A sequential control for Full Size Converter wind turbine generating systems to mitigate power pulsations during unbalanced conditions

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Abstract - *Several technical challenges are observed during grid integrations with the renewable power system comprising of models which precisely reckon of short circuit contributions and system protection studies. Compared to traditional generators, Wind Turbine Generators (WTGs) integrated through converter produce different current and power waveforms which may contain harmonics during normal as well as abnormal conditions. This paper proposes a sequential control topology that eliminate the second harmonic components and accounts for impacts on active and reactive power with Full Size Converter (FSC) under different fault conditions.*

***Key Words*: Full Size Converter, Wind Turbine Generators, Second Order Harmonics, Unbalanced Faults**

1. INTRODUCTION

Modern Wind Parks (WPs) install variable speed wind turbines (WTs) in order to absorb maximum wind energy and fulfil the grid code requirement and also reducing the drive train stress. Integrating large scale WP with the grid has several issues and has sever impacts on power system transient behaviour. Failing to which not only leads to un-optimized design and operations of WPs but also problems of grid operation and stability. Majority of research work is carried on time domain behaviour of short circuit characteristics of WTs [1]-[5] as well as on dynamic phasor modeling [6]-[8] of generators coupled electronically. This paper demonstrates the behaviour of active power, and reactive power as well as positive and negative sequence current by implementing the proposed sequential control scheme which eliminates the second harmonic component in comparison to conventional control scheme. The paper comprises of following sections: Modeling of FSC WTGs, Conventional control scheme, proposed control scheme, Test system and Test cases, Results and Discussions, Conclusion.

2. Modeling of FSC wind turbine generators

Figure 1 shows the typical configuration of a full size converter wind turbine. This type of turbine may or may not include a gearbox and a wide range of electrical generator types can be employed, for example, induction, wound-rotor synchronous or permanent magnet synchronous. As all of the power from the wind turbine goes through the power converters, the dynamic operation of the electrical generator is effectively isolated from the power grid [15]. The electrical frequency of the generator may vary as the wind speed changes, while the grid frequency remains unchanged, thus allowing variable-speed operation of the wind turbine. The considered topology uses a permanent magnet synchronous generator (PMSG) and the AC-DC-AC converter system. It consists of two voltage source converters (VSCs): machine side converters (MSC) and grid side converters (GSC). The DC bus over voltage protection is provided by DC resistive chopper. Also to improve the power quality, a line inductor (choke filter) and AC harmonic filter are used at the grid side converter (GSC).

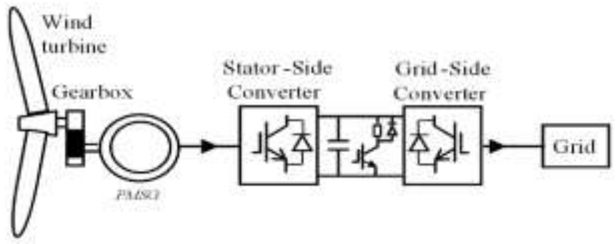

Fig -1: FSC WT Configuration

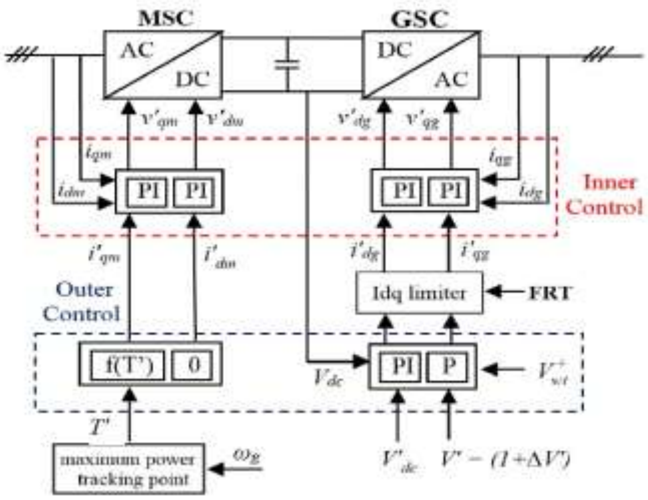

Fig -2: FSC WT Control scheme

Vector control technique is used for controlling the MSC and GSC. This further allows the control of active and reactive power through proposed control. Based on AC flux or voltage, the projection of d- and q- current components are made on rotating reference frame. Real Power and Reactive Power are represented by q-component and d-component of flux based rotating reference frame. As the flux-based reference frame lags by 90^0 to voltage-based frame, representation of d and q component interchanges.

Figure 2 shows the schematic diagram of FSC wind turbine control scheme. In this Figure 2 the q axis and d axis currents of the MSC and GSC are given by i_{qm} , i_{dm} , i_{qg} and i_{dg} respectively. The DC bus voltage, electromagnetic torque of the PMSM and the positive sequence voltage at FSC transformer MV terminal are given by V_{dc}, T, V^+_{wt}. In the control scheme shown in Figure 2 stator flux reference (SFR) frame and stator voltage reference (SVR) frame are used to operate the MSC and GSC respectively. T is controlled by i_{qm} , V_{dc} is maintained by i_{dg} and V^+_{wt} is controlled by i_{qg}. Both MSC and GSC are controlled by a two level controller. The slow outer control calculates the reference dq-frame currents (i'_{dm}, i'_{qm}, i'_{dg}, i'_{qg}) and the fast inner control allows controlling the converter AC voltage reference that will generate the modulated switching pattern. The reference for PMSM electromagnetic torque is given by MPPT control ($T' = K_{opt}\,\omega_t^{\,3}$) and the reference for the positive sequence voltage at FSC transformer MV terminal (V') is calculated by the WPC.

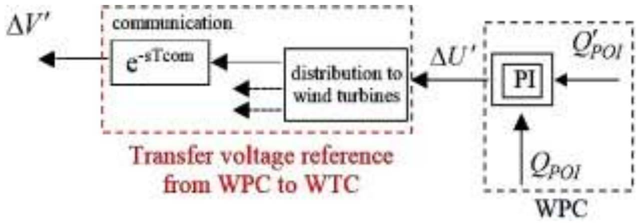

Fig -3: Reactive power control at POI

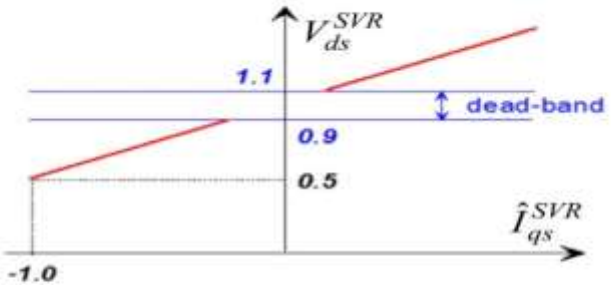

Fig -4: Reactive output current of WT during voltage sags

The proportional integral (PI) regulator helps in achieving the desired reactive power flow at the Point Of Interconnection (POI). If WPC is operating under V-control function mode, then the reactive power reference (Q'_{POI}) is calculated using

$$Q'_{POI} = K_{V_{poi}}\left(V'_{POI} - V_{POI}\right) \tag{1}$$

Where V_{POI} and $K_{V_{poi}}$ are the positive sequence voltage at POI and the voltage regulated gain at WPC respectively. If WPC is operating under power factor (PF) control function, the reactive power reference (Q'_{POI}) is computed using active power at POI (P_{POI}) as well as desired power factor at POI (PF'_{POI}). The PI regulator output ($\Delta V'$) is kept constant by blocking the input ($Q'_{POI} - Q_{POI}$) to avoid overvoltage following the removal. The WTs are also equipped with Fault-Ride-Through (FRT) function to fulfill grid code requirements as shown in the figure 4 and is activated (V_{FRT-ON}) when voltage deviation exceeds its pre-defined value from 1 p.u. and deactivated($V_{FRT-OFF}$) when the voltage deviation reduces below pre-defined value. Reactive current is injected by FSC in proportion to voltage deviation from 1pu when FRT function is in active mode.

2.1 Conventional control scheme of DFIG

The q-axis reference current is calculated by outer voltage control loop, as follows

$$i'_{qg} = K_v\left(V' - V^+_{wt}\right) \tag{2}$$

Here K_v is the voltage regulator gain. V' is the positive sequence voltage reference at MV terminal of FSC WT transformer and it is calculated by the WPC. While the V^+_{wt} is the positive sequence voltage at MV terminal of FSC WT transformer and is not directly measured by the WT controller, it is approximated by

$$V^+_{wt} = (V^+_{dwt})^2 + (V^+_{qwt})^2 \tag{3}$$

Where

$$V^+_{dwt} = \hat{V}^+_{dwt} + R_{tr}\hat{I}^+_{dwt} - X_{tr}\hat{I}^+_{qwt}$$
$$V^+_{qwt} = \hat{V}^+_{qwt} + R_{tr}\hat{I}^+_{qwt} + X_{tr}\hat{I}^+_{dwt}$$

In Eq. 3, the d-axis and q-axis positive sequence voltage at MV side of FSC wind turbine transformer are given by V^+_{dwt} and V^+_{qwt}, respectively. The d-axis and q-axis positive sequence voltage at LV side of FSC wind turbine transformer are given by $\hat{V}^+_{dwt}$ and $\hat{V}^+_{qwt}$, respectively. The d-axis and q-axis positive sequence currents at LV side of FSC wind turbine transformer are given by $\hat{I}^+_{dwt}$ and $\hat{I}^+_{qwt}$, respectively. Resistance and Reactance values of FSC wind turbine transformer are given by R_{tr} and X_{tr} , respectively.

The PI regulator calculates d-axis and q-axis reference voltage for the converters by using feed forward compensating terms ($\omega L_{choke}\, i_{qg} + v_{d-choke}$) and ($-\omega L_{choke}\, i_{dg} + v_{q-choke}$) as follows

$$v'_{dg} = -\left(k_p + k_i/s\right)\left(i'_{dg} - i_{dg}\right) + \omega L_{choke}\, i_{qg} + v_{d-choke} \tag{4}$$

$$v'_{qg} = -\left(k_p + k_i/s\right)\left(i'_{qg} - i_{qg}\right) - \omega L_{choke}\, i_{dg} + v_{q-choke} \tag{5}$$

Priority is given to active currents by the controller during normal operations

$$i'_{dg} < I^{lim}_{dg} \tag{6}$$

$$i'_{qg} < I^{lim}_{qg} = \sqrt{\left(I^{lim}_{g}\right)^2 - \left(i'_{dg}\right)^2} \tag{7}$$

Where, I^{lim}_{dg} and I^{lim}_{qg} represents the d-axis and q-axis currents whereas I^{lim}_{g} represents the total GSC currents. The FRT function is activated when

$$|1 - V_{wt}^{+}| > V_{FRT-ON} \tag{8}$$

And deactivated when

$$|1 - V_{wt}^{+}| < V_{FRT-OFF} \tag{9}$$

By reversing the d-axis and q-axis current limit, GSC controller provides priority to the reactive current when FRT function is active

$$i'_{qg} < I_{qg}^{lim} \tag{10}$$

$$i'_{dg} < I_{dg}^{lim} = \sqrt{\left(I_{g}^{lim}\right)^2 - \left(i'_{qg}\right)^2} \tag{11}$$

2.2 Proposed control scheme of FSC

During unbalanced loading conditions or faults, the terminal voltage of FSC WT contains negative sequence components which lead to second harmonic oscillations in GSC power output. The instantaneous active and reactive power in unbalanced grid conditions can be also written as [9].

$$p = P_0 + P_{C2}\cos(2\omega t) + P_{S2}\cos(2\omega t) \tag{12}$$

$$q = Q_0 + Q_{C2}\cos(2\omega t) + Q_{S2}\cos(2\omega t) \tag{13}$$

Where P_0 is average value of instantaneous active power and Q_0 is the average values of the instantaneous reactive powers. P_{C2} , P_{S2}, Q_{C2} , Q_{S2} represent the magnitude of the second harmonic oscillating terms in the Eq.12 and Eq.13. The amplitude of these power magnitudes can be calculated as follows:

$$P_0 = \frac{3}{2}(v_d^+ i_d^+ + v_q^+ i_q^+ + v_d^- i_d^- + v_q^- i_q^-) \tag{14}$$

$$P_{C2} = \frac{3}{2}(v_d^- i_d^+ + v_q^- i_q^+ + v_d^+ i_d^- + v_q^+ i_q^-) \tag{15}$$

$$P_{S2} = \frac{3}{2}(v_q^- i_q^+ - v_d^- i_q^+ - v_q^+ i_d^- + v_q^+ i_q^-) \tag{16}$$

$$Q_0 = \frac{3}{2}\left(v_q^+ i_d^+ - v_d^+ i_q^+ + v_q^- i_q^- - v_q^- i_q^-\right) \tag{17}$$

$$Q_{C2} = \frac{3}{2}(v_q^- i_d^+ - v_d^- i_q^+ + v_q^+ i_d^- - v_d^+ i_q^-) \tag{18}$$

$$Q_{S2} = \frac{3}{2}(-v_d^- i_d^+ - v_d^- i_q^+ - v_q^+ i_d^- + v_q^+ i_q^-) \tag{19}$$

Where i_d^+,i_q^+ and v_d^+,v_q^+ are calculated by Park transform [10] and represent the dq components of the positive-sequence current and voltage vectors expressed in synchronous reference frame, whereas i_d^-, i_q^- and v_d^-,v_q^- are the components of the negative-sequence current and voltage respectively on a synchronous reference frame rotating at same speed as in positive sequence component but in opposite direction. For a given grid voltage conditions, P_{S2}, P_{C2}, Q_{S2} and Q_{C2} can be controlled with proposed control method. Active power terms P_{C2} , P_{S2} cause oscillations in DC bus voltage V_{dc}. In order to nullify P_{C2} & P_{S2} , GSC current references ($i_{dg}^{+\prime}$,$i_{qg}^{+\prime}$,$i_{dg}^{-\prime}$,$i_{qg}^{-\prime}$) are recalculated.

The I_{dq} limiter and outer control calculatei'_{dg},i'_{qg},i_{dg}^{lim}, i_{qg}^{lim} and further calculate the GSC current references $i_{dg}^{+\prime}$,$i_{qg}^{+\prime}$,$i_{dg}^{-\prime}$,$i_{qg}^{-\prime}$ for the proposed current controller. During the fault, positive sequence reactive current injection in defined by the grid code and hence the GSC current references are calculated [6] as below:

$$\begin{bmatrix} i_{qg}^{+\prime} \\ i_{dg}^{+\prime} \\ i_{qg}^{-\prime} \\ i_{dg}^{-\prime} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ v_{qg}^{+} & v_{dg}^{+} & v_{qg}^{-} & v_{dg}^{-} \\ v_{qg}^{-} & v_{dg}^{-} & v_{qg}^{+} & v_{dg}^{+} \\ -v_{dg}^{-} & v_{qg}^{-} & v_{dg}^{+} & -v_{qg}^{+} \end{bmatrix}^{-1} \begin{bmatrix} i'_{qg} \\ P_0 \\ P_{C2} \\ P_{S2} \end{bmatrix} \tag{20}$$

Where P0 is given by

$$P_0 = i'_{qg}\, V'_{wt} \tag{21}$$

Keeping due care of the converter limit I_{dg}^{lim} and I_{qg}^{lim}, the reference values of Eq.20 are recalculated. The priority is providing I_{dg}^{+} as specified by grid code specially during fault conditions. The remaining reserve of GSC are used in elimination of P_{C2} and P_{S2}. Thus, the performance deteriorates with the decrease in electrical distance between the fault location and the WP.

3. Test system and Test Cases

Figure 5 shows single line diagram of the 120KV, 60 Hz test system of WP having installed capacity of 67.5 MW comprising of 45 WTs each having capacity of 1.5 MW FSC operating at full load under unity power factor (QPOI = 0). The loads connected from bus to ground on each phase and are represented by equivalent impedance. Distributed constant parameters models are used to represent transmission lines.

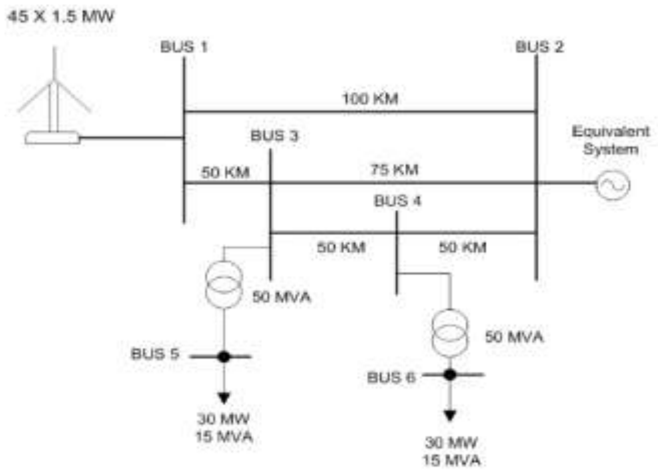

Fig -5: 120 KV Test System

Table -1: Simulation Cases

Fault Location	Case	Type of Fault	Control Scheme
Bus 4	Case A	LG Fault	Conventional Control
			Proposed Control
	Case B	LLG Fault	Conventional Control
			Proposed Control
	Case C	LLLG Fault	Conventional Control
			Proposed Control

Table 1 represents the simulation cases for different types of faults at Bus 4. The different fault cases are also simulated at different location but due to the space constraint it is not shown. The similar results are obtained for fault at Bus 6.

4. Results and discussion

Figure 6, Figure 7 and Figure 8 shows the comparative responses in per unit for the active power components, active power, reactive power, positive and negative sequence currents for conventional and proposed schemes for all three types of faults i.e. LG, LLG and LLLG respectively. The fault is initiated at 2 seconds and it is cleared after 250ms. It is clearly depicted from the Fig. 6 and Fig. 7 that the proposed sequential control scheme reduces the second harmonic pulsation in the active power components which is present in asymmetrical fault. The negative sequence current compensates the second harmonic components and tries to make is zero. It can also be concluded from Fig. 8 that the second harmonic component is absent because of symmetrical fault (LLLG) and thus proposed and conventional scheme have the similar responses.

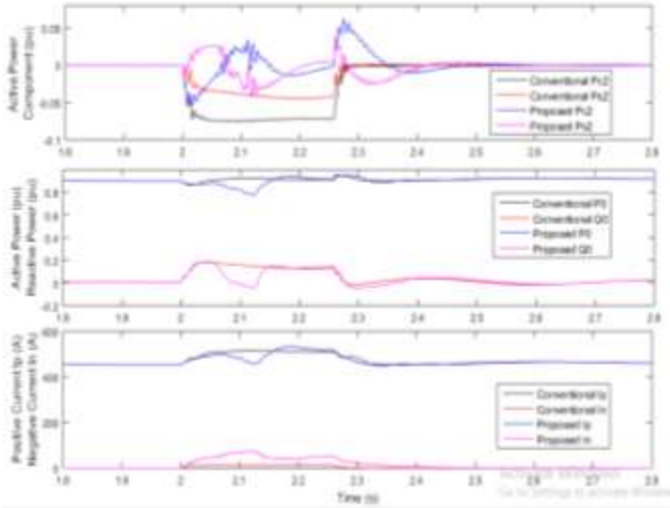

Fig -6: Case A LG Fault at BUS 4

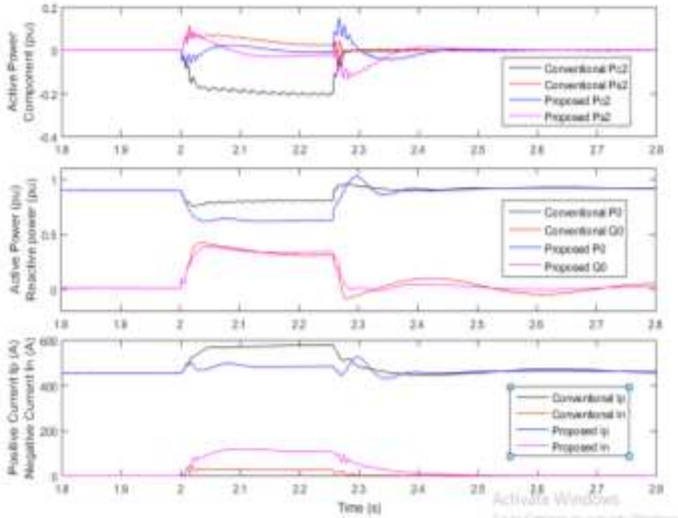

Fig -7: Case B LLG Fault at BUS 4

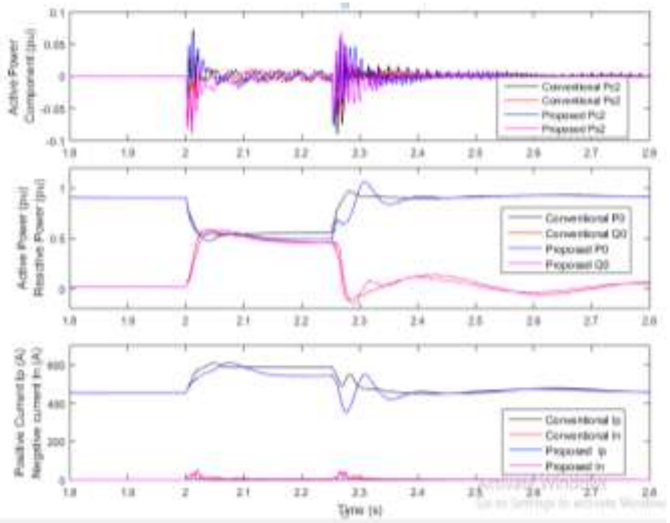

Fig -8: Case C LLLG Fault at BUS 4

The active and the reactive power outputs are almost similar for conventional and proposed control scheme except the amplitude of the variation is slightly less in the proposed scheme compared to the conventional scheme.
A higher value of negative sequence fault current is obtained using the proposed scheme compared to conventional scheme.

5. CONCLUSION

This paper presents a proposed control scheme which can be adopted for short circuit analysis of any type of wind turbine generating system having electronically coupled generator. WT are expected to be equipped with a DC resistance chopper which limits the DC voltage, avoids crowbar ignition and deliver continuous control of FSC during faults that occur outside WP. Impact of WT control is responsible to provide solution in both normal operating mode as well as fault-ride-through operating mode. The proposed control scheme helps in stabilizing the electromechanical torque, increase the negative sequence current and lower the peak variations in active and reactive power. Results are validated by simulating various fault condition at different locations and comparing the results of proposed control scheme to conventional control scheme. Additionally, the proposed control scheme is also flexible to FRT capabilities.

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