

Design of a Harmonic Filter for a Grid Connected Doubly Fed Induction Generator under Unsymmetrical Fault Conditions



Chilla Soumya, Ranuva Nageswara Rao

Abstract--The analysis and controlling of harmonics in a doubly fed induction generator (DFIG) is studied under the unsymmetrical fault conditions in MATLAB/SIMULINK software. The proposed DFIG uses wind energy as the primary source for which is used for power generation. Wind energy is a non-polluting renewable energy resource that is available free of cost but when the wind is used, harmonics are introduced into the power system, so voltage imbalances occur in the grid. In order to mitigate the voltage imbalances (or) ripples in the voltage or current, LCL filters are introduced in the wind turbine because they are chiefly used for high power and low-frequency applications. Various unsymmetrical faults are simulated by referring the specifications selected and analysed with the tripping time for the desired duration of time in the circuit breaker, voltage and current waveforms are analysed only during the transient period on the basis of FFT analysis to know about THD content.

Keywords— Average value model, DFIG, LCL filter, THD, unsymmetrical faults.

I. INTRODUCTION

In recent scenario, the most predominantly used renewable non-polluting resources (or) non-conventional energy sources which available in the universe are: solar, wind, geothermal, biogas, biomass, hydro-electric power, tidal power, etc. The wind is most preferably used for power generation in DFIG (Doubly Fed Induction Generator) because it is available cheaply and can be used for low power rating switches also[1]. With the increased involvement of wind energy into the grids, DFIG wind turbines are mostly preferred, such that suitable models for DFIG are integrated. DFIG utilizes the turns ratio of the machine so that the converter need not be to be rated for machines full load power. But with the wind as the source, there are more chances of the establishment of harmonics into the system and voltage disturbances which may lead to the damage of the entire system as the power system is under a large period of time. So to reduce these specified voltage imbalances, a passive LCL filter is introduced into the system such that more amount of harmonics can be mitigated (or) reduced which increases the stability of the system. Such that total harmonic distortion (THD) content or value can be reduced to a more extent.

There are many types of filters namely L, LC, LCL. The LC filter is used for higher harmonics attenuation than L filter but when compared with LC, the LCL filter gives greater harmonics compensation so it is preferred in this aspect. DFIG can provide reactive power compensation whenever there is a fault in the power system[2]. The power electronic switches are used in rectifier and inverter circuit, such that power electronic interface controls currents in the rotor to achieve variable speed. This is also necessary for the maximum energy capturing of variable speeds, as the wind cannot be blown for a continuous duration of time.

In the power system analysis, most of the time, there will not be a normal (continuous) operation, because of faults occurring in the transmission lines, so there is a need to know and evaluate with the unsymmetrical fault conditions which may hold in the transmission lines. There are symmetrical and unsymmetrical faults in the power systems. Symmetrical faults LLL and LLLG and unsymmetrical faults are LG, LL, LLG[2]. Single line-to-ground faults are most commonly occurring faults for more than half of the total percentage of faults in the power system. Line-to-line faults are one-tenth of the total percentage of faults and line-to-line-to-ground faults are one-fourth of the total percentage of faults. These faults introduce harmonics into the whole power system[3],[4].

II. BLOCK DIAGRAM OF DFIG

A wind turbine uses DFIG which consists of a wound rotor induction generator. The connection of DFIG is in such a way that the stator windings of DFIG are directly connected to the grid and rotor windings are connected via slip rings with the help of AC/DC/AC converter (rectifier and inverter with a common DC link connected) to the grid.

A 9MW wind farm of each 1.5MW of six turbines is being designed in the wind turbine model in dynamic average model converter circuits[5]. The wind turbine is connected to the grid with the help of a 120KV supply system and transmitted through a transmission line of length 30km with a 25KV feeder line.

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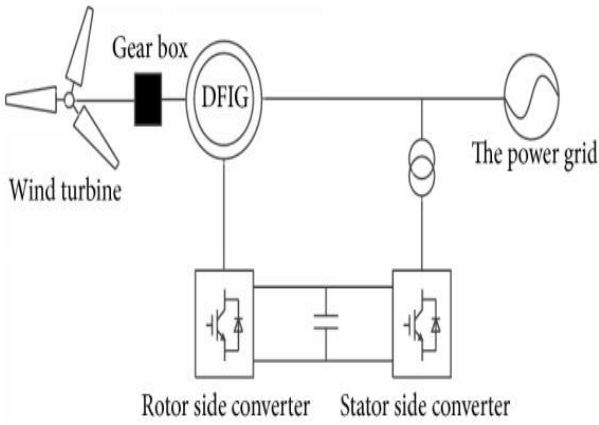


Fig.1: Wind turbine connected DFIG

The rotor is connected through a converter average model to the grid of 25KV.

The converter mentioned uses insulated gate bipolar transistor (IGBT'S) in the alternating current to direct current (AC-DC) conversion called rectifier and DC-AC conversion called an inverter which uses pulse width modulation like sinusoidal pulse width modulation for the generation of gate signals i.e., triggering pulses for IGBT'S. The pulses should be given such that no two IGBT'S in leg conduct at a time which results in a short circuit. The rectifier and inverter circuits are connected by a common DC link with a voltage of 1150V. This converter circuit is connected between passive harmonic filter and DFIG.

III. MATHEMATICAL MODELLING OF DFIG

For the modelling of DFIG in a synchronously rotating frame of reference, we have to represent two-phase stator (ds-q_s) and that of rotor (dr-q_r) circuit variables in a synchronously rotating (d-q) frame of reference.

d-q equivalent circuit (DFIG):

The d-axis circuit (in d-q frame) and q-axis circuit (in d-q frame) are shown in below figure.

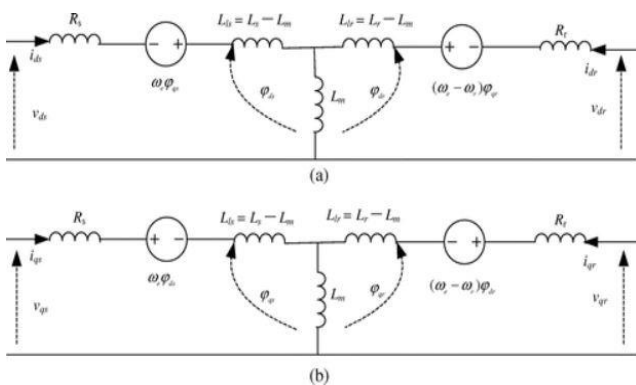


Fig.2: Equivalent Circuit

The voltage equations at the stator side in direct and quadrature axis is,

$$V_{ds} = R_s i_{ds} + \omega_s \phi_{qs} \quad (1)$$

$$V_{qs} = R_s i_{qs} + \omega_s \phi_{ds} \quad (2)$$

The voltage equations at the rotor side in the direct and quadrature axis is,

$$V_{dr} = R_r i_{dr} - s \omega_s \phi_{qr} + d\phi_{dr}/dt \quad (3)$$

$$V_{qr} = R_r i_{qr} - s \omega_s \phi_{dr} + d\phi_{qr}/dt \quad (4)$$

The Flux linkages at stator and rotor in direct and quadrature axis is,

$$\Phi_{ds} = L_s i_{ds} + L_m i_{dr} \quad (5)$$

$$\Phi_{qs} = L_s i_{qs} + L_m i_{qr} \quad (6)$$

$$\Phi_{dr} = L_s i_{dr} + L_m i_{ds} \quad (7)$$

$$\Phi_{qr} = L_s i_{qr} + L_m i_{qs} \quad (8)$$

The Active and reactive power at the stator side is,

$$P_s = V_{ds} i_{ds} + V_{qs} i_{qs} \quad (9)$$

$$Q_s = V_{qs} i_{qs} - V_{ds} i_{ds} \quad (10)$$

The Active and reactive power at the rotor side is,

$$P_r = V_{dr} i_{dr} + V_{qr} i_{qr} \quad (11)$$

$$Q_r = V_{qr} i_{dr} - V_{dr} i_{qr} \quad (12)$$

The Electromagnetic torque is obtained by the product of flux induced and current flowing,

$$T_e = 3/2 P/2 (\phi_{ds} i_{qs} - \phi_{qs} i_{ds}) \quad (13)$$

Where R is resistance in ohms, L_s is self inductance in henry, L_m is mutual inductance of windings in henry, V is voltage in volts, i is current in amperes, ϕ is flux in webers respectively indicate stator and rotor direct and quadrature axis.

IV. SIMULATION MODELS

Initially, 120KV of the source voltage is given as supply voltage to the grid with the help of controlled voltage source and mutual inductance in series with the grid. Mutual inductance is only preferred here in order to avoid a short circuit. A step-down distribution transformer of 120KV to 25KV with 47 MVA base power is connected along the transmission lines of length 30Km and connected to the wind turbine.

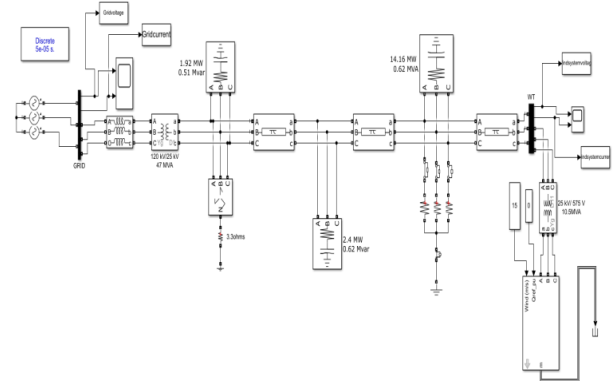


Fig.3: Simulation Circuit Model for Grid.

For the same turns ratio, the same input voltage, the output voltage of a star-delta transformer is least, a current is high. Therefore star-delta connection is more economical for step down applications. Now wind turbine is connected to a 25KV grid with the help of step-down transformer of rating from 25KV to 575V with 10.5MVA base power. Three linear loads are placed across the transmission line of length 30Km with 1.92MW, 14.16MW, 2.4MW of real power rating across the transmission line. Grounding transformer is used to provide a source for zero-sequence current. If grounding transformer is lost, LG fault causes the phase to neutral voltages on the un faulted phases.

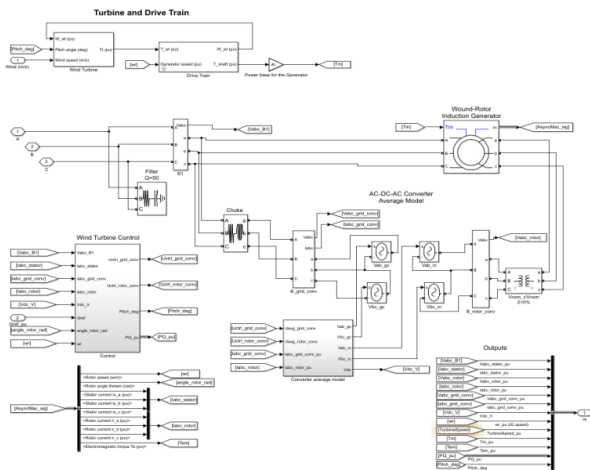


Fig.4: Subsystem of wind turbine average value model.

In the average value model, the value of current or voltage waveform, which gives the DC value of variables over the specified selected interval of time and the ripples are neglected[6], [7], [8], [9]. DFIG technology allows maximum energy extraction from the wind by modulating turbine speed and also minimizes mechanical stress on the turbine whenever there is more flow of wind. The turbine speed is proportional to wind speed.

The simulated waveforms for grid voltage, grid current and wind voltage, wind current is given below with per unit values selected.

V. RESULTS AND DISCUSSION

In every waveform, Phase-A is denoted by red color, Phase-B is denoted by a yellow color, Phase-C is denoted by blue color. In waveforms 1st waveform is Grid Voltage, 2nd waveform is Grid Current, 3rd waveform is Wind Voltage, 4th waveform is Wind Current.

A. Without fault without filter

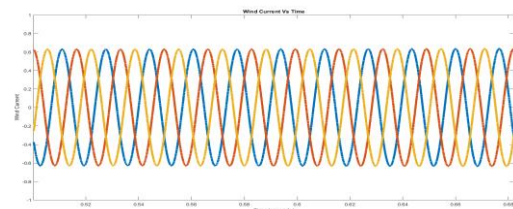
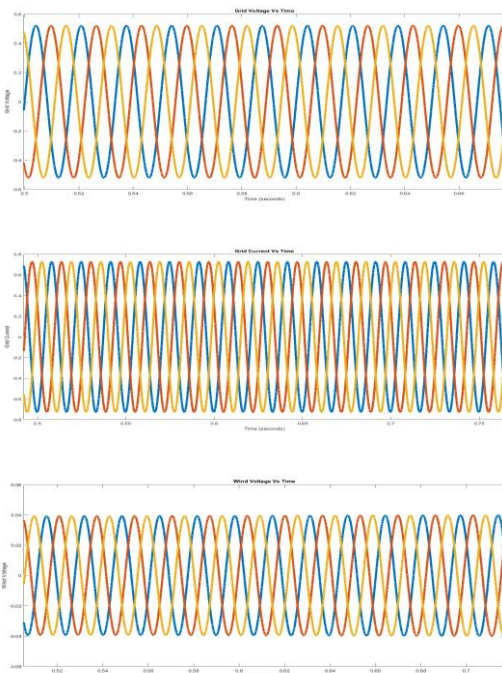


Fig.5: Grid Voltage, Grid Current, Wind Voltage, Wind Current Waveform Without Fault Without Filter.

From the above waveforms, it is clear that the magnitude of grid voltage is 0.5p.u (per unit) root mean square (rms) value and Grid current is 0.7p.u rms value i.e, same for without filter and without fault, it continues till the stop time, here the stop time is selected as 1sec. The magnitude of wind voltage is 0.04p.u rms value and wind current is 0.6p.u rms value and continues till stop period for without filter and without fault.

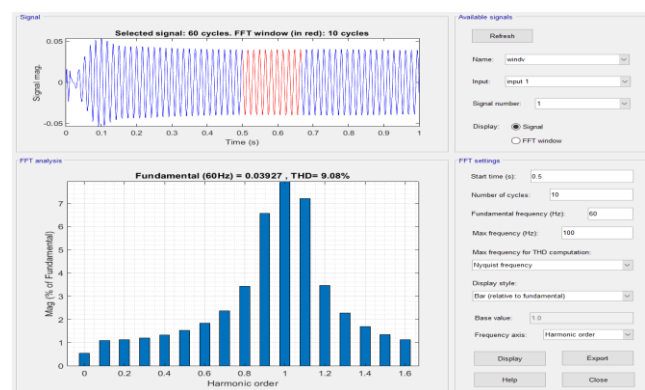


Fig.6: THD Analysis Without Fault Without Filter.

THD analysis is done under no-fault and without using the filter and it is observed as 9.08% in 10 cycles of duration.

B. Fault analysis:

During the normal operation, the circuit breaker contacts are closed. If a fault occurs then the moving contact is separated from the fixed contact of the circuit breaker so that an arc is developed. The circuit is isolated unless an arc is break. This breaking of arc results as the heat release, which depends upon breaking current. The heat released by arc should withstand by the circuit breaker contacts. During fault occurrence in the power system, a circuit breaker will be open and up to some extent the fault will appear and after that, there will be no fault appearance i.e, it comes to a steady-state position.

C. Case studies without filter:

1. LG fault: Fault analysis is carried out by considering and setting the time for 0.6sec. For LG fault, one of the circuit breaker in line is set for 0.6sec and ground circuit breakers for 0.6sec and simulated.

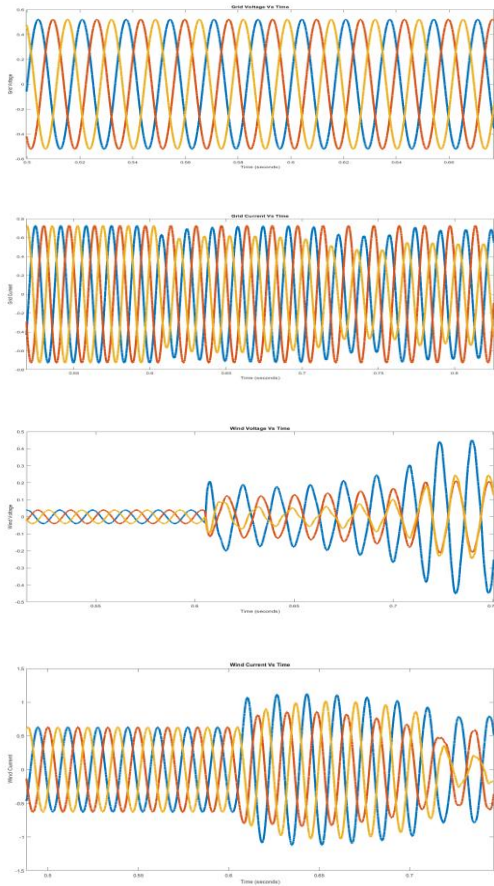


Fig.7: Grid Voltage, Grid Current, Wind Voltage, Wind Current Waveform With LG Fault Without Filter.

From the above waveforms, it is observed that, as the fault is selected from 0.6sec then, there is a voltage imbalance from 0.6sec of time duration. In wind voltage waveform, initially there is a magnitude of 0.04p.u rms value and from fault, there is an increase from 0.6sec of time. Only phase-C is increased drastically. When the fault occurs then the steady-state and transient components depend on the phase angle of the voltage source, X/R ratio and degree of fault current asymmetry. In wind current waveform, initially, there is a magnitude of 0.6p.u rms value and from fault, there is an increase from 0.6sec time. The only Phase- C is increased more and the remaining two phases increase less to that of the first phase.

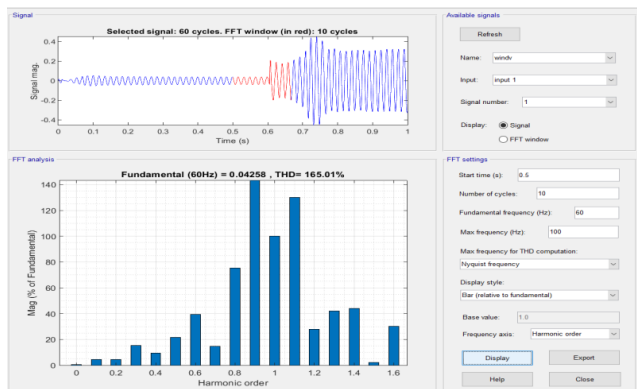


Fig.8: THD Analysis of LG Fault Without Filter.

The steady-state component will be the ac component which is symmetrical and transient will be dc component which decays exponentially with time which is based on the system's X/R ratio. This means the fault is asymmetrical.

2. LLG fault: For LLG fault, two of the circuit breakers in line are set as 0.6sec and ground circuit breaker for 0.6sec and simulated. The simulated waveforms under LLG fault, with grid voltage, grid current and wind voltage, wind current, THD analysis without using the filter is shown below.

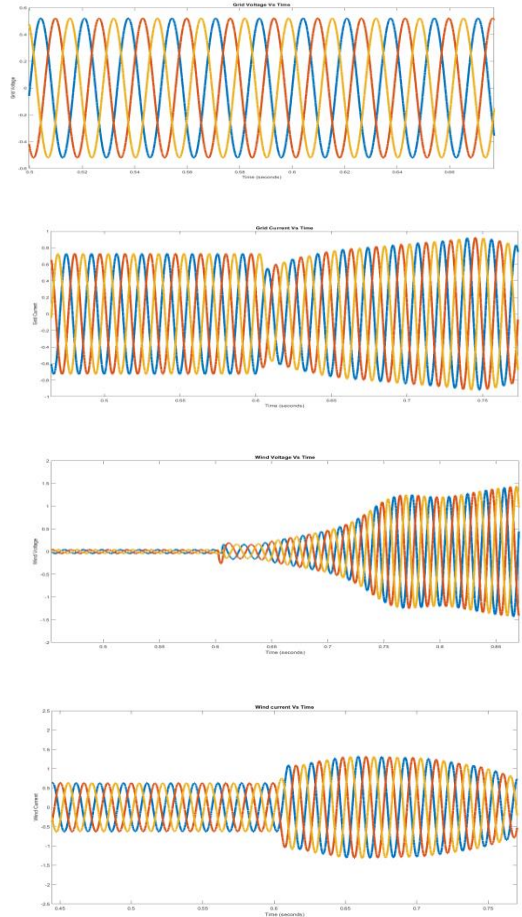


Fig.9: Grid Voltage, Grid Current, Wind Voltage, Wind Current Waveform With LLG Fault Without Filter.

In the grid current of LLG fault, from fault time i.e., 0.6sec the waveform is increased from 0.4p.u rms value up to 0.8p.u rms value till stop time. In the wind voltage, the magnitude is suddenly raised in phases A, B, C from 0.04p.u rms value to 1.5p.u rms value. In wind current waveform, the current raised from 0.5p.u rms value to 1.3p.u rms value in phases A, B, C from 0.6 sec duration of time and it is continued till the stop time. When the fault occurs voltage and current deviate from normal ranges as shown above. The fault causes over current, under voltage, unbalance of phases.

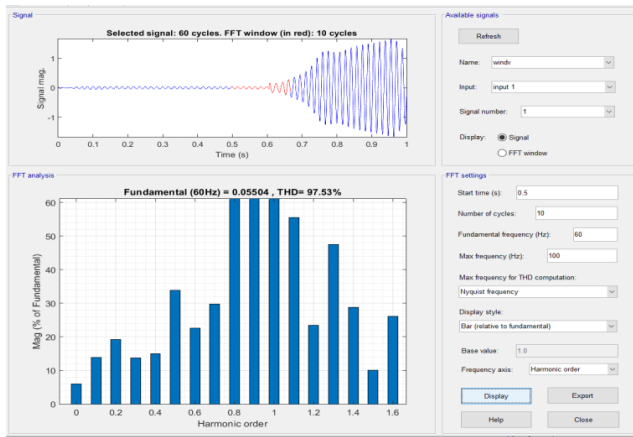


Fig.10: THD Analysis of LLG Fault Without Filter.

3. LL fault: For LL fault, two of the circuit breakers in line are set as 0.6sec.

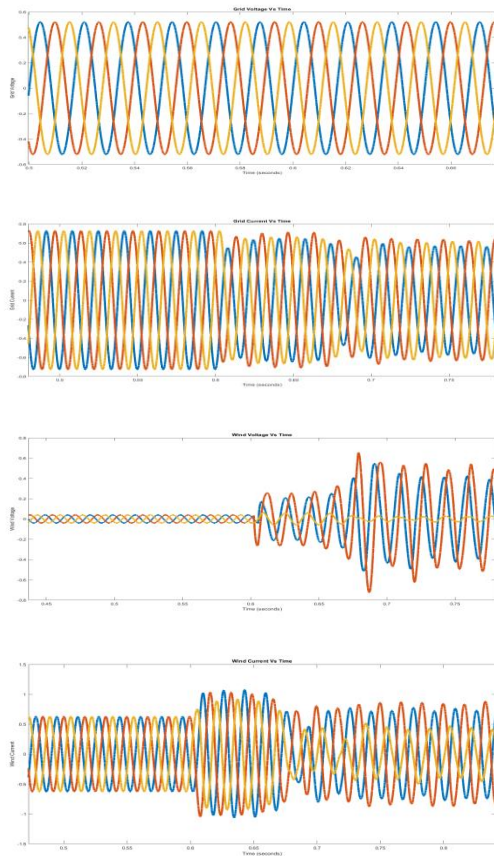


Fig.11: Grid Voltage, Grid Current, Wind Voltage, Wind Current Waveform With LL Fault Without Filter.

From the above grid current waveform, as the fault is selected from 0.6sec duration then, there is voltage is decreased from 0.7p.u rms value from 0.6sec of time. In wind voltage waveform, there is a magnitude of 0.04p.u rms value and from the fault, there is an increase from 0.6sec of time up to 0.7p.u rms value. Only phase AC is increased more. When the fault occurs, there will be reversed power and high voltage surges. In the wind current waveform, there is a magnitude of 0.6p.u rms value and from the fault, there is an increase from 0.6sec duration of time. Only phase

AC is increased more and the remaining one line increases less to that of both lines, as it is the LL fault.

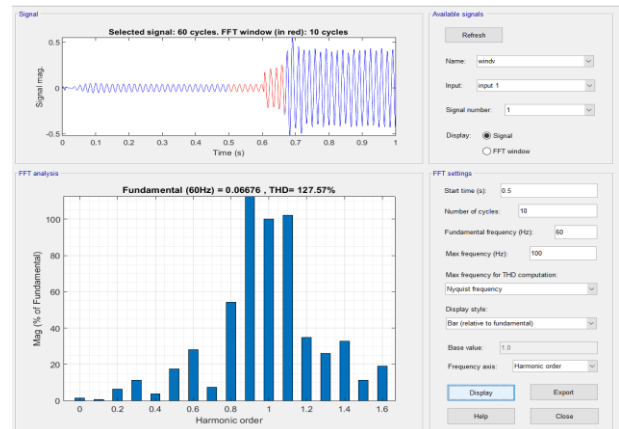


Fig.12: THD Analysis of LL Fault Without Filter.

D. Passive LCL filter: Passive harmonic (LCL) filter is used to reduce the THD content of above mentioned i.e, without using a filter. This passive filter is placed between the converter and the grid.

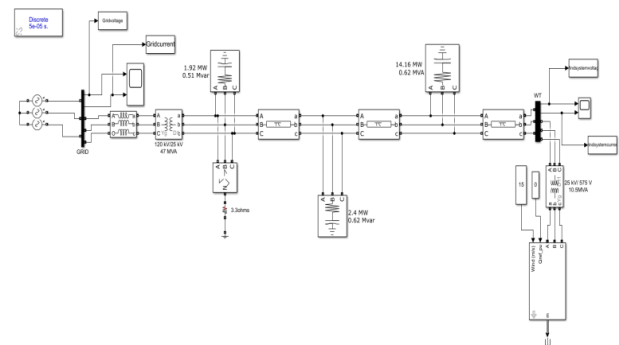


Fig.13: With Harmonic Passive (LCL) Filter Without Fault.

The placement of harmonic passive (LCL) filter is within the wind turbine is shown in the below circuit.

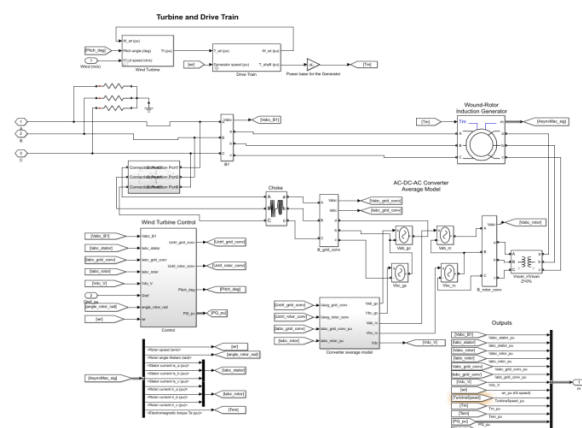


Fig.14: Subsystem of Wind Turbine Model With LCL Filter.

The LCL filter has converter side filter inductance of $100\mu\text{H}$, grid side filter inductance of $5.71\mu\text{H}$, filter capacitance of $418.6\mu\text{f}$, damping resistance of 0.0395Ω . A resistance of 0.0001Ω is connected across the grid outside the harmonic filter.

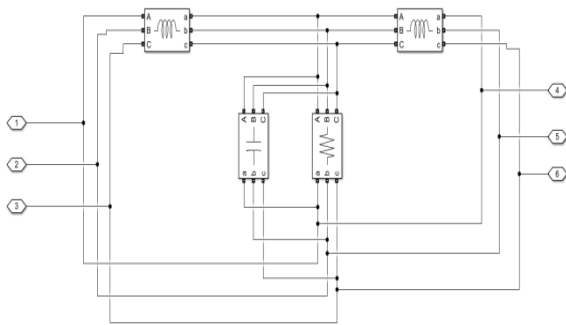


Fig.15: Subsystem of LCL Filter.

Now the simulated waveforms across grid and wind voltages and currents are shown below.

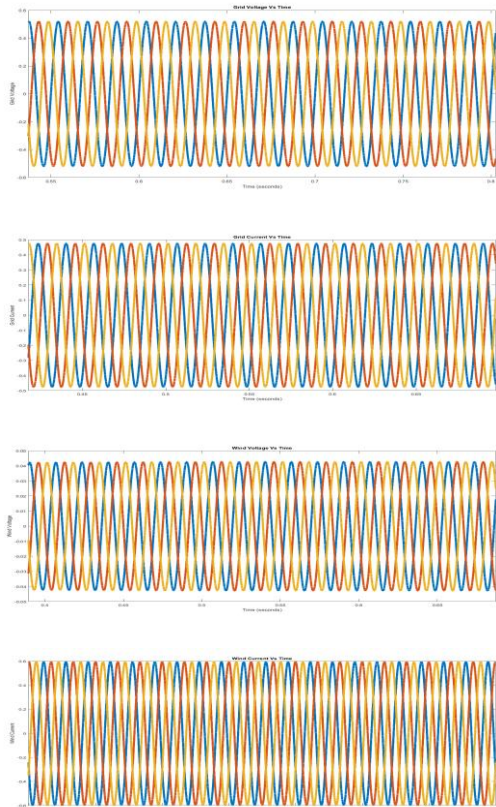


Fig.16: Grid Voltage, Grid Current, Wind Voltage, Wind Current Waveform Without Fault With Filter.

It is observed from the above waveforms that there are no voltage disturbances in any of the waveforms between them because the passive filter is placed among them and no fault is created between them.

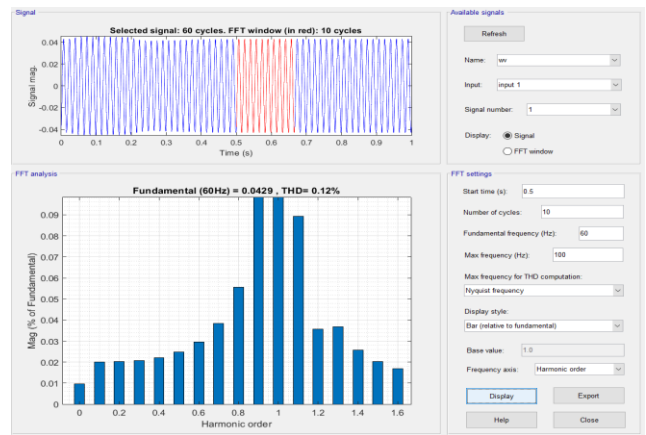


Fig.17: THD Analysis Without Fault With Filter.

E. Case studies with filter:

1. LG fault: Fault analysis is carried out by setting the time for 0.6sec with the usage of the filter. In every fault analysis, only circuit breaker fault starting time is mentioned. We can also select fault clearance time. The simulated waveforms under LG fault with using the filter is given below.

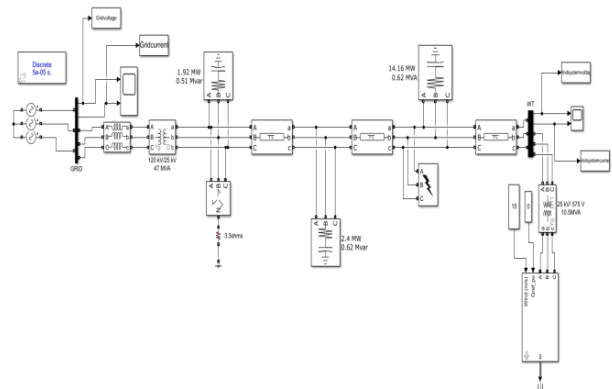
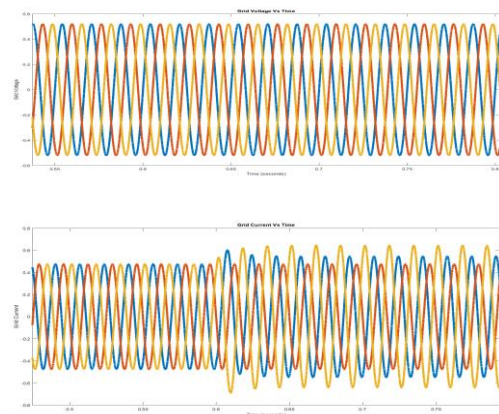


Fig.18: Simulation Circuit With Filter With Fault.

The fault time is selected in the fault block with one of the phases and ground is selected and the switching time period is selected at 0.6sec and analysis is carried out.



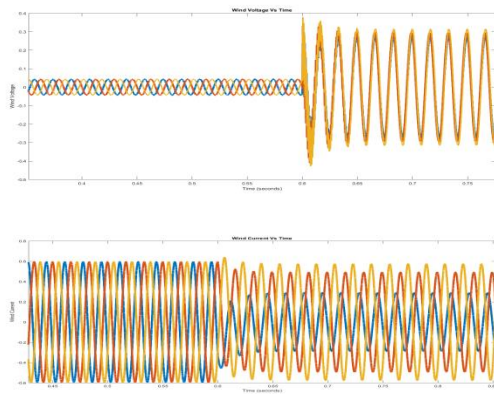


Fig.19: Grid Voltage, Grid Current, Wind Voltage, Wind Current Waveform With LG Fault With Filter.

From waveforms, in the grid voltage waveform, magnitude and waveform are similar in different types of faults mentioned. In the grid current waveform, the magnitude up to 0.6sec is 0.45p.u rms value and it raises to 0.7p.u rms value due to the fault switching time selected as 0.6sec. High current is due to mechanical overload and high magnetic flux densities. In wind voltage waveform, one of phase C is raised more and the magnitude is raised from 0.04p.u rms value.

In wind current waveform, every line voltage is imbalanced, but specifically one of the phase C is more, increased from 0.6p.u rms when compared to the other line voltages.

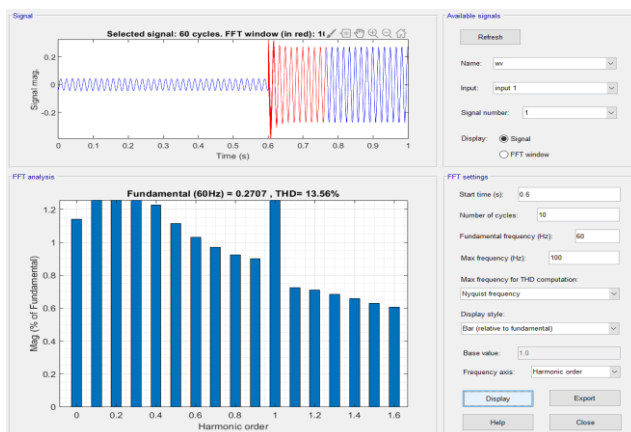


Fig.20: THD Analysis of LG Fault With Filter.

2. LLG fault: The fault time is selected in the fault block with two of the phases and ground is selected and the switching time period is selected at 0.6sec and analysis is carried out.

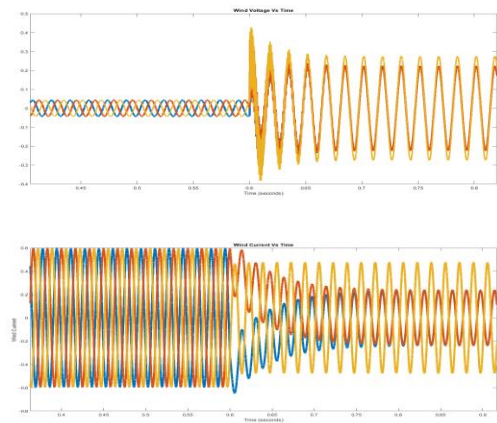
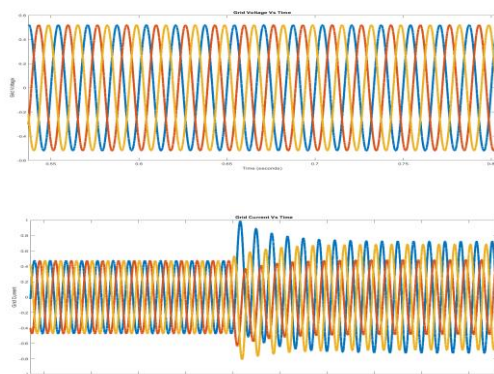


Fig.21: Grid Voltage, Grid Current, Wind Voltage, Wind Current Waveform With LLG Fault With Filter.

From waveforms, in the grid voltage waveform, magnitude is 0.5p.u rms value. In the grid current waveform, the magnitude up to 0.6sec duration is 0.45p.u rms value and it raises due to the fault switching time selected from 0.45p.u rms value to 1p.u rms value and then decreases. In wind voltage waveform, phases A, B, C are raised more, as it is LLG fault and the magnitude is raised from 0.04p.u rms value up to 0.4p.u rms value and then decreases. In wind current waveform, two line-voltages are imbalanced, specifically, one of phase A is more i.e., increased from 0.6p.u rms value compared to the other line voltages and phases C is decreased to -0.6p.u rms value when compared to the other line voltages and other phase C is constant but less than the remaining voltages.

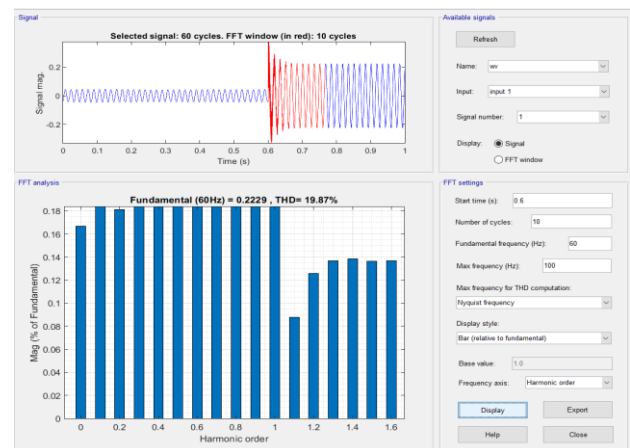
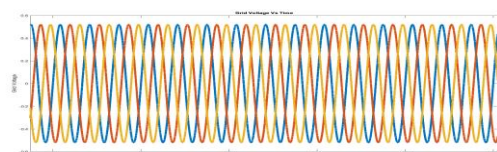


Fig.22: THD Analysis of LLG Fault With Filter.

3. LL fault: The fault time is selected in the fault block with two of the phases and ground is not selected and the switching time period is selected at 0.6sec and analysis is carried out.



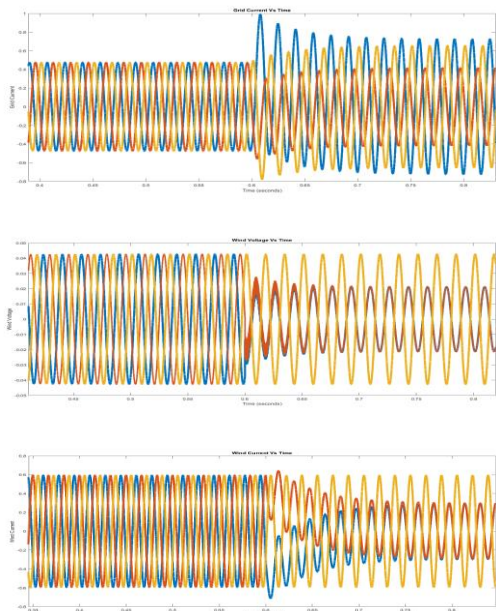


Fig.23: Grid Voltage, Grid Current, Wind Voltage, Wind Current Waveform With LL Fault With Filter.

From waveform, in the grid voltage waveform magnitude is 0.5p.u rms value. In the grid current waveform, the magnitude up to 0.6sec is 0.45p.u rms value and it raises due to the fault switching time in the fault block selected as 0.6sec, from 0.45p.u rms value to 1p.u rms value and then decreases. In wind voltage waveform, one of phase B is maintained constant as 0.04p.u rms value till the stop time but other phase AC has been decreased to a low value other than before value. In wind current waveform, two-line voltages are imbalanced, in that specifically, one of phase A is more i.e, increased from 0.6p.u rms value when compared to the other line voltages and phase C is decreased to -0.6p.u rms value when compared to the other line voltages and other phase B is constant.

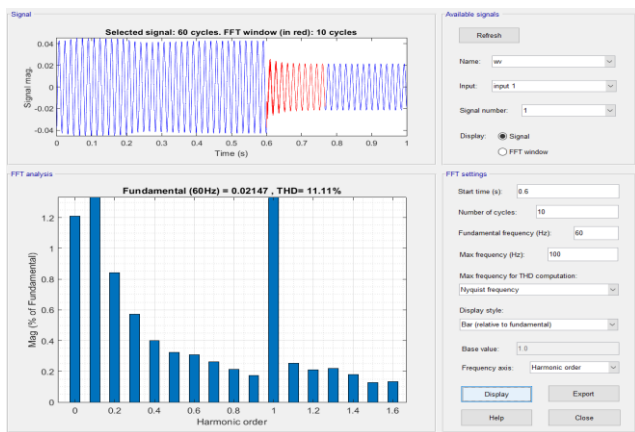


Fig.24: THD Analysis of LL Fault With Filter.

VI. COMPARISON OF DIFFERENT TYPES OF FAULTS IN TRANSIENT PERIOD IN WAVEFORMS:

Comparison is considered with respect to THD value from the above prescribed waveforms, which is taken from the circuit breaker switching time (from 0.6 sec), i.e., the THD comparison is given in the following table.

Table: comparison of different types of faults

Without Filter			
Without fault (THD)	With fault (THD)		
9.08%	LG	LLG	LL
	165.01%	97.53%	127.52%
With Filter			
Without fault (THD)	With Fault (THD)		
0.12%	LG	LLG	LL
	13.56%	19.97%	11.11%

The above THD value is considered and calculated only in the transient period.

VII. CONCLUSION

The analysis of harmonics in a doubly fed induction generator (DFIG) is studied under different types of unsymmetrical faults using THD analysis during the transient period only. The analysis based on the criteria of about initially using without fault without filter, with fault without filter, with filter without fault and with a filter with fault. The required voltages and currents are obtained by varying wind speed also i.e, this is checked because whether the wind turbine is responding to the wind variations or not. As mentioned, with LCL filter in the system the THD gets reduced and it is reduced from 9.08% to 0.12%. In LG fault, THD is reduced from 165.01% (without filter) to 13.56% (with filter), in LLG fault from 97.53% to 19.97% and in LL fault from 127.52% to 11.11% which is a significant improvement in suppressing the harmonics and it demonstrates the capability of the designed filter. These mentioned unsymmetrical faults THD is only measured during the transient period in a specified waveform. Also, the filter is analyzed with the systematic procedure under the fault condition and it is found that the filter performance improved significantly.

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