Parallel Operation of Permanent Magnet Synchronous Generator Based Windmills Connected to HVDC-VSC Link

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***Abstract*— Development and implementation of a control scheme for wind farms based on Permanent Magnet Synchronous Generators (PMSGs) connected to a single HVDC-VSC converter is the main objective of this paper. The presented scheme is based on computing the optimal frequency at which the power converter must work to extract the maximum power from parallel operated PMSG based windmills. The power extraction from wind turbines connected to PMSGs and its control, grid-side converter control which is connected to AC grid are discussed in detail. The control scheme is validated by means of case studies using PSCAD/EMTDC simulation software on a wind farm consisting of two wind turbines.**

Keywords*— *Permanent Magnet synchronous generator; Maximum power extraction; High Voltage Direct Current – Voltage Source Converter.

I. Introduction

Large scale wind farms consisting of wind turbines of huge size in MW coupled to different types of electrical generators like Squirrel Cage Induction Generators (SCIGs), Doubly Fed Induction Generators (DFIGs), Synchronous Generators (SGs) and Permanent Magnet Synchronous Generators (PMSGs). The aggregate of power output from these wind farms will be in few hundreds or sometimes in few thousands of MW. Due to the non-availability of land space and presence of high wind velocity at the middle of the ocean, offshore wind farms are more popular nowadays for not only generating electrical power but also providing ancillary services [1]. The interconnection of these wind farms offers lot of technical challenges because of the location of the units and the stochastic nature of produced power [2].

Most of the offshore wind turbines are direct drive wind turbines coupled with PMSGs delivering power through full scale power converters [3]. In order to transfer the power generated from remote offshore wind farms to onshore AC grid, High Voltage AC (HVAC) or High Voltage DC (HVDC) transmission system is essential. HVDC technology has proven its superiority over HVAC for long distance transmission lines and submarine applications [2], [4]. In general HVDC technology is based on either Line Commutated Converters (HVDC-LCC) or Voltage Source Converters (HVDC-VSC) [1], [2], [4].

In literature, centralized power converter based HVDC power transmission has been investigated for offshore wind farms with SCIGs [5] and SGs [6]. Another topology, which has a central power converter at grid side and individual converter for each wind turbine, has been proposed for power transfer from DFIG based offshore wind farms [7]. In this paper, a controlled scheme for PMSG based offshore wind farms connected to a centralized HVDC-VSC converter has been investigated. In the presented technique, the sending end HVDC-VSC is responsible for maximum power point tracking, which is achieved by making a variable frequency offshore grid. The tip speed ratio and power coefficient of individual wind turbines are used to find the optimal frequency at which the offshore gird needs to operate to extract the maximum power [6]. The Field Oriented Control (FOC) is employed at wind farm power converter and conventional d-q current control is used for grid side converter. The procedure explained in [8] has been used for tuning the PI controllers of both wind farm and grid side converters. In this work, parallel operation of PMSG based wind turbines connected to AC grid through a HVDC-VSC link is simulated using PSCAD/EMTDC software. Different case studies with machines of same and different rating under normal and abnormal grid conditions have been performed and the results are presented.

II. Wind Turbine System

A. Wind power, P_w

The power available in the wind can be written as

$$P_w = \frac{1}{2}\rho A v_w^3 \tag{1}$$

where Pw is the air stream kinetic power (W), ρ is the air density (kg/m^3), A is the swept area of the rotor (m^2), v_w is the wind speed (m/s).

B. Wind turbine power generation, P_{wt}

Power generated in a single wind turbine is given as

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$$P_{wt} = C_p * P_w = \frac{1}{2} C_p \rho A v_w^3 \quad (2)$$

where C_p is the power coefficient which is the percentage of power in the wind that is converted in to mechanical power.

C. Power coefficient and Tip speed ratio

Let C_p be the power coefficient which can be written as

$$C_p(\lambda, \theta_{pitch}) = c_1 (c_2 \frac{1}{\Lambda} - c_3 \theta_{pitch} - c_4 \theta_{pitch}^{c_5} - c_6) e^{-\frac{c_7}{\Lambda}} \quad (3)$$

where θ_{pitch} is the pitch angle and λ is the tip speed ratio defined as,

$$\lambda = \frac{\omega_t R}{v_w} \quad (4)$$

$$\frac{1}{\Lambda} = \frac{1}{\lambda + c_8 \theta_{pitch}} - \frac{c_9}{1 + \theta_{pitch}^3} \quad (5)$$

where $[c_1, \ldots, c_9]$ are characteristic constants for each wind turbine.

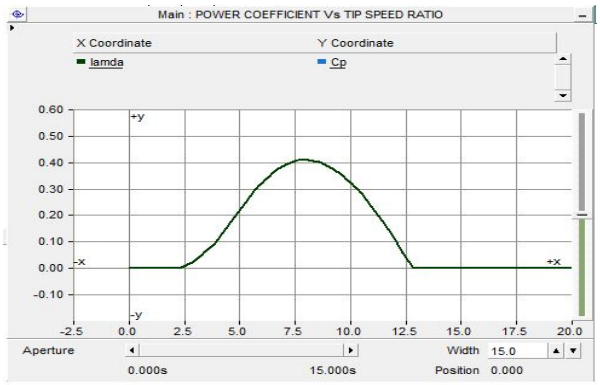

Fig.1 power coefficient Vs tip speed ratio of typical wind turbine

A typical $C_p - \lambda$ curve is shown in Fig.1. The $C_p - \lambda$ curve has a maximum value which corresponds to the optimum operating point of the wind turbine to extract maximum power at the corresponding wind velocity.

D. Wind farm power analysis

The total power generated by a wind farm composed of N_{wt} number of wind turbines can be written as

$$P_{wf} = \sum_{i=1}^{N_{wt}} P_{wti} \quad (6)$$

If all the wind turbines are of equal rating then all the constants will have the same value.

$$P_{wf} = \frac{1}{2} \rho A \sum_{i=1}^{N_{wt}} C_{pi} v_{wi}^3 \quad (7)$$

Equation (7) can be rewritten as,

$$P_{wf} = \frac{1}{2} C_p \rho A \sum_{i=1}^{N_{wt}} v_{wi}^3 \quad (8)$$

For instance, if two wind turbines are subjected to different wind speeds then the power generated by the individual wind turbine and the aggregated power of both the wind turbines at different electrical frequency of stator voltage can be plotted as given in Fig. 2.

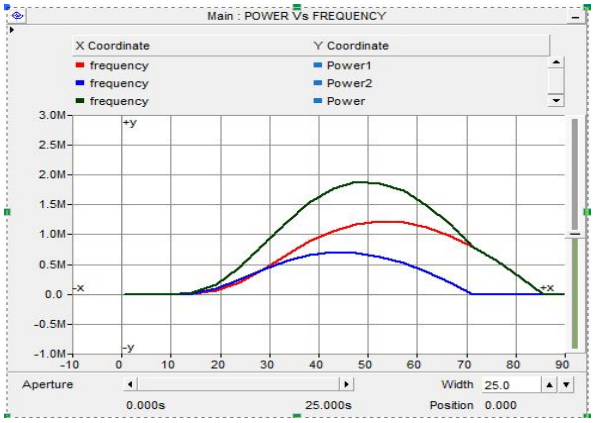

Fig. 2 Generated power Vs. frequency

In order to extract the maximum power from the wind farm, the operating frequency of the wind farm converter has to be set at the optimal frequency corresponding to the peak point of the aggregated power (P) as indicated in Fig.2.

E. Wind farm electrical analysis

The schematic of the electrical system considered for investigation in this work is shown in Fig.3. It has the wind farms with two wind turbines. Each wind turbine is coupled with a PMSG, whose stator terminals are connected to the wind farm transformer. The wind farm transformer is feeding the whole wind farm power to the grid through HVDC-VSC link.

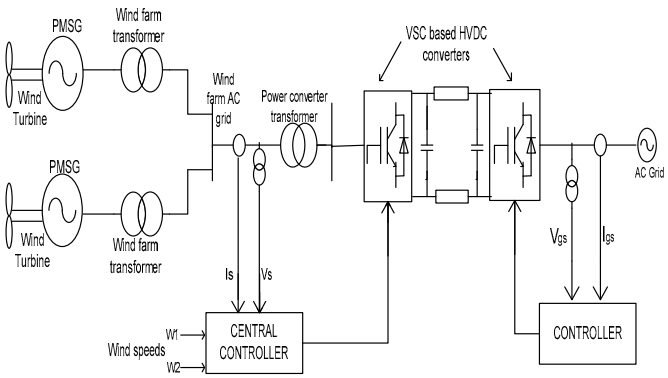

Fig. 3 Offshore wind farm connected to the main AC grid through HVDC-VSC link

(i) Wind farm electrical grid: Referring all the electrical quantities to the generator side and considering all the voltages and currents with respect to the synchronously rotating reference frame, the wind farm voltage can be written as:

$$v_{sq} = v_{cq} + R_l i_{sq} - L_l w_e i_{sd} + L_l \frac{d}{dt} i_{sq}$$
$$v_{sd} = v_{cd} + L_l w_e i_{sq} + R_l i_{sd} + L_l \frac{d}{dt} i_{sd} \quad (9)$$

where v_c is the converter side voltage, v_s is the wind farm grid voltage and i_{sd} , i_{sq} are the total wind farm currents in rotating reference frame. The wind farm power converter transformer is modeled as RL series branch with resistance R_l and inductance L_l. Here, sub-indexes d, q stand for direct and quadrature axis quantities in the rotating reference frame.

The active power and reactive power provided by the wind farm power converter can be written as

$$P_c = \frac{3}{2}(v_{sd} i_{sd} + v_{sq} i_{sq})$$
$$Q_c = \frac{3}{2}(v_{sq} i_{sd} - v_{sd} i_{sq}) \quad (10)$$

(ii) Permanent magnet synchronous generator: The PMSG stator voltage with respect to the rotating reference frame can be written as:

$$v_{gq} = r_s i_{gq} + \omega_r L_q i_{gq} + L_q \frac{d}{dt} i_{gq} + \lambda_m \omega_r \quad (11)$$

$$v_{gd} = r_s i_{gd} - \omega_r L_d i_{gd} + L_d \frac{d}{dt} i_{gd} \quad (12)$$

where i_{qd} , i_{gq} are the generator currents and v_{gd} , v_{gq} are generator voltages in rotating reference frame. The generator stator winding resistance is r_s , λ_m is the flux due to permanent magnet, and L_d and L_q are the generator inductances. The generator torque can be expressed as

$$T_m = \frac{3}{2} p(\lambda_m i_{gq} + (L_d - L_q) i_{gq} i_{gd}) \quad (13)$$

where, p is the number of pole pairs of PMSG.

The FOC plays a significant role in the control of PMSGs, which makes it possible that PMSGs can be controlled as easily as DC machines. In FOC approach, the flux producing current component, i_d and the torque producing current component, i_q are along the d-axis and q-axis respectively. Thus, the dq-axes currents can be controlled independently by two closed loop controls, which indirectly controls the speed and the torque of the PMSGs.

III. Control Startegy

In the wind turbine PMSG system discussed in section II, there are three control variables as follows: the optimal power generated by the PMSGs at different wind speed, the active and reactive power injected into the grid and the DC link voltage of the HVDC-VSC link. In this system, the wind farm side converter regulates the speed of the PMSGs to implement the MPPT control. Meanwhile, the grid-side converter controls the active and reactive power injected into the grid and the DC link voltage.

A.Generator-side converter

Generator electromagnetic torque can be expressed as

$$T_e = \frac{3}{2} p(\lambda_m i_{gq} + (L_d - L_q) i_{gq} i_{gd}) \quad (14)$$

In a surface mounted PM machine which is considered in this case study, the d-axis and q-axis inductances are equal ($L_d = L_q$) . Thus, the torque expression can be simplified as

$$T_e = \frac{3}{2} p(\lambda_m i_{gq}) \quad (15)$$

From the above expression, it is clear that there is a linear relationship between the electromagnetic torque and q-axis current i_q, such that the electromagnetic torque is easily controlled by regulating the q-axis current. The control scheme of the wind farm side converter is shown in Fig. 4.

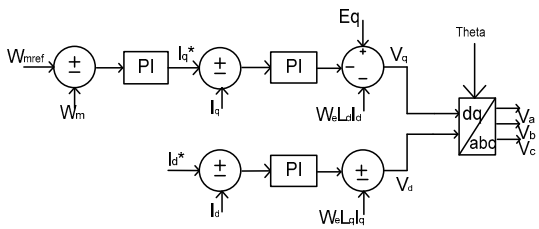

Fig. 4 Wind farm side converter control scheme

As stated earlier, the FOC approach coupled to the optimal tip speed ratio based MPPT control strategy is applied here as the control algorithm for the wind farm-side power converter. As seen in Fig. 4, there are three feedback loops in the control system: speed control loop, q-axis current control loop and d-axis current control loop. In the speed control loop, at every sampling time, the actual speed of the generator is sensed and compared with its reference value, which is generated by the optimal tip speed ratio control. Then the error in speed is sent to a PI controller which provides the reference q-axis current (i_q*). The reference d-axis current, i_d*, is always set at zero. The q-axis reference current obtained from the speed control loop and d-axis reference current are used in the respective current control loop. In the current control, three-phase stator currents are sensed and transformed into the dq-axes reference frame using Park's transformation. The PI controllers present in the current control loop provide reference stator voltages in dq-axis reference frame. The dq-axis reference voltages are transformed into abc frame by inverse Park's transformation. Sinusoidal Pulse Width Modulation (SPWM) approach is

employed as the modulation strategy in this work, because it generates less harmonic distortion in the output stator voltage/current and leads to more efficient use of the DC supply voltage than the conventional Pulse Width Modulation (PWM). The output of the SPWM strategy are six PWM signals to control the ON/OFF state of the six IGBT switches in the wind farm side converter.

B. Grid-side converter

As stated earlier, the main objective of the grid-side converter control is to regulate the active and reactive power fed to the grid and the dc link voltage. The expressions of the active and reactive power injected into the grid can be written as follows

$$P_g = \frac{3}{2}(v_{gd} i_{gd} + v_{gq} i_{gq})$$
$$Q_g = \frac{3}{2}(v_{gq} i_{gd} - v_{gd} i_{gq}) \tag{16}$$

where, i_{gd} and i_{gq} , are the grid currents, and v_{gd} and v_{gq} , are the grid voltages in dq-axes reference frame. From the above expressions, it can be understood that the d-axis and q-axis components of the grid currents and voltages are coupled in cross-product fashion in the reactive power term, which makes the active power and reactive power control complex. In order to tackle this cross coupling issue, the Voltage Oriented Control (VOC) approach is selected for the grid-side converter control. In the VOC approach, the *q*-axis of the rotating reference frame is aligned with the rotating grid voltage space vector. Accordingly, the d-axis component of the grid voltage space vector is equal to zero. Using VOC approach, the expressions of the active and reactive power can be written as follows

$$P_g = \frac{3}{2}(v_{gq} i_{gq}) = v_{dc} i_{dc}$$
$$Q_g = \frac{3}{2}(v_{gq} i_{gd}) \tag{17}$$

where, v_{dc} and i_{dc} , are the voltage and current of the DC link, respectively.

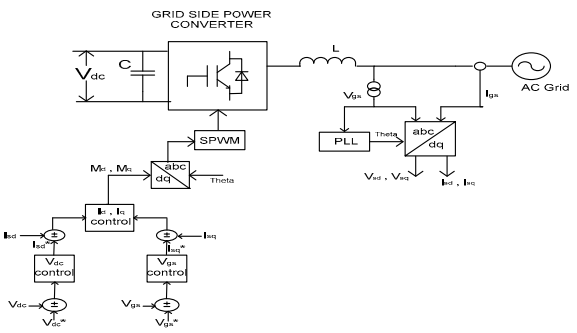

Fig. 5 Grid-side converter control

From the above expressions, it can be observed that the active and reactive power can be controlled independently by the d-axis and q-axis components of the grid currents, respectively. The control scheme of the grid-side converter is shown in Fig. 5.

IV. Parallel Operation of PMSGs

The major advantage of parallel operation of PMSGs connected to single HVDC-VSC converter is that no requirement of individual power converter for each wind turbine, which reduces the cost and increases the reliability of the system.

A) Optimal electrical frequency search for maximum power extraction

In order to generate the maximum possible power from the wind farm, it is proposed to operate the electrical wind farm at the optimal frequency. To find the optimum electrical frequency that maximizes the total power of the wind farm, the expression for the total power is differentiated with respect to the angular electrical speed and equated to zero. The individual power in each wind turbine is

$$P_{wti} = \frac{1}{2}\rho A C_{pi}(\lambda, \theta_{pitch}) v_{wi}^3 \tag{18}$$

The total power in the wind farm having 'n' wind turbines is written as

$$P_{wf} = P_{wt1} + P_{wt2} + \ldots + P_{wtn} \tag{19}$$

$$P_{wf} = \frac{1}{2}\rho A \sum_{i=1}^{n} C_{pi}(\lambda, \theta_{pitch}) v_{wi}^3 \tag{20}$$

where C_p is function of λ and it is function of angular speed and wind speed. The optimal electrical frequency for maximum power extraction of wind farm can be obtained as follows

$$\frac{d}{d\omega_e} P_{wf} = 0 \tag{21}$$

B) Simulation results and analysis

The control scheme discussed above is tested on a system with two PMSG based wind turbines by means of simulations using PSCAD/EMTDC. The wind farm feeds power to the grid through HVDC-VSC link.

The system is analyzed with two different case studies as discussed below

1. Performance study of two wind turbines under normal grid condition
2. Performance study of two wind turbines with grid disturbance

1. Performance study of two wind turbines under normal grid condition

Two 1.5 MW wind turbines connected to the AC grid through HVDC-VSC link are considered in this case study. It is assumed that both the wind turbines are exposed to same wind speed. However, the wind speed is assumed to vary from 10

m/s to 8 m/s and then to 12 m/s and 9 m/s as shown in Fig. 6. The Fig. 7 depicts that the machines coupled with the wind turbines are tracking the wind speed. As the wind speed changes, the mechanical power, which is proportional to wind speed, also changes as shown in Fig. 8. While doing the parallel operation of the machines line-to-line voltages and frequency of both the machines have to be same else circulating current may exists between two machines. The results presented in Figs. 9-11 confirm the parallel operation of PMSGs. Figs. 14 and 15 show the power output of two PMSGs. The DC link voltage is maintained constant by grid-side converter control, which is shown in Fig.16. The grid voltage is set at constant magnitude of 690V. The grid currents, whose magnitude is proportional to wind speed are shown in Fig. 17. The active power injected into the grid is indicated in Fig. 18.

Fig. 6 Wind speed

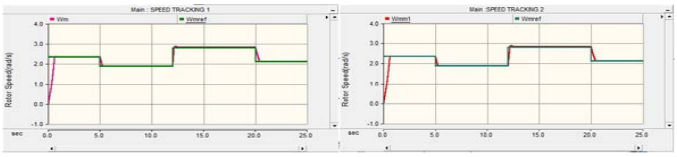

Fig. 7 Speed tracking of two wind turbines

Fig. 8 Total power in the wind (Mechanical power)

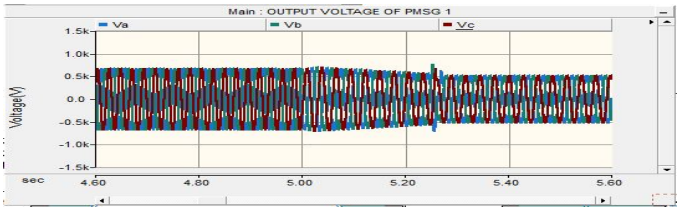

Fig. 9 Output voltage of PMSG-1

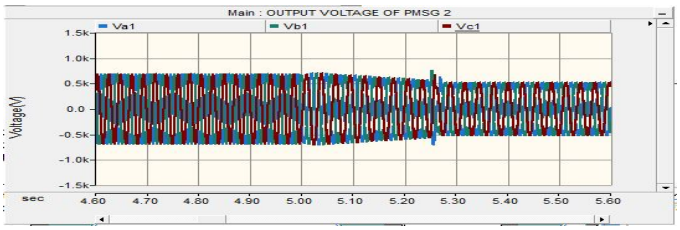

Fig. 10 Output voltage of PMSG-2

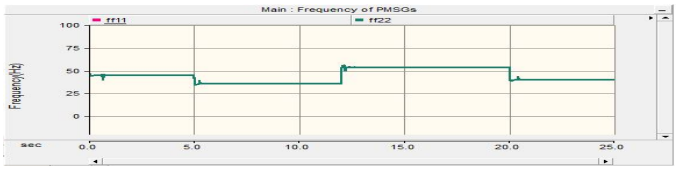

Fig.11 Frequency of both machines

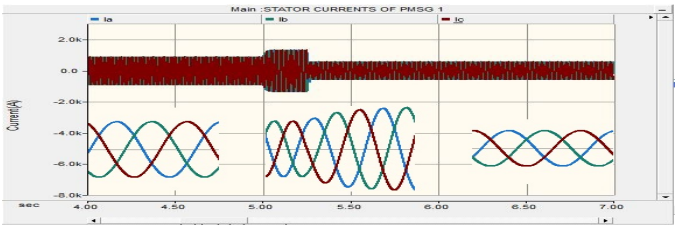

Fig.12 Stator current of PMSG-1

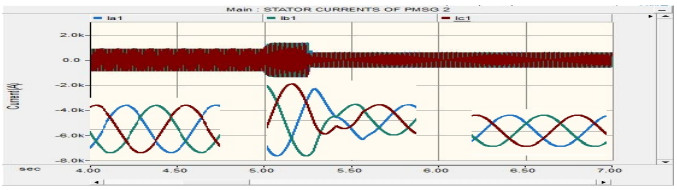

Fig.13 Stator current of PMSG-2

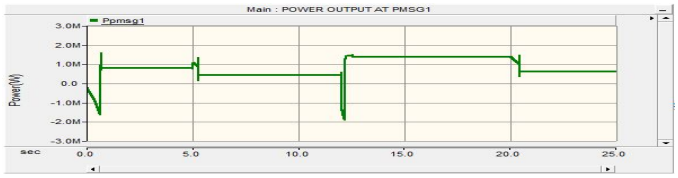

Fig.14 Power output of PMSG-1

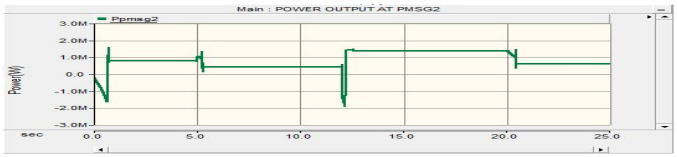

Fig.15 Power output of PMSG-2

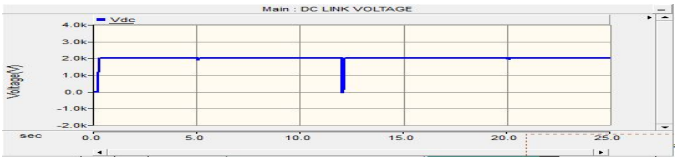

Fig.16 DC link voltage

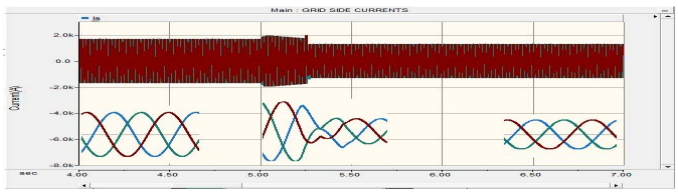

Fig. 17 Grid current of the system

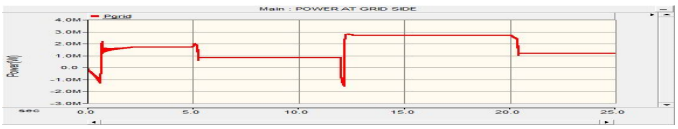

Fig.18 Active power injected into the grid

2. *Performance study of two wind turbines with grid disturbance*

The performance of the system has been analyzed with 20% sag for a small duration in grid voltage as shown in Fig. 19. During this study the wind speed is assumed to be constant. Since the wind speed is assumed to be constant at 10 m/s, the power extracted from the wind by the wind turbine is constant and hence the electrical power developed by the machine is constant, which is shown in Fig. 20. However, dips in the DC link voltage can be observed at particular points as seen in Fig. 21 because the DC link voltage is maintained by grid-side converter which is connected to AC grid. As the power output at the wind farm side is constant, the power injected to the grid should be maintained constant. Here, as the voltage decreases, the grid current increases to keep the injected power constant. The waveform of grid currents and RMS value of grid current is shown in Fig. 22 and 23. The Fig. 24 shows the active power injected into the grid.

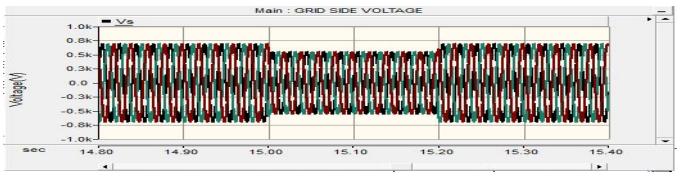

Fig. 19 20% sag in grid voltage for 0.2 sec

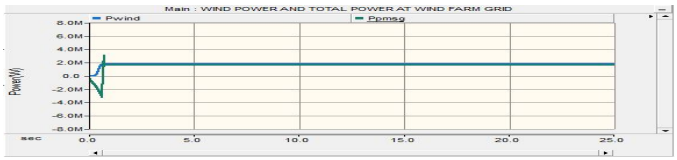

Fig. 20 Mechanical Power and total power output of PMSGs

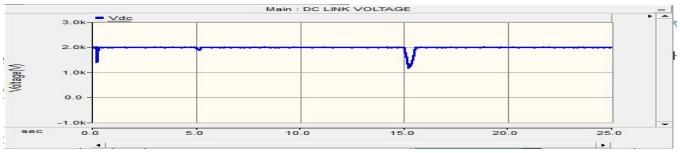

Fig.21 DC link voltage

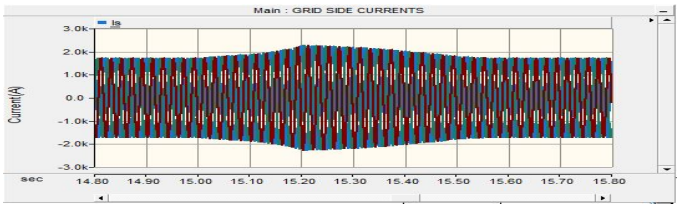

Fig.22 Grid current at 20% sag in voltage

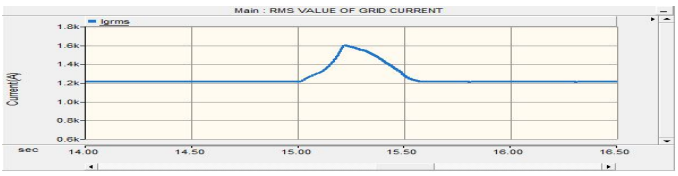

Fig. 23 RMS value of grid current at 20 % sag in voltage

Fig. 24 Active power injected into the grid

V. Conclusion

A control scheme for wind farm based on permanent magnet synchronous generators (PMSGs) connected to the main grid through HVDC-VSC link has been presented. Parallel operation of PMSGs under normal and abnormal grid conditions are studied in this work. The optimal frequency at which maximum power can be extracted is computed and MPPT controller is implemented to control the wind farm power converter. For a grid disturbance of voltage sag, the power, voltage and current at grid-side is analyzed. The stator currents and voltages of both PMSGs, DC link voltage, grid-side voltage, current and power injected into the grid for different cases are presented and analyzed. The performance of the investigated control scheme is satisfactory under normal and abnormal grid conditions.

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