EFFICIENT SLIDING MODE PI CONTROLLER FOR FAULT RECOVERY IN GRID CONNECTED WIND ENERGY CONVERSION SYSTEM

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Abstract: *This research paper deals with the performance analysis of wind energy conversion system during grid fault conditions. In most of the surveys, the DC link voltage oscillations are not regulated properly as per the safety required safety factor limit during various grid fault conditions. Regulating the DC link voltage and minimising its oscillations during grid fault condition is very essential in the interconnected power system. Failing to provide proper DC link voltage regulation will affect the connected converter topologies and also the controllers associated with it. In order to overcome the drawbacks faced in the previous research works, sliding mode PI controller is designed and it is mathematically modelled towards the grid side converter. The simulation results are obtained for symmetrical and unsymmetrical fault using MATLAB Simulink software.*

Keywords: *Three phase grid, DC link capacitor, DC link voltage oscillations, Sliding mode PI Controller, Permanent Magnet Synchronous Generator, Wind turbine, Symmetrical fault, Unsymmetrical fault.*

1. Introduction

Wind energy is the most common renewable energy which is readily available in nature. Due to the low availability of coal and tar, the current trend is moving towards the green energy. In the performance analysis of wind energy conversion system, there are two different types of analysis namely steady state analysis and dynamic analysis. The system cannot operate always in a steady state. Henceforth, it is highly important to analyze the dynamic performance of the grid connected wind energy conversion system that is during grid fault conditions.

All the surveys related to the dynamic performance of the grid connected wind energy conversion system states that, when the fault namely symmetrical fault occurs towards the towards the grid side converter, the first component that gets primarily affected is the DC link capacitor. During the period of fault occurrence towards the grid, there occurs a high shoot up and oscillations in the level of DC link voltage.

Most of the research papers were conveying the idea to bring the system quickly back to the normal state during fault conditions. Other part of the work is focused on replacement of controllers to improve the time response of the existing controllers pertaining to the fault occurrence in the system. The shoot up that occurred during that duration of fault is not thoroughly reduced.

In this research work, it is primarily focused on the dynamic performance analysis, especially when the faults namely symmetrical and unsymmetrical fault is injected towards the grid side, there occurs a high shoot up in the level of DC link voltage of the DC link capacitor. As per the industry standards, Each DC link capacitor will have varying safety factor value.

It is highly important to maintain the value of DC link capacitor as per the safety factor value. Incase if it exceeds the value of safety factor of DC link capacitor, it will affect the entire converter topology. This will finally lead to a pathway, where the system will get collapsed and become unstable.

The proposed work will give a solution for peak shoot up that normally occur in the DC link voltage value during the period of fault occurrence. Also, it will pay way for quick response with improvement in time parameters in bringing the system back to the normal state from the abnormal state.

The forthcoming paragraphs will elucidate the surveys pertaining to the performance of the wind energy conversion system and associated control techniques during fault conditions.

The new controller of wind power for power system transient stability improvement, which the wind turbine is based on a doubly-fed induction generator (DFIG) is described. A field-oriented control is used to control of the power flow exchanged between the DFIG and the power system. A simplified wind turbine model based on power injection is proposed in this paper[1].

The required code and the control capabilities of the converters after examining the LVRT capability of DFIG based wind energy conversion system in asymmetrical grid faults. The positive sequence reactive current is given to the power grid for supporting the DFIG. It reduces the DC link voltage and also the oscillations of generator torque. This will help the wind farm to perform in better way and will also improve the power system [2].

The new fuzzy schedule fault tolerant control method which stabilizes a non-linear system with uncertainties in parameters, wind disturbance, faults in sensors and also provides an improved closed loop performance in the presence of state variables unavailable for measurement. The advantage of this proposal is that, the power production is maximum, voltage ripple is very low and the stability of the system is maintained to a great extent during fault conditions [3].

Superconducting Fault Current Limiter (SFCL) plays a vital role in suppressing the DC link voltage oscillations when the grid-connected PMSG based wind system is subjected to fault. The wind system has the DC link capacitor which acts as a coupler between rectifier and inverter. Since the system is connected in series, when fault occurs there is a high shoot up in the level of DC link voltage which affects the grid side converter. Hence, the peak shoot up is mitigated by means of SFCL [4].

Flywheel energy storage system which is based on doubly fed induction machine to improve the transient stability of a grid connected wind farm. Thus, to control the frequency converters which is based on insulated gate bipolar transistor switches, in which a cascaded Adaptive Neuro Fuzzy Controller (ANFC) is introduced. The result of the system using ANFC and the conventional black box optimisation technique based proportional controllers are composed and their transient performance is observed [5].

The proposed control scheme which allows dynamical specification like operational requirement and ancillary services imposed by reactive power regulation and Fault Ride Through (FRT) capabilities. Two stage cascade structure is used to control actions during normal grid operation. The proposed controller regulates the active and reactive power delivered to the grid. It also reduces the losses due to resistance in the generator and maintains the desired range of the internal variables [6].

The idea in which only the phase current is used to diagnose the fault in current sensor. The conventional state observer – based methods for current sensor faults requires a system mode and susceptive parameters. In the proposed idea the current sensor fault, open circuit faults and the affected phases are identified separately [7].

Torsional oscillations act up when the turbine has direct driven configuration and to reduce that the author suggests a damping device installation for assistance. A switch function with the help of control of pulse width modulation can be applied which will improve the performance and result in steadiness [8].

The control technique to protect the grid side converter system under various types of short circuit fault conditions [9]. The proposed algorithm based on altering the dynamics of non-linear system by application of discontinuous signal to overcome non-ideal grid conditions for doubly fed induction generators. Also, the fluctuations that causes vibration and mechanical stress are eliminated as well as compensation for stator current harmonics is done along with directly controlling the powers in DFIG. Besides the intermittent nature switching frequency is achieved [10].

The second order non-linear system stabilising method to avoid uncertainties in a DFIG which is turbo driven. The task of matching the speed and frequency of grid and power control the RSC at constant switching frequency of grid and power control are tackled by two computations to control the RSC at constant switching frequency. Deduction of tuning frequency and controller parameters are done and a hazardless alteration among two controllers is done at the moment of DFIG and grid connection [11].

2. Problem Description

This section will describe the technical issues faced during the grid fault conditions. There are two different types of faults. They are symmetrical fault and unsymmetrical fault. Symmetrical faults namely LLL (L-Line) fault and LLLG are the rarely occurring faults in power system. Once there occurs a symmetrical fault, the entire system will get collapsed. There will be a predominant increment in the level of DC link voltage that will affect the grid side converter, since the output of DC link voltage should be effectively controlled and it should be maintained at a desired nominal value before it is fed to the grid side. It takes time to bring the system back to the normal state. Hence effective controller strategy must be used towards the grid side for quicker fault recovery.

Unsymmetrical faults namely a) Single line to ground fault b) Double line to ground fault c) Double line fault.

Table 2.1
Type of fault with fault severity

Type of Fault	Percentage of fault occurrence
LLL Fault	2 to 5 percent
LLL Fault	2 to 5 percent
LG Fault	65 to 70 percent
LLG Fault	15 to 20 percent
LL Fault	5 to 10 percent

As shown in Table 2.1, the rate of fault occurrence is more in the case of unsymmetrical fault and less in the case of symmetrical fault. Though the rate of fault occurrence is less with respect to symmetrical fault, the impact created by it in the power system is more. Hence the sliding mode PI controller is designed towards grid side converter and controller action in terms of fault recovery and DC link voltage oscillation minimisation is realised by injecting symmetrical and unsymmetrical fault towards the grid side.

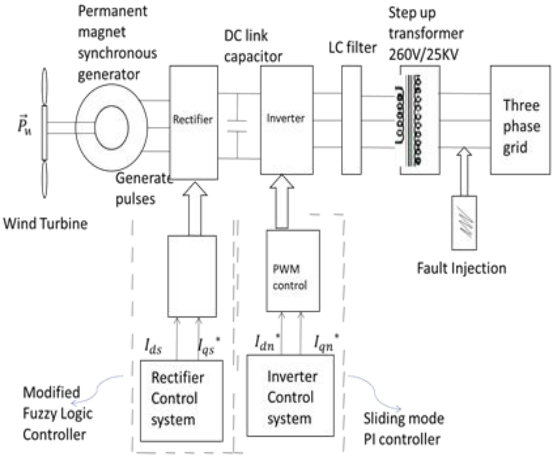

Fig. 2.1 Block diagram of PMSG based grid connected wind energy conversion system

As shown in Fig. 2.1, the permanent magnet synchronous generator-based wind energy conversion system is integrated with three phase grid. The design parameters of wind energy conversion system and PMSG is shown in Table 2.2 and Table 2.3.

Table 2.2
Parameters of Wind turbine

Rating	1.5 MW
Blade radius	38m
No. of Blades	3
Air density	0.55kg/m3
Rated wind speed	12 m/sec.
Rated speed	3.07rad/sec.
Cut-in speed	4m/sec.
Cut-out speed	25m/sec.

Table 2.3
Parameters of Wind Parameters of PMSG and other devices

Rating	1.75MVA
Rating of step up transformer	100kVA,260V/25Kv
Capacitive filter	10kVAr
Inductance (RL branch)	2.5000x10^-4 H
Resistance (RL branch)	0.0019Ω

In the rectifier side converter, closed loop PWM control is implemented to trigger the firing pulse for MOSFET switches. The main theme of the proposed work is the injection of fault towards the three-phase grid. In order to overcome the undesirable impacts created by the injection fault in the system and to mitigate the DC link oscillations, sliding mode PI controller is designed and the improved outcome is realised.

3. Methodology-Sliding Mode PI Controller

The drawbacks found in the normal PI controller is that, it has a constant gain, suitable only for steady state, fault recovery is not so efficient and the response time in bringing the system back to the normal state from the faulty state from the faulty state is also comparatively low.

In order to overcome this drawback, sliding mode PI controller is proposed. In this section, modelling of sliding mode PI controller and its implementation will be explained.

If transmission lines fell down, then it will get short circuited. During the fault condition.by natural calamity there are high chances of fault to happen. The steps must be taken regarding how to prevent the system from unsafe conditions. The changes that happen across the inverter during the fault and after the fault clearance is realised. The response pertaining to the fault recovery is also realised by means of the proposed sliding mode PI controller.

Normally inverter operates with modulation signal, incase suddenly if a fault happens, the power production across the inverter will suddenly come to zero. For implementing the fault analysis in this paper, the short circuit fault is simulated, at that instance circuit breaker will trip then the voltage starts to build and transient will occur.

When current change is higher across the inverter, it is mandatory to prevent the inverter leg. Circuit breaker will prevent it by tripping when the current value goes beyond the normal value. After the current come back to the normal value, Circuit breaker will be turned on. Then the voltage and current waveform will start to build up.

During the build up process, transient will occur towards the grid side voltage and current waveforms and also towards the DC link capacitor voltage. It will not get settled easily. It will get settled slowly to a normal value. That settling point can be decided only by the inverter control system. The inverter control system is implemented with traditional PI controller and sliding mode PI controller.

3.1 Simulation Parameters

Table 3.1
Input simulation values required for PMSG based grid connected WECS during grid fault conditions.

Parameters	Rating
Rating	0.1 ohms.
MOSFET Internal Diode Resistance (Rd)	0.01 ohms
Nominal DC Link Voltage (VDC Nominal)	1150 V
Low pass filter cut off frequency	10000 Hertz
Low pass filter Damping factor	0.707
Capacitor	15000 Micro Farad
Resistor(R)	0.02 ohms
Inductance(L)	0.0002 H
Series RLC Load with Y grounded configuration	Nominal Vrms=240 V, Nominal frequency= 60 Hz, Active power=100W, Inductive reactive power(QL)=0 H, Capacitive reactive power=10kVar
Inverter Switching Frequency	1980 Hertz
Single phase step up transformer rating	100kVA,260V/25kV
Single phase step up transformer configuration	Nominal power and frequency = 200kW and 60 Hz, Winding 1=25kV Phase to phase Vrms, Resistance (R1) = 0.001 pu, Inductance (L1) = 0.03 pu. Winding 2 = 690V Phase to phase Vrms, Resistance (R1) = 0.001 pu, Inductance (L1) = 0.03 pu.
Single phase step up transformer Magnetisation resistance(Rm)	500 pu
Single phase step up transformer Magnetisation Inductance(Lm)	500 pu
Three phase Power Grid	25kV

Table 3.1 gives the necessary simulation details in order to design the PMSG based grid connected system during fault conditions. It clearly gives the value of each element that are used in the

simulation modelling of the test system presented in the simulation model as shown in Fig. 3.1.

3.2 Mathematical Modelling of Sliding Mode PI Controller

Mathematical modelling of sliding mode PI controller made. It is governed by the following set of equations.

DC link voltage tracking error equation is given by

$$e_v = V_{DC} - V_{DC}^{*} \qquad (3.1)$$

$$= B_v i_d - \frac{1}{c} i_s + d_v - V_{DC}^{*} \qquad (3.2)$$

$$\text{Where } B_v = \frac{1}{c}\frac{3}{2}\frac{V_d}{V_{DC}*} \qquad (3.3)$$

With V_{DC}^{*} is the DC link voltage reference

ΔB_v represent the variation between the actual voltage and the reference voltage

$$e_v = u_v + d_v \qquad (3.4)$$

Where u_v is the new control input and given by

$$u_v = B_v i_d - \frac{1}{c} i_s + d_v - V_{DC}^{*} \qquad (3.5)$$

Second order sliding mode control strategy is applied for the DC link voltage reference such as

$$uv = -k1 \,|\, ev \,|^{1/2} \operatorname{sgn}(ev) + w \qquad (3.6)$$

$$\dot{w} = -k_2 \operatorname{sgn}(e_v) \qquad (3.7)$$

The command id is carried out from (3.6) and (3.7) such as

$$i_d = \frac{1}{B_v}\left(-k_1 \,|\, e_v \,|^{1/2} \operatorname{sgn}(e_v) + w + \frac{1}{C} i_s + V_{DC}^{*}\right) \qquad (3.8)$$

$$\dot{w} = -k_2 \operatorname{sgn}(e_v) \qquad (3.9)$$

k1 and k2 are steady state and transient state constants.

These equations form the framework in modelling the sliding mode PI controller. These equations are mainly framed with the motive of regulating the DC link voltage by determining the DC link voltage error values and also to determine the reference current that has to be fed into the SMC simulation toolbox.

3.3 Simulation Conceptual Diagram of PMSG Based Grid Connected Wind Energy Conversion System During Grid Fault Condition

This section will give the simulation diagrams of the grid connected wind energy conversion system with the implementation of PI and Sliding mode PI controller. Fig. 3.1 gives the simulation modelling of grid connected wind energy conversion system with the fault that is injected towards the grid side.

The rectifier side control system is operated with closed loop PWM control. the major focus of this design is to analyse the performance under transient conditions. The inverter control system is tested with PI controller and sliding mode PI controller.

As shown in Fig. 3.2, the reference voltage Vabc and reference current Iabc is taken as reference values from the grid before the implementation of control system towards the inverter. In order to provide the switching control strategy all, the nominal values of each series connected element must be taken into account. Here in this research work The DC link voltage oscillations minimisation is more focused. If the injection or occurrence of fault is towards the grid side DC link capacitor is the main element which will get majorly affected since it acts as a coupling device between rectifier and inverter. The usage of DC link capacitor is to provide the constant fixed DC input to the inverter. If there is high shoot up in the level of DC link voltage during the period of fault occurrence, the entire system will be affected.

As shown in Fig. 3.3, In the process of DC link voltage regulation, Inside the Vdc regulator PI controller is implemented. Nominal value of DC link voltage is set as the reference value and to get the actual value, the loop is connected across the capacitor and the actual value that is coming from the output of the DC link capacitor is taken as input and that is fed to the PI controller. The reference Id current that is the current from the inverter side and also the actual current from the inverter side is fed to the PI controller. During the different fault conditions, there occurs some deviations or oscillations in the DC link voltage. PI Controller compares the actual DC link voltage value with the reference or nominal value of 1150 V. PI controller by controlling the reference currents and voltages, the PI controller self-tune the switching strategy in inverter control system and clear the fault and bring the system back to the normal state.

Fig. 3.4 shows that the same Vdc regulator is implemented with sliding mode PI controller which is shortly mentioned as SMC. In PI controller the reference current is directly taken from the inverter side and given as input for generation of gate pulses by means of pulse width modulation technique. Where as in Sliding mode PI controller the focus is given on tracking the exact error equations pertaining to DC link capacitor voltage and also the reference current id is determined by means of mathematical modelling as discussed in section 3.2. The equations discussed in section 3.2 will give the two constants k1 and k2 that will be suitable for both steady state and transient state condition and also it results in the effective DC link voltage regulation which is discussed with evidential simulation results in section 4. The proposed model is thoroughly tuned observing the DC link regulations during different grid fault conditions.

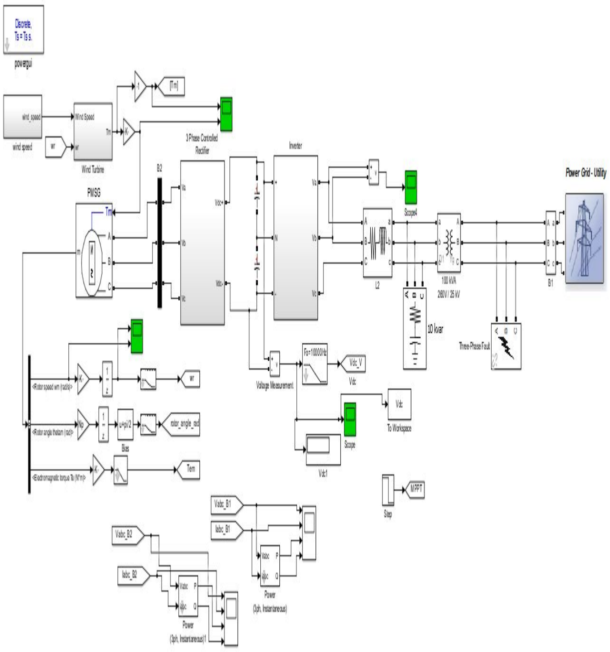

Fig. 3.1 Grid connected WECS simulation diagram with fault injected towards the grid side

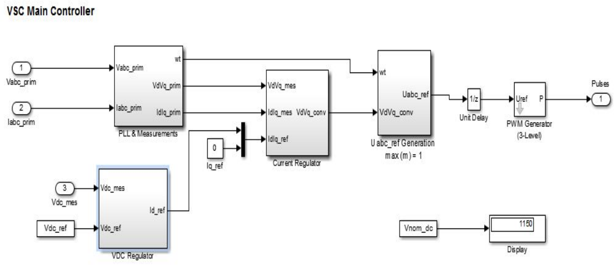

Fig. 3.2 Inverter subsystem

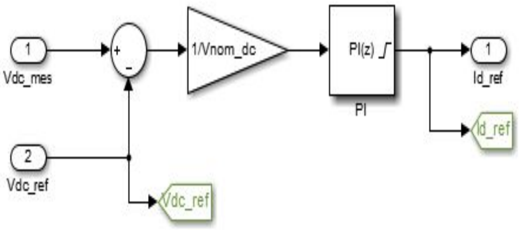

Fig. 3.3 Subsystem of Vdc Regulator with PI controller

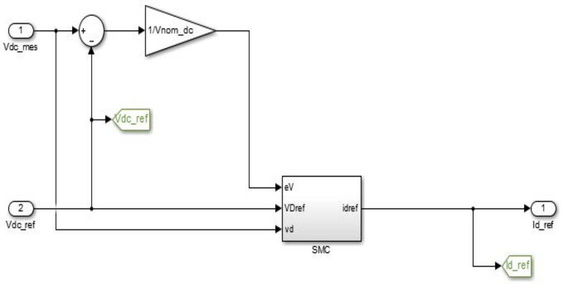

Fig. 3.4 Subsystem of Vdc Regulator with sliding mode PI controller

4. Results and Discussions

The performance analysis of the traditional PI controller and the effectiveness of the proposed sliding mode PI controller used inside the DC link voltage(Vdc) regulator during different grid fault condition will be discussed.

4.1 Simulation Results-Fault Analysis with Sliding Mode PI Controller Implemented Towards the Grid Side Control System

This section will give the simulation results of the symmetrical fault namely LLL fault and unsymmetrical fault namely LG fault and LLG fault that is injected towards the grid side and the effectiveness of sliding mode PI controller used inside the Vdc regulator in bringing the system from fault state to the normal state can be realised by means of the Fig. 3.2. In this section fault duration of half cycle and five cycles are given towards the grid side and the performance of the system during different fault condition is simulated and the results are realised with the implementation of sliding mode PI controller.

LLL Symmetrical Fault Condition Simulation Results with Different Fault Durations

LLL fault is the type of symmetrical fault. Though this is the rarest fault in terms of power system perspective, it is the major fault that will create high impact in the system. An effective controller must hold good for any kind of severe fault. Hence this type of fault is chosen and its injected towards the grid side and the performance is analysed. The system is analysed for even unsymmetrical faults. The investigated values and inferences during unsymmetrical fault is even tabulated as shown in Table 4.1.

Fig. 4.1 indicates the grid side voltage waveform, during the period of fault occurrence (1.1 to 1.11s) voltage value drops to zero and after the fault clearance the controller brings the voltage value back to normal.

Fig. 4.2 indicates that during the period of fault occurrence (1.1 to 1.11s) there is high increment in the current value about 2500 A and the proposed controller subsides it and bring the current value to normal by the quicker clearance of fault.

Fig. 4.3 indicates that there is dip in the level of DC link voltage during the period of fault occurrence (1.1 to 1.11s).With the implementation of normal PI controller as shown in comparison graph Fig. 4.7 during the same fault duration of 1.1 to 1.11s,the shoot up in the level of DC link capacitor voltage is about 1600 voltage and the settling point of the waveform is about 1800v where as the nominal value of DC link voltage to be maintained is about 1150 V. After the implementation of sliding mode PI controller as shown in Fig. 4.3, Though there is dip in the level of DC link voltage which will not create any problem pertaining to stability. Also, it is observed that the settling point of the DC link capacitor voltage is 1200 V which is close to the nominal value.

The system should sustain and withstand for any kind of fault and for any kind of fault duration. Fig. 4.1 to Fig. 4.3 explains the Sliding mode PI controller effectiveness in bringing the system back to the normal state for the fault duration of half a cycle. The controller must bring the same effectiveness even for the prolonged fault duration. Hence the analysis of the system is also carried out by injecting the same three phase fault LLL by setting the time duration of 1 to 1.1 s which is about five cycles.

Fig. 4.4 to Fig. 4.6 explains the effectiveness of controller actions in terms of Grid side voltage and current waveforms, DC link capacitor voltage waveforms during the fault duration of five cycles. Through the voltage waveform, it can be depicted that during the period of fault occurrence that is during the duration of 1 to 1.1 s, the voltage value drops to zero and after the fault clearance the voltage value return back to normal value. The current waveform shoots up to 2100 A and after the fault clearance, it is maintained at a nominal value. The DC link capacitor voltage during the fault duration of 1 to 1.1 s the voltage dip is more compared to half a cycle duration but still the settling point is almost closer to 1200 V even under the five cycle of fault duration. This shows that the proposed controller holds good for any kind of fault duration and fault severity.

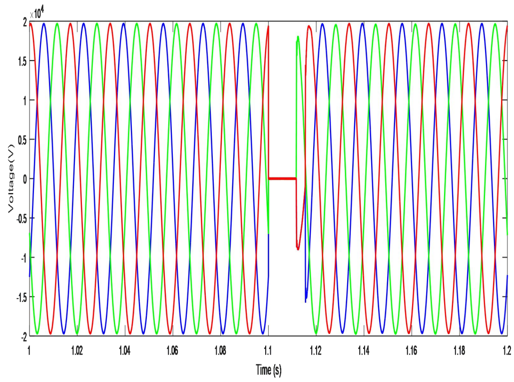

Fig. 4.1 Grid side voltage waveform with fault created between 1.1 to 1.11s-LLL symmetrical fault condition

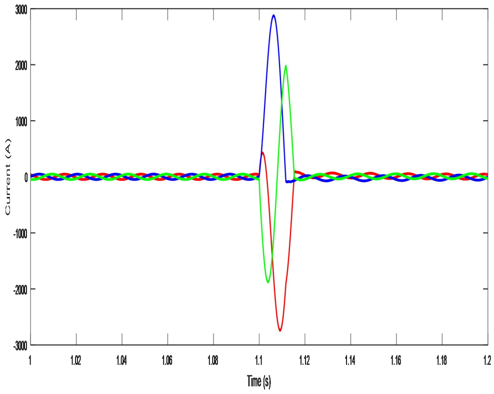

Fig. 4.2 Grid side current waveform with fault created between 1.1 to 1.11s-LLL symmetrical fault condition

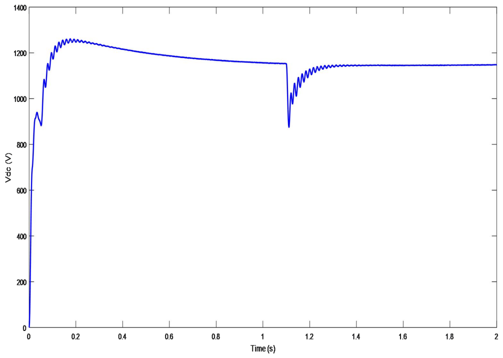

Fig. 4.3 DC link voltage with fault created between 1.1 to 1.11s-LLL symmetrical fault condition

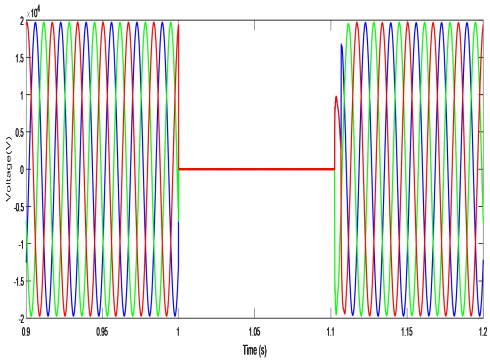

Fig. 4.4 Grid side voltage waveform with fault created between 1 to 1.1s-LLL symmetrical fault condition

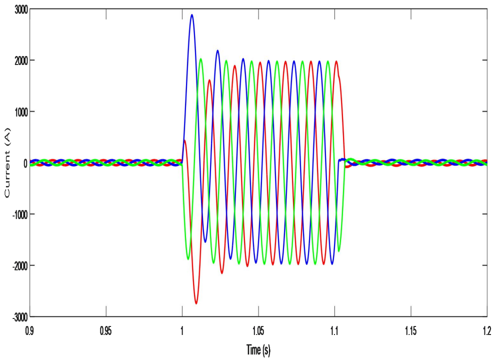

Fig. 4.5 Grid side current waveform with fault created between 1 to 1.1s-LLL symmetrical fault condition

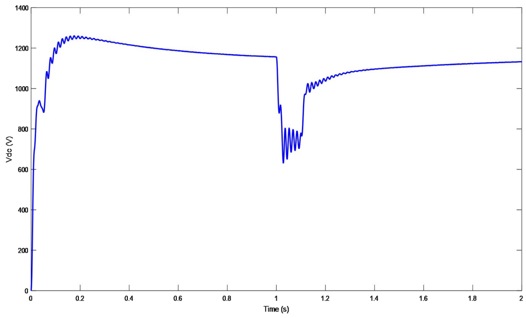

Fig. 4.6 DC link voltage with fault created between 1 to 1.1s-LLL symmetrical fault condition

4.2 DC Link Voltage Regulation - Comparison Graph of PI and Sliding Mode PI Controller during Different Grid Fault Condition

In this section the comparison graphs namely Fig. 4.7 will show the effectiveness of sliding mode PI controller and PI controller in regulating the DC link voltage when the system is subjected for the fault duration of 1.1 to 1.11s. The red colored waveform indicates the DC link capacitor voltage waveform with the implementation of PI controller. The blue colored waveform indicates the DC link capacitor voltage waveform after the implementation of sliding mode PI controller. It indicates that the initial shoot up in the level of DC link voltage is significantly reduced. Also, the settling point of the DC link capacitor voltage is maintained close to nominal DC link voltage as per standard requirements with the aid of proposed sliding mode PI controller.

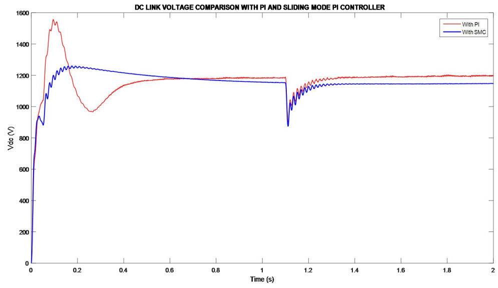

Fig. 4.7 DC link voltage regulation when LLL fault created between 1.1 to 1.11s with PI and Sliding mode PI controller

4.2 Steady State Value of DC Link Voltage with PI and Sliding Mode PI Controller after the Fault has been removed

Table 4.1

DC link voltage regulation with PI and Sliding mode PI controller after the fault clearance

Nominal DC link Voltage = 1150V				
Type of Fault	Steady State Value of DC Link Voltage in Volts After the Fault Clearance of Half Cycle (Volts)		Steady State Value of DC Link Voltage in Volts After the Fault Clearance of Five Cycles (Volts)	
	With PI Controller	With Sliding Mode PI Controller	With PI Controller	With Sliding Mode PI Controller
LLL	1099V	1148V	1073V	1142V
LLLG	1099V	1150V	1072V	1148V
LG	1099V	1150V	1100V	1150V
LLG	1098V	1150V	1090V	1148V
LL	1100V	1150V	1093V	1150V

As shown in Table 4.1, the steady state value of DC link voltage in terms of bringing the voltage close to the nominal value after the fault clearance for the duration of half a cycle of fault and also for the duration of five cycle of fault is tabulated. This tabulated reading gives the inference that various type of faults namely symmetrical and unsymmetrical fault analysis is carried out by means of simulation and it gives an evidential proof that the proposed sliding mode PI controller is better in terms of DC link voltage regulation.

5. Conclusion

Thus, the fault is injected towards the grid side and the performance analysis of the wind energy conversion system during different grid fault condition is thoroughly studied. From the Table 4.1, it can be concluded that that the proposed sliding mode PI controller is proved to be the best in terms of dynamic performance as it brings the grid side converter back to the normal state very quickly and also the regulation of DC link voltage is carried out effectively during the various grid fault conditions as compared to other research works in the same area of grid fault analysis**.**

It is also evident through the results obtained from the Fig. 4.1 to Fig. 4.7 that the proposed sliding mode PI controller brings the value of DC link voltage close to the safer nominal value with reduced peak shoot up and minimized oscillations after the fault has been cleared compared to the tested normal PI controller.

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