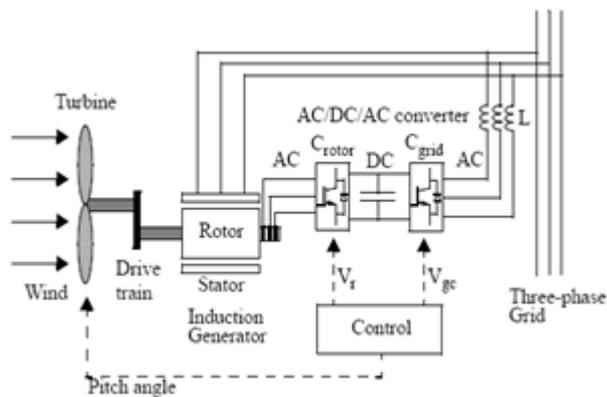

Fig 2. Basic representation of Doubly-fed induction generator with converters

Figure 2 shows the basic representation of DFIG with converters. Where V_{gc} is grid side three-phase voltage and V_r is the rotor voltage of doubly-fed induction generator. Here C_{grid} is grid side converter and C_{rotor} is rotor side converter of Doubly Fed Induction Generator (DFIG). The AC/DC/AC converter is basically a PWM converter which uses sinusoidal Pulse Width Modulation (PWM) technique. It is used to reduce the harmonics present in the wind turbine driven DFIG system. The speed of wind turbine is controlled by gear boxes or electronic control.

The operating principle of doubly-fed induction generator (DFIG) is explained with the help of power flow diagram shown in Fig.3. The Power Electronics Converter is connected to the wound rotor via slip rings to allow Doubly-Fed induction Generator to operate at a variety of speeds in response to changing wind speed, whilst the stator is connected directly to the AC mains. Indeed, the basic concept is to introduce a frequency converter between the fixed frequency grid and variable frequency induction generator.
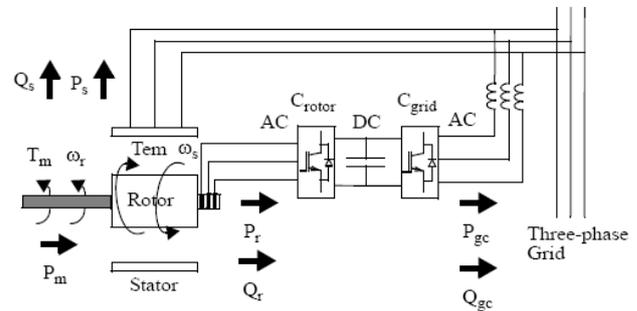

Fig -3: Power flow diagram of DFIG

The stator-side and rotor-side converters of DFIG are linked by a DC capacitor, which allows the storage of power from induction generator for further generation of electric power. To achieve full control over grid current, the DC-link voltage must be increased to a higher level than the amplitude of line-to-line voltage of power grid. The slip power can flow in both directions, i.e. from the supply to the rotor and from rotor to the supply and hence the speed of the machine can be controlled from either stator- or rotor-side converter in both super and sub-synchronous speed ranges.

As a result, the DFIG can be controlled as a motor or generator in both super-synchronous and sub-synchronous operating modes thereby realizing four operating modes. Above the synchronous speed in the generating mode and below the synchronous speed in the motoring mode is observed, rotor-side converter operates as a rectifier and stator-side converter as an inverter, when slip power is returned to the stator of DFIG. Below the synchronous speed in the generating mode and above the synchronous speed in the motoring mode, then rotor-side converter operates as an inverter and stator side converter acts as a rectifier, and slip power is supplied to the rotor. When DFIG behaves as a synchronous machine at the synchronous speed, slip power is taken from power supply to excite the rotor windings of DFIG.

B. Converter Control System

The single line diagram of the Doubly Fed Induction Generator (DFIG) is shown in Fig. 4. The rotor windings of the DFIG are connected to the low-voltage side through a Rotor Side Converter (RSC), a HVDC link, a Grid Side Converter (GSC), a step-up transformer, and a connection line, while the stator windings of the Doubly Fed Induction Generator are connected directly to the low-voltage side of the step-up transformer.
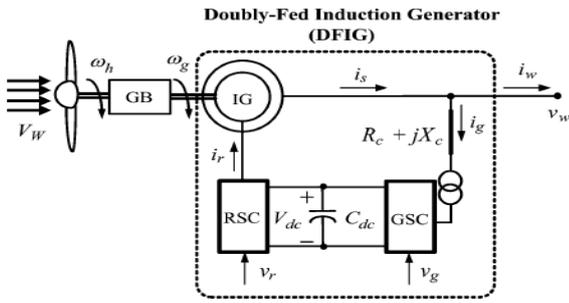
Fig 4. Single-line diagram of the doubly-fed induction generator

The per unit active power balance equation or the per unit voltage-current equation of the DC link capacitor (C_{dc}) between the GSC and the RSC of the DFIG shown in Fig. 4 can be expressed by

$$V_{dc} \cdot C_{dc}\, p(V_{dc}) = v_{qg} \cdot i_{qg} + v_{dg} \cdot i_{dg} - v_{qr} \cdot i_{qr} - v_{dr} \cdot i_{dr}$$

Where i_{qg} and i_{dg} are the pu q- and d-axis currents of the GSC, i_{qr} and i_{dr} are the per unit q-axis and d-axis currents of the RSC, respectively, v_{qg} and v_{dg} are the per unit q-axis and d-axis AC-side voltages of the GSC, respectively, v_{qr} and v_{dr} are the per unit q-axis and d-axis AC-side voltages of the RSC, respectively, and V_{dc} is the per unit DC-link voltage. To achieve the normal operation and simultaneous control over output active-power and reactive-power of a wind Doubly Fed Induction Generator (DFIG), the input AC-side voltages of the Rotor Side Converter and the Grid Side Converter should be effectively controlled.
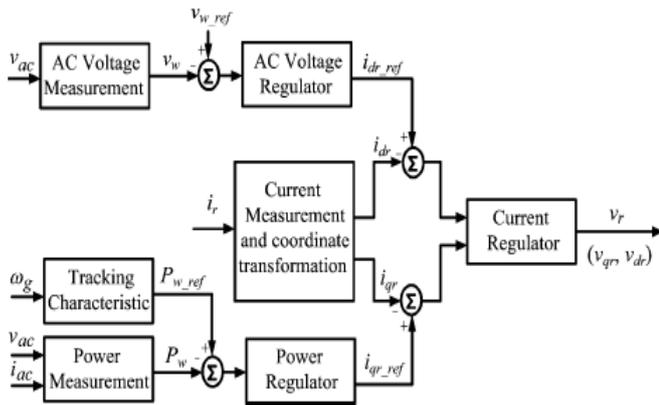

Fig -5: Control block diagram for Rotor Side Converter of the DFIG

The control block diagram for the Rotor Side Converter of the Doubly-Fed Induction Generator is shown in Fig. 5. The operation of the RSC requires i_{qr} and i_{dr} to follow the variable reference points that are determined by maintaining the output active power and the stator winding voltage of the DFIG at the prescribed values, respectively. The required voltage for the RSC (v_r) is derived by controlling the pu q- and d-axis currents of the RSC.

For d-q transformation aligned with air-gap flux for the rotor-side controller (RSC), the d-axis of the rotating reference frame is used. The actual electrical output power measured at the grid terminals of the wind turbine is added to the total power losses (electrical and mechanical) and is compared

with the reference power obtained from the tracking characteristic. An Proportional-Integral (PI) regulator is used for reducing the power error to zero,. The output of PI regulator is the reference rotor current $I_{qr\text{-}ref}$, that should be injected in the rotor by converter C_{rotor}. This is the component of current that generates the electromagnetic torque T_{em}. The actual I_{qr} component is compared to I_{qr}-ref and the error is minimised to zero by a current regulator (PI). . The current regulator is followed by feed forward terms predicts the voltage V_{qr}. The output of this current controller is the voltage V_{qr} , that is generated by C_{rotor}

The reactive power generated or absorbed by the rotor side converter C_{rotor} is used to control the voltage at grid terminals. To supply its mutual and leakage inductances, the generator absorbs reactive power and the excess of reactive power is sent to the grid or to C_{rotor}. There is exchange of reactive power between the C_{rotor} and grid, via generator.
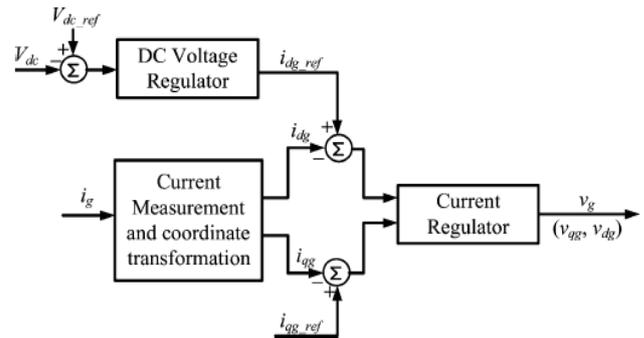

Fig 6. Control block diagram for Grid Side Converter (GSC) of DFIG

The control block diagram for Grid Side Converter of the DFIG is shown in Fig. 6.

1. A measurement system measures the DC voltage V_{dc} and q-axis and d–axis components of AC currents are to be controlled.
2. An outer regulation loop consists of a DC voltage regulator.
3. An inner current regulation loop consists of a current Regulator.

The i_{dg} and i_{qg} are the per unit d-axis and q-axis currents of the Grid Side Converter (GSC) respectively. They are determined by maintaining the DC link voltage V_{dc} at the setting value and maintaining the unity power factor at output of the Grid Side Converter (GSC) respectively to track the reference points. By controlling the per unit d-axis and q-axis currents of the GSC, the required per unit voltage of the GSC (v_g) is derived.

III. OPERATIONAL DYNAMIC STABILITY CHARACTERISTICS OF A DFIG DRIVEN BY A WIND TURBINE

An 80-MW offshore wind farm consists of forty 2MW Doubly Fed Induction Generators driven variable speed wind turbines connected to a 25kV distribution system and exports power to a 120kV power grid via 30km transmission line from 25kV feeder. The wind turbines have a protection system that monitors current, voltage and machine speed.

The line-commutated HVDC link model comprises a DC-to-AC inverter, AC-to-DC converter, and a DC line. The selection of base values for both AC and DC quantities should be such that, the per unit values of DC quantities should be remains unchanged when they are changed to the synchronous reference frame of the AC system. The per unit output DC current and voltage of the AC-to-DC converter should be properly converted with reference to the dq-axis of the AC system. The DC link voltage of the Doubly Fed Induction Generator is also monitored with simulation

IV. SIMULINK DIAGRAM

The Simulink diagram of a doubly fed induction generator connected to grid side converter with wind turbine protection schemes. The protection scheme is used for protecting offshore wind farm over single phase faults and ground faults and also under various disturbance conditions and wind speeds.
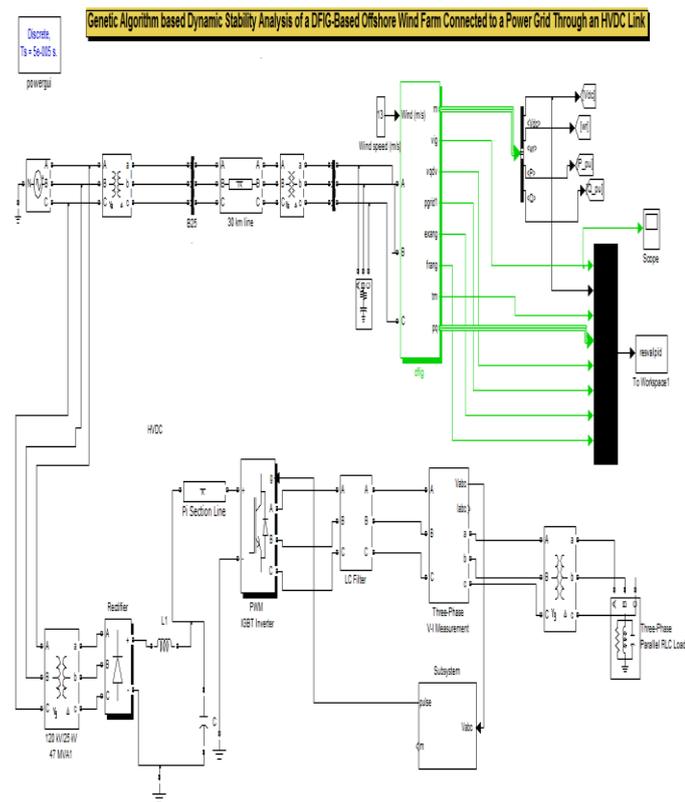

Fig 7. Simulink model of Genetic Algorithm based dynamic stability analysis

The simulink model of genetic algorithm based dynamic analysis of doubly-fed induction generator driven offshore wind farm is shown in Fig.7. An 80MW offshore wind farm is connected to a power grid via an high-voltage direct-current (HVDC) link, which is obtained by aggregating fourty 2MW Doubly Fed Induction Generators and is modelled by an equivalent 80MW Doubly Fed Induction Generator driven by an equivalent variable speed wind turbine through an equivalent gear box (GB) via step down transformers, fault protection system and pi-transmission line.

The turbines of offshore wind farm uses a doubly-fed induction generator (DFIG) consisting of an AC/DC/AC IGBT-based Pulse Width Modulation (PWM) converter and a wound rotor induction generator. The rotor winding of DFIG is supplied at variable frequency via AC/DC/AC converter while stator winding is directly connected to the 50 Hz power grid. The DFIG technology allows extracting maximum energy from the lower wind speeds by optimizing speed of wind turbine. The other advantage of DFIG technology is minimizing mechanical stresses on the wind turbine during wind gusts.

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The simulink model containing offshore wind turbine model that allows dynamic stability analysis with long simulation times. In this, the system is observed during 200 s. The simulink model of doubly-fed induction generator (DFIG) based offshore wind farm with PID controller is shown in Fig.8.
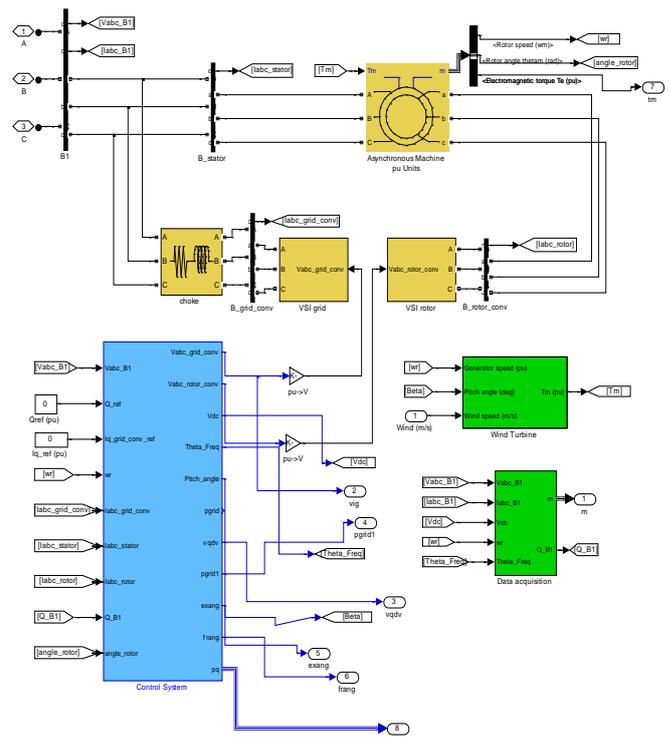

Fig 8. Simulink model of DFIG fed offshore wind turbine with PID controller

The maximum mechanical energy is produced for optimum turbine speed for a given wind speed is proportional to the wind speed. The rotor is running at sub synchronous speed for wind speeds lower than 10 m/s. At higher wind speeds, the rotor is running at hyper synchronous speed. Another advantage of the DFIG technology is the ability of power electronic converters to absorb or generate the required reactive power, thereby eliminating the requirement of capacitor banks installation as in case of squirrel cage induction generators.

V SIMULINK DIAGRAM

The Dynamic responses of the DFIG fed offshore wind farm system with and without the PID controller under a pulsed torque disturbance is shown in Figures obtained with simulation using Genetic Algorithm.
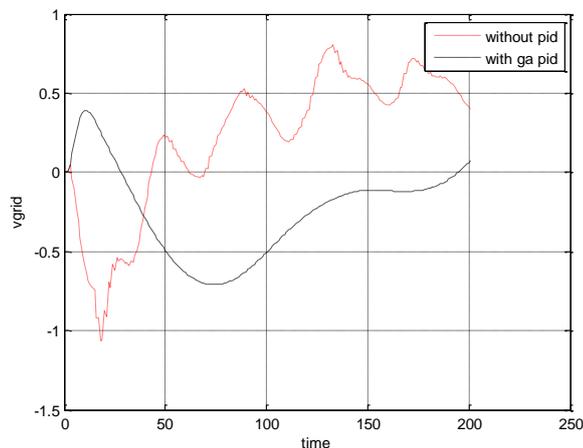

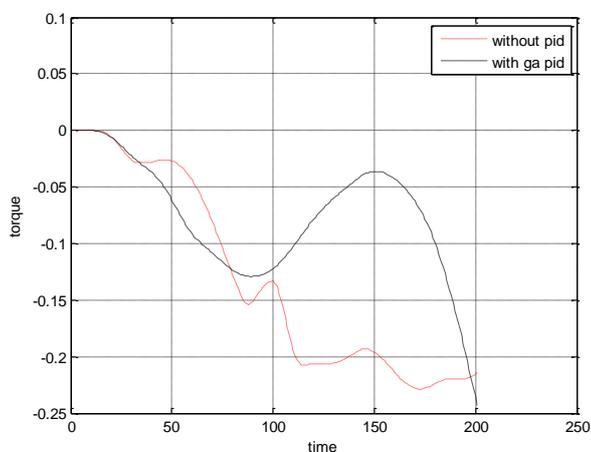Fig 9. Terminal voltage of Power Grid.
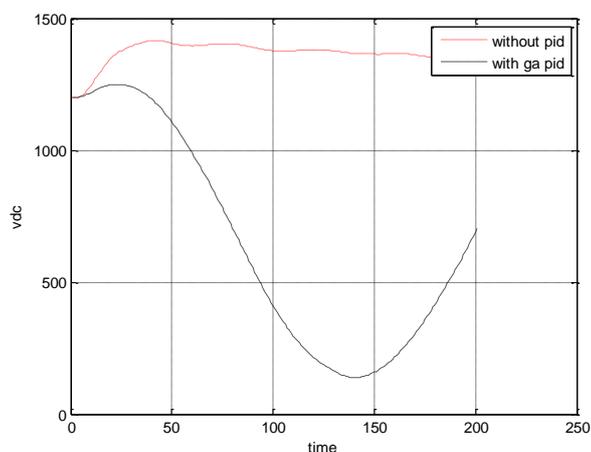

Fig 10. Mechanical input torque of DFIG

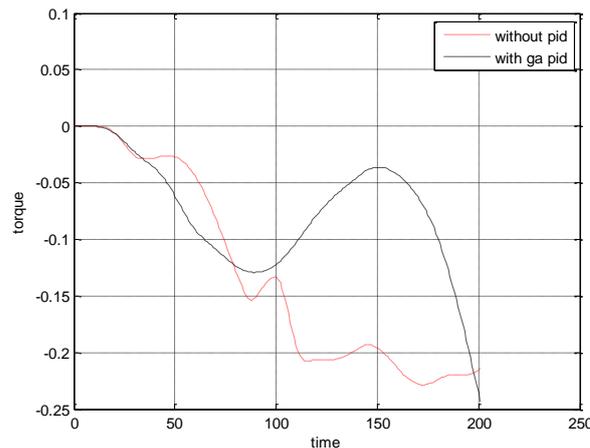Fig 11. DC-link voltage of HVDC link

Fig 12. Mechanical input torque of DFIG

CONCLUSION

The simulink model of a Doubly-Fed Induction Generator driven offshore wind farm is presented with both mitigation of power fluctuations and damping enhancement of a DFIG-based offshore wind farm using a line-commutated HVDC link joined with a Genetic algorithm designed PID controller. For best efficiency the DFIG system connected to grid side is used which has better control. The rotor side converter (RSC) usually provides reactive and active power control of the DFIG machine while the grid-side converter (GSC) keeps the DC-link voltage constant. So finally we simulated wind turbine and grid side parameters and the corresponding results have been displayed. When wind speed decreased to a lower value or it has persistent fluctuations, faults can occur. During short-circuit periods, doubly fed induction generator can provide a considerable grid voltage support. Considering the results it is proved that doubly fed induction generator is more reliable and stable system when connected to grid side with the proper converter control system of genetic algorithm based PID controller. The HVDC link joined with the designed PID controller based on genetic algorithm mitigates the power fluctuations in Doubly-Fed Induction Generator driven offshore wind farm effectively.

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