

OPERATION OF DFIG UNDER UNBALANCED AND DISTORTED SYSTEM

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Abstract: *The interest towards renewable energy resources like wind and solar are increasing over a decade due to the concern over the nature, economic and long run operation and many such. Among all these type of sources, wind energy based renewable energy resource with doubly fed induction generator (DFIG) seems to be more promising due to low converter cost, better operation during distorted, unbalanced grid, better fault ride through and more over effective control of real and reactive power. However, such DFIG system faces challenges because of unbalanced voltage operation because load or grid disturbances or due to transmission line perturbations. This paper gives a rough idea of present literature survey about fault ride through strategies, power control and unbalanced and distorted DFIG operation. The paper also gives brief picture on the challenges of DFIG grid connected system and future scope for extending the research in these areas.*

Key words: *doubly fed induction generator, fault ride through, unbalanced and distorted load, voltage compensation, direct power control, flux control strategies.*

1. Introduction.

Renewable energy resources are becoming a faster alternative to commercial electricity generation due to the facts like availability, eco-friendly, high power generation capability etc. The doubly fed induction generator (DFIG) among wind energy conversion system (WECS) is having better preference due to its small size of higher MVA ratings available in the market, low power ratings of converters, variable generator speed and constant frequency operation, robust four quadrant reactive power control and much better performance during the low voltage ride through (LVRT). From many wind turbines based generators, DFIG is getting added significance due to maximum power extraction capability, variable speed generator running operation, and strong reactive power control, resist capability during low voltage and high voltage fault ride through. Also, low cost of converters, can deliver real power even generator speed reduces from super-synchronous speed to sub-synchronous speed makes DFIG more preferable. Because of low power rating of RSC, the cost acquired on converter devices decreases. For a DFIG wind turbine system, both stator and also the rotor can deliver power to the grid. Over the next few decades non-conventional wind energy will be a great contribution to the increased power

demand. DFIG based wind power generator unit rating raised from few kilowatts in 1990's to tens of megawatts now and still increasing.

To produce electric power from wind turbine-generator set air (or wind) has to flow. This air flow makes the turbine blades rotate. This helps the turbine shaft to rotate at certain low speed. This shaft is coupled with or without gears to a generator rotor to rotate at higher speeds to generate electricity from the stator. Multiple numbers of wind turbines produce more electric power than a single set. The power produced is cheaper than conventional coal based generators or solar based. It gives considerably constant power for long time. Many such factors attracted wind power production as a better alternative electric power source. At least 83 countries are using this energy for generation. Denmark is having about 40% of total generation because of wind energy. Countries like USA, China, Denmark, Germany and India are also using wind energy for power generation and these are among top five countries with wide usage. Many nations are developing policies to create more interest and research on wind power production. Slowly favor is created and people, politicians and industrialists are turning towards wind power production. The major reason to use this wind resource is to decrease the deficit in electric power demands, decreasing losses and high investments from other sources of electric power.

India is developing at a faster rate to meet the balance between generation and load demand. In the financial year 2008-09, the deficit in electric power is about 12% and is decreasing gradually from then and reached 5% during 2013-14 and is now only 2% deficit. The load demand is more than the power supplied. It is achieved mostly by erection of new power plants along with many renewable resources especially wind source. In mostly around two years, there will be no deficit in electric power in India. From 2020, it is estimated that India will evolve as a pool of electric resource which can deliver power to other neighboring countries and within country abundantly and at cheaper and with better quality. India is developing towards wind electric power production during each financial year. The major wind power production started around year 2005 with capacity of

6270MW and increasing linearly and reached 26866MW generation only from wind in India. It is expected that this wind power generation crosses 50GW by 2020. Hence from the statistics, interest in wind power is increasing and hence more research and development as well as interest towards erection from capital investors and government is required. The total renewable energy capacity installed till date (April 2016) is 89,6602MW in India with wind alone around 27,000MW. The wind power is nearly 8.6% of total power produced from all sources of energy in India in 2016. India started its wind power production only from 1990 and is producing at a remarkable rate competing with many developed and developing countries.

2. Literature Survey on Power Control and Fault Ride through Strategies.

Practically, the DFIG rotor blades failure rate is 0.54% until 2016 April. There is a recorded failure of 3800 out of 7000,000 wind turbine- generators installed globally. 35% failures are with gearbox and 10% failures are due to the generator. There is an electrical subassembly failure on an average of every 2 to 2.5 years as per statistics from 2011. Electrical system and components continue to cause a high rate of failures resulting in unplanned servicing campaigns because they are unpredictable as other types of failures [1].

The DFIG is getting more importance [2-3] than other class of generators because of partial rated converters [4], maximum power extraction capability [5-7], variable rotor speed operation [8] and desired and faster control of reactive power [9-10]. DFIG works efficiently during flickering and unbalanced types of load, can deliver real power to grid still generator speed is below synchronous speed. The rotor side converter (RSC) is designed to have good control on stator reactive power, rotor current and hence generator efficiency can be improved and RSC operates at maximum 30% rating of stator. Due to its low power rating, the cost incurred on converter devices will be low. Besides all the advantages, the DFIG is very sensitive to voltage dips caused by grid faults [11].

For DFIG system, it is observed that from above that, both stator and rotor windings are able to deliver real and reactive power to the grid. If generator speed changes from super-synchronous to sub-synchronous speed [8], the real and reactive power flow from rotor reverses in order to maintain the same direction of power flow in the stator. However, at super-synchronous speed, the rotor also delivers power to the grid and absorbs power when the generator runs below synchronous speed. Efficient controller scheme is needed in such cases to control surge voltages and currents in stator which may damage rotor windings. The reversal of real power from grid to rotor winding is

observed when generator speed reaches below synchronous speed. Therefore there is a necessity to study the effect in the variation of wind speed on generator performance. With an increase in the wind speed, real power extraction from DFIG can be improved.

In direct and indirect methods of reactive power control schemes aims to achieve actual reactive powers equal to the reference value. The different methods extensively used for DFIG are direct power control technique [12-13], direct torque control with stator field oriented control [14-15]. The stator voltage oriented control schemes [16] and [17] are sub-divisional classification of vector control for DFIG.

The doubly fed induction generator (DFIG) is having a better preference due to its low power ratings of converters, small size with higher MVA ratings available in the market, variable generator speed and constant frequency operation, robust four quadrant reactive power control and much better performance during the low voltage ride through (LVRT). However, such DFIG is sensitive to external disturbances like the voltage sag. If grid voltage falls suddenly due to any reason, large surge currents enter rotor terminals and voltage induces drastically. Hence, the rotor side converter (RSC) will get damaged due to exceeding voltage or the current rating. Apart from this, there will be huge electromagnetic torque pulsations and increase in rotor speed which may reduce gears of the wind turbine-generator lifetime.

Many developed and developing countries aiming for sustainable growth are predicted to have a considerable increase in the wind electric power generation in the near future. Hence, each country has its own particular individual grid codes for the wind power integration [18-22]. To get better voltage security and power system stability in the grid faults, the modern grid codes recognized by Germany and soon followed by a number of countries are strict toward the wind energy conversion system (WECS) based fault ride-through (FRT) capabilities.

One of the preliminary schemes is a crowbar in the rotor circuit to protect the power electronic converters from the fault currents by short circuiting the rotor windings through an external resistance [23-26]. Other schemes that use series dynamic braking resistors (SDBRs) to restrict the high current in rotor circuit during the fault are proposed in [27]. Such FRT schemes cannot be deployed in the current scenario due to their incompatibility with the recent FRT requirements discussed earlier. Several FRT schemes for DFIG WTs have been proposed in the few years of early development of DFIG to enhance the transient stability [23- 32]. All these methods can be briefly summarized as 1) preliminary schemes, which add additional resistors to the WT system during the grid fault; and 2) advanced schemes that inject series voltage to maintain the pre-fault voltages across the

stator terminals of DFIG using an additional voltage-source converter (VSC).

On the other hand, advanced FRT schemes using an additional VSC as a dynamic voltage restorer (DVR) have been reported in [28-32]. In these schemes, the DVR compensates the voltage dip seen at DFIG terminals during the grid faults for transient free operation. This series voltage compensation (SeVC) schemes can offer the following merits: 1) smooth FRT; 2) excellent transient stability; 3) applicability for all kinds of grid faults; and 4) retaining electromechanical energy conversion during short interruptions. However, these merits come at the expense of an additional full-rated series transformer and VSC. Alternately, a series-transformer-less FRT scheme for DFIG WTs has been proposed in [32] using the nine-switch converter.

The status of research on the LVRT issue for DFIG for symmetrical and asymmetrical faults and comparison with different control strategies are given in [33-49], recurring faults [50-51]. In these papers, if the stator and rotor voltages are dropped to a certain value during the fault, the DFIG turbine system got synchronized quickly after fault cleared and is made to operate as in pre-fault state.

The major effects due to faults on DFIG are the production of dc component of emf in rotor current [52] and over-current in rotor windings and over-voltage in dc link voltage across the capacitor [53-55]. These will make the DFIG WECS system to lose synchronism with grid and finally leads to the damage in the stator and rotor windings. The DFIG operation is studied under different frames of reference [56-57] to understand its behavior during steady state and transient state. Stationary reference frame [58] and synchronous reference frame [59-61] are famous techniques adapted to draw the performance of DFIG during different types of faults and measures to overcome them. The basic step to overcome the above effects is the application of crowbar [62-63] and placed on the rotor side of the DFIG. The crowbar disconnected the RSC during fault and makes the DFIG operate as an induction motor. This method has disadvantage like, over speeding of the machine, drawing huge reactive power from the grid and discontinuity of power supply. The basic disadvantage with crowbar arrangement is, power supply interruption will occur during voltage sag and this method can protect the rotor circuit from inrush current but cannot solve issues for improving performance during a fault. Hence mostly this method is as an auxiliary technique instead of a solution for LVRT. Also connecting and disconnecting the system with crowbar makes DC link voltage across the capacitor to fluctuate with larger magnitudes.

Although single symmetrical faults are more severe, as per modern grid rules, wind generator system needs to withstand to more symmetrical or asymmetrical faults. Many proposed methods in the literature can

work effectively for tough single faults but has failed to overcome during recurring faults. There are few situations in which faults may not be cleared in single reclosing and is found to occur multiple times. This type of situation is called recurring faults. In general, for this automatic re-closures will open the circuit permanently and will protect the system from damage. From the literature, it is found that dc offset components will lead to large torque fluctuations, increased stator and rotor currents, over speeding of the generator and over voltage in the dc capacitor. FFCC and SRCC will have larger transient currents after the second fault starting instant. The authors in [54] for symmetrical and asymmetrical faults proposed an improved strategy without using flux observer, using a setup switching function to change its mode of operation during normal and recurring faults to damp torque oscillations and to improve ride through during recurring faults.

Sustained operation of the power system is classified into three phases: pre-fault, during fault or fault on and post-fault. The capability of the system to withstand for any fault during low voltage, is LVRT and for voltage, swell is called HVRT. The major challenges for LVRT issues are rotor winding fault current during or instant of fault occurrence, over-voltage in DC link capacitor, large electromagnetic oscillations and rotor speed increasing beyond control during the fault. The better strategy for limiting them is enhanced control of reactive power and efficient control of rotor and stator flux by using RSC. A lot of research was done on LVRT issues for DFIG and most of the methods achieved better control over fault inrush current and DC voltage control of back to back converters.

The overall performance of DFIG will be improved further if fast acting controllers are used by replacing a conventional PI controller in outer and inner control loops. Also crowbar as passive and RSC strategy as active compensation for LVRT reactive power compensation [62-63], dual PI controller [64-65], with PIR [66-70] and robust controllers and meta-heuristic techniques [71-72] with symmetrical and asymmetrical faults for improving uninterrupted P, Q supply from WT to grid. In these papers, authors claim that, instead of using a conventional PI controller, PI + Resonant controller can perform better during asymmetrical faults for DFIG system. Few intelligent control techniques [73-74] are used in control strategies for improving the performance during LVRT and can improve voltage and current levels during fault and makes system more sustainable during and after fault. Fuzzy and neural networks [75-76] are also extensively used to fasten the operation with more accurate control during steady state and especially during transients. Few advanced controllers like hysteresis [77-82].

Some external passive elements and active sources are used in coordination for improving stability and thereby providing a better LVRT operation of DFIG

during symmetrical and asymmetrical faults. The external energy storage devices are used for additional real and reactive power support to the DFIG to overcome the fault and to build voltage quickly when the fault is cleared. The external sources namely ultra-capacitor [83-84], battery energy storage system [85-86], SFCL, SMES coordination are used in coordination [87-92] are connected at back to back of the converter across the dc capacitor or connected between stator and converters. Series dynamic resistors [93-94] are used to protect as well as to improve performance during FRT. From these papers, active energy storage devices are much helpful for rapid real and reactive power compensation for stator and rotor terminals with improved stability during symmetrical or asymmetrical faults.

The FACTS family is used to overcome the system to lose synchronism because of external disturbances like large variations in wind speed, symmetrical and asymmetrical faults and sub-synchronous resonance. In these papers, decreased STATCOM rating with optimal VSC capacitor switching was implemented. The DVR or SSSC [95-96] is used to find the solution for balanced and unbalanced faults at the grid for DFIG system. In order to improve power system stability during disturbances, SVC [97] and UPFC is used [98-99]. The UPFC is a better device than SSSC or STATCOM as it is a combination of both. Frequency domain approach with Eigen analysis for sea shore wind farm with generators like DFIG and SCIG were compared. In [100-101], offshore multiple wind turbine based DFIG system was connected to a common bus and transferred by using HVDC network.

Because of high penetration due to interconnected wind energy based power system, the stability of system will get disturbed [102-104]. In these papers, certain measures like improvement in rotor control scheme are incorporated for inertia of generator. The study on performance improvement of DFIG because of unbalanced and distorted loads [105-107] is also getting importance as mostly the loads are not balanced and the generation firms need to supply mostly power to industrial customers. Such loads will produce unbalanced torque pulsations in DFIG and need to be damped. If these pulsations or oscillations sustain in the generator, it will impose severe stress on the DFIG shaft and overall life time decreases. A very detailed research was conducted for distortion type of loads and their effects and overcome measures are studied [108-109] to enhance the DFIG performance. Distorted loads and their effects on the performance of DFIG are well examined in these papers.

One of the best solutions to overcome issue because of unbalanced, distorted and asymmetrical faults is to use constant switching frequency technique. Harmonic mitigation with extensive reactive power control mechanism [110-111] helps in compensating unbalanced flux production using the converters of the

DFIG. Sometimes series capacitors are used for additional reactive power support in the transmission lines. These passive devices improve voltage profile, power factor, and reactive power support at the point of connection at low cost. But these will produce sub-synchronous resonance (SSR) [112-114] with the line-load inductance leading to internal low frequency oscillation in the DFIG. These oscillations need to be mitigated otherwise the stability of the system will be lost within a small time and also lead to the huge drawing of current in the generator windings and will get damaged. Because of heavy load switching operation, frequency and power oscillations are produced. If the frequency is regulated [115-117], the effect due to load switching and SSR can be compensated. Large power systems with multiple buses, loads, and generator with wind energy conversion system interconnections are also getting popular nowadays. A very famous two area system called Kundur system is examined in [118] for DFIG wind energy conversion system.

From literature survey, it is found that minimization in the rotor fault current by incorporating specific control scheme in RSC the performance of DFIG can be improved drastically. The techniques like feed-forward current compensation, magnetization current control etc are designed to limit the fault current entering to rotor windings and damaging the converters, the crowbar is widely used. However, it requires additional hardware and it cannot completely make the system free from fault. So, recently few papers proposed a control scheme that does not require a crowbar. Few papers used fault current limiters SMES etc. to limit surge currents. These additional power based techniques are cost effective but are sophisticated techniques. The LVRT with external devices like fault current limiter is used to suppress surge currents produced in the rotor during severe faults. In the above control schemes, the torque is fixed to zero and the reactive power must be drawn from the grid. This makes the DFIG system to more prone to the fault and weakens the system.

A rigorous analysis of the power swings is challenged by three distinct aspects of the problem. a. The rapidity of short duration wind variations makes deterministic description difficult [119-120]. b. The source wind does not affect the power network directly, but rather “through” the nonlinear power output curve that applies to the wind-turbine/generator included within each WECS unit [119]. c. Rapid variations of source wind around cut-out limits of WECS units [120] may frequently result in their automated disconnection from the grid with a consequent quantum change in overall output power. As in [121] and the online debate associated with it indicate, questions and opinion on the phenomena of short duration variations are extremely diverse. The much-deliberated aspects of the problem have led to the evolution of short-term wind

power generation as a new and distinct area of research interest [122]. Depending on the fault severity, these high voltages/currents in rotor circuit may damage the power electronic converters in the rotor circuit.

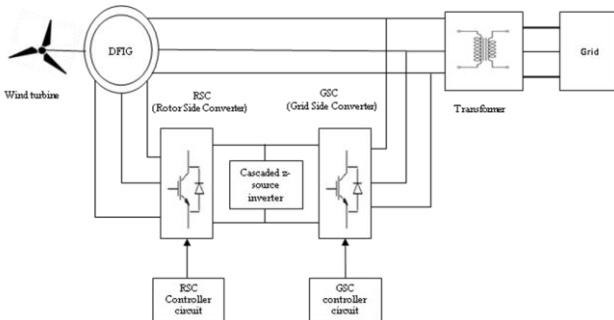


Fig. 1. DFIG with Z-Source Inverter Wind Generation System

3. PROBLEMS AND CHALLENGES FOR GRID CONNECTED DFIG

Despite many advantages with DFIG wind turbine system, there are few major problems need to be encountered. Unlike other types of wind generators, this DFIG stator is connected directly to the grid. Hence disturbance at grid will directly impact the performance of DFIG. Similarly, any disturbance in DFIG will also make the grid to face the issue of the grid is a weak one. Hence, lot of care is to be taken for DFIG system from the point of synchronizing to till shutting down of the generator. The major issues faced by grid connected DFIG is classified as source side issues, transmission line side and grid side issues. These issues or challenges for DFIG grid connected WECS is found from literature and are summarized below.

3.1 Source side issues

The problems or challenges at source side are because of the mechanical turbine or electrical generator issues. Mechanical control and speed sensor issues are mechanical, power electronics converter or converter faults comes under electrical issues. The rotor speed is estimated using techniques like signal injection, phase locked loop (PLL), MRAS etc. The wind speed is estimated using statistical methods, weather prediction techniques etc. if any of this sensor-fewer methods fail to operate for some time, the total performance of DFIG WECS fails. The rotor speed is estimated mostly with encoders, these too often fail. There are few issues with power electronic converters like extraction of optimal real power from the generator or accurate or rapid control of reactive power or rotor speed adjustment issues. Sometimes, DFIG converters may fail to operate. The problems like a misfire, fire-through etc may occur. Inter-turn faults in DFIG may also happen but is very often.

3.2 Transmission line side issues

In the transmission lines, many faults will occur, which has very high impact on DFIG as the stator is directly connected to the grid via the transmission lines. Balanced, unbalanced low voltage faults, over-voltage faults, and sub-synchronous resonance are most frequent faults occur in the transmission lines. The resonance issues take place when compensation in the transmission line is done by series capacitor placement used for voltage regulation or power factor correction. The resonance fault is a serious issue which makes the DFIG rotor to have small internal oscillations with low frequency around 2 to 15Hz. This make overall DFIG system to lose its operation, life time and hence reliability. The other issues like balanced, unbalanced and over-voltage are very frequent disturbances which will influence DFIG WECS considerably. Most of the national grid synchronizing policies are very strict, which does not allow the DFIG WECS to lose synchronism and must forcibly stay connected to the grid even grid voltage falls to zero voltage or voltage increase up to 1.3 times its nominal value. Hence these issues are also very challenging and are taken proper steps to have better protection as well as operation during faults.

3.3 Grid side issues

The loads or other generators are also connected to a common point called as the grid. From here, power will be transmitted to load centers. If the loads at grid point are disturbing or flickering or large reactive power demand type, the grid will become weaker. If the number of wind power plants connected to the grid is less in number, the conventional power plants will become dominate in nature and force the WECS to operate as per their characteristics. If the number of wind turbine-generator sets increases, it leads to penetration issues. In general, the wind speed is not constant and hence output power injected to grid is also varying. Due to this, the grid power is flickering, which make voltage and/ or current to flickering and disturbing. This makes sensitive loads to damage or lose its performance and operates with less reliability.

In a similar way, strong loads with varying voltage or current will cause varying copper losses and hence nonlinear heating in the machine, which makes the performance of the device to decrease and also its life time. If the load on all the three phases is not nearly uniform or having distorted load, the grid will produce fluctuating voltage and reactive power to the DFIG. If the DFIG is unable to recover from these voltage disturbances or due to sudden varying reactive power, it may lose synchronism. If weakest DFIG WECS fail to stay in synchronism, the voltage at DFIG point of common coupling (PCC) varies drastically.

The breakdown in one generator set will affect the second sensitive generator and continues. This finally makes all the generators to trip by losing synchronism. This ultimately led to weaken the grid and possibly

make the loads shed if no proper control action is taken. Among these issues, load frequency control (LFC) is also a major one. If there is an increase or decrease in load at a tie-line, it makes the frequency and power of the grid to oscillate. A stator of DFIG is directly connected; its frequency will also fluctuate. Therefore without proper frequency regulation, synchronism to grid gets affected. Hence most of these issues need to be answered.

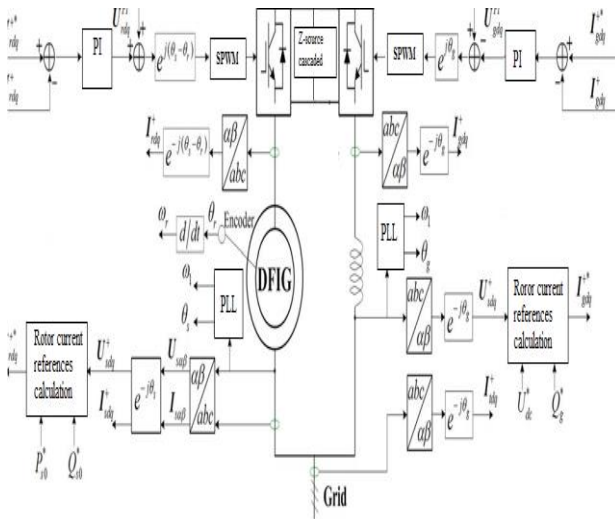


Fig. 1. RSC and GSC Controllers

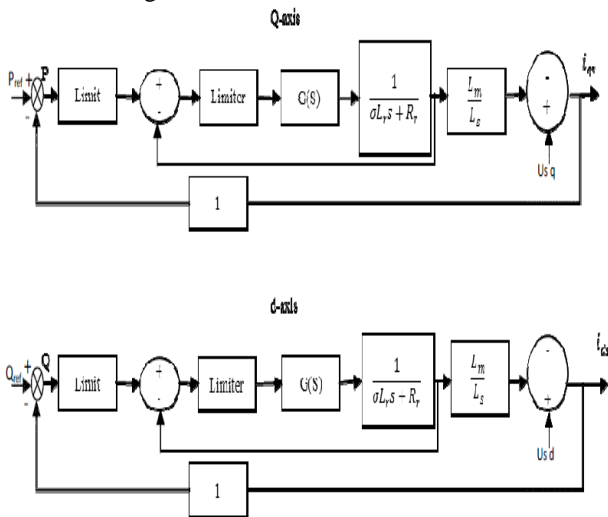


Fig. 3. RSC Current Reference Controller

4. Works observed from the literature survey for unbalanced DFIG systems.

Since most of the wind energy conversion systems are connected at remote locations due to the factors like obstruction free wind flow, low cost land and station system etc. generation from these remote areas the grid is in general weak and also unbalanced voltages are more common [123-125]. Certain situations practically

arise where DFIG is operated under standalone where unbalanced and distorted loads are mostly encountered [126-129]. Such unbalanced voltage on induction generators, especially DFIG leads to local hunting in the stator and further without proper care and continuous operation under this situation tend the DFIG to overheating in the windings and further decreases its lifetime [123, 125, 127, 130-132]. During the unbalanced voltage operation, negative sequence current components are produced which results in electromagnetic torque oscillations, generates acoustic noise with increased unbalance in the voltage generation which affects the gearbox of the wind turbine and mechanical assemblies [123, 125, 127, 134]. Different control algorithms like d-q axis based counter rotating synchronous frame [123, 125, 127, 132, 133], resonant PIR and PR controllers [126, 135, 136], sliding mode control [137], direct power control [124, 140] and predictive control [129, 138, 139] strategies are available in the literature.

4.1 DFIG operation for standalone load system.

The DFIG stator and the load in standalone operation are four wire based star connected with neutral is connected to have an effective zero sequence current path circulation. Battery or ultra-capacitor bank is often used to start up the DFIG system with RAC and GSC are used to compensate the unbalance in the load [127]. In some papers as in [128], RSC is used to make unbalanced voltage to be balanced and is tested for non-linear loads using large dc link rating voltage. The technique in this paper has a disadvantage of large negative sequence components. To solve this issue, predictive control technique proposed in [129 and 138] were successful to a greater extent using predictive control strategy. The d-q control scheme with resonant controllers in [126] adopted in RSC and GSC are successful to a major extent by dissolving the negative sequence components in the DFIG.

4.2 DFIG operation for unbalanced grid conditions.

Many control schemes are available in the literature finding different solutions for DFIG operation effectively under unbalanced and distorted grid conditions [129, 132, 133, 135, 136, 140 and 141]. The objectives in these control systems are a) controlling real power oscillations, b) controlling reactive power oscillations and c) supplying the grid without any negative sequence components. Few papers GSC alone to compensate the voltage, few papers use RSC only, while other papers use both RSC and GSC with direct power control scheme in d-q reference frame.

5. Conclusions of the works.

The DFIG grid connected system has many challenges for the issues identified from the literature survey. Results obtained are described in brief here [144].

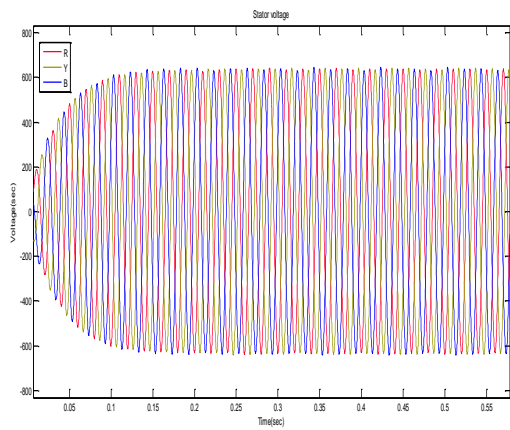


Fig. 4. Stator Voltage

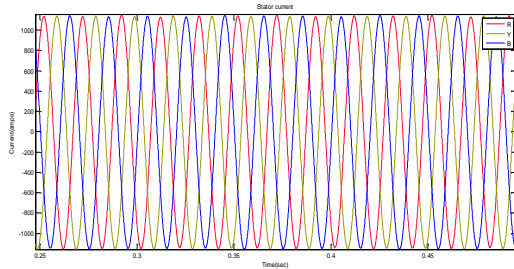


Fig. 5. Stator Current

The above figure 4 and 5 shows the stator current and voltage. The plot shows the stator voltage and current during balanced condition. It can be seen that stator voltage is completely same as the grid voltage after balance.

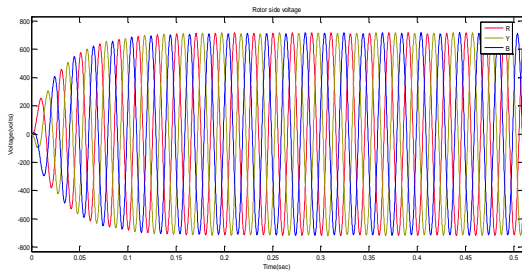


Fig. 6. Rotor Voltage

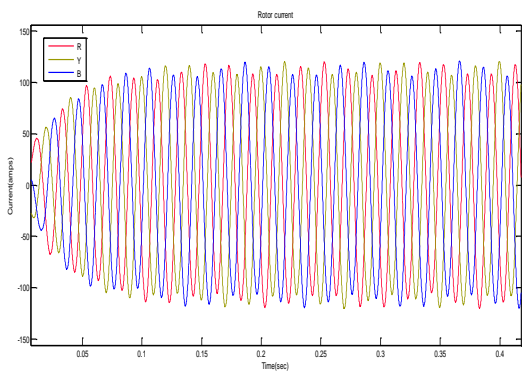


Fig. 7. Rotor Current

The above figure 6 and 7 shows the rotor current and voltage. The plot shows the rotor voltage and current during balanced condition.

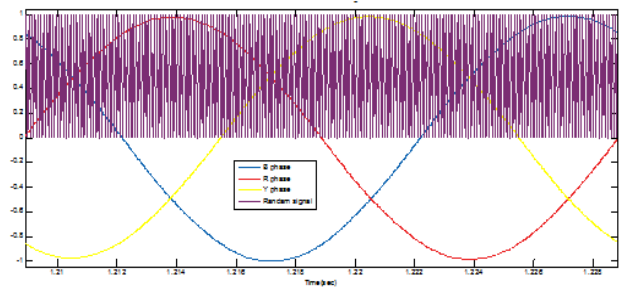


Fig. 8. SPWM Signal Generation

The figure 8 shows the SPWM signal generation. The SPWM is a constant amplitude pulse with different duty cycle for each period and this technique is used in DFIG motor controlling and harmonic reduction. The sinusoidal pulse width modulation technique generates multiple output pulse per half cycle. The gating signal is generated based on dq current reference controller.

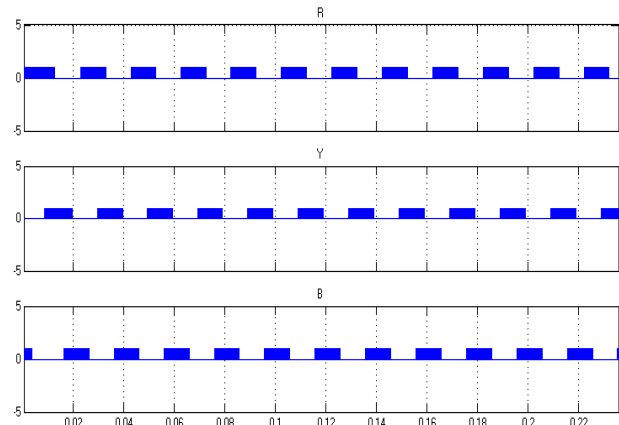


Fig. 9. Rotor Side Converter Pulse

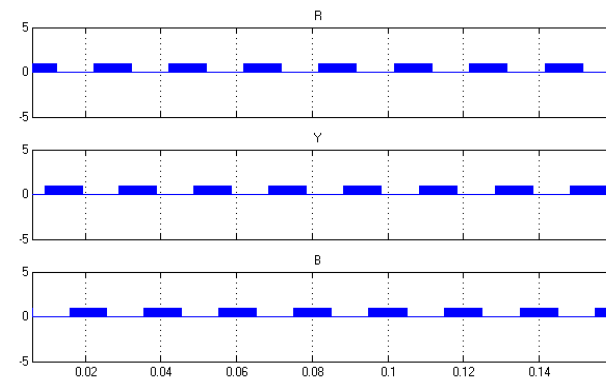


Fig. 10. Stator Side Converter Pulse

The figure 9 and 10 shows the rotor and stator side converter pulse. The stator and rotor generate the pulse in R, Y, B phase. These pulse generations is input of the SPWM signal.

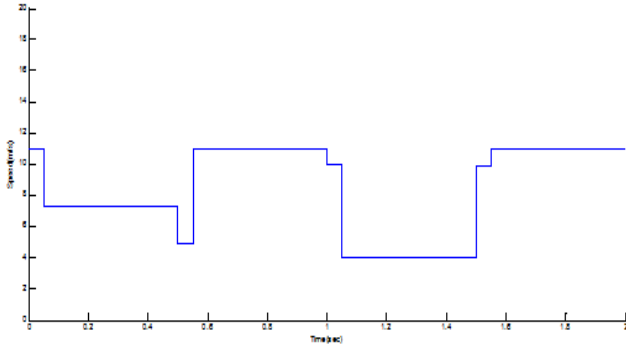


Fig. 11. Variable Wind Speed

The above figure 11 shows the variable wind speed. The variable speed 50 Hz frequency of DFIG allows the motor speed to follow the change of wind speed. The motor input speed ranges vary from 4 m/s to 11 m/s. The variable speed ranges are developed and the output variations are analyzed to compensate the voltage error. The constant frequency is 50 Hz.

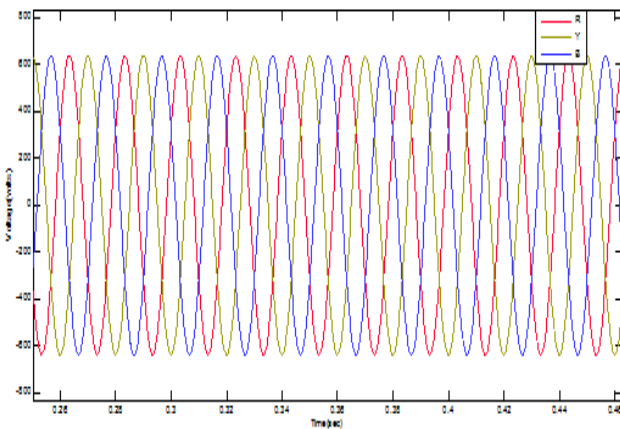


Fig. 12. Grid Voltage

The grid voltage is shown in figure 12. The simulation result of grid voltage is 690V and present result is verified and the simulation technique is successfully fulfilled balanced voltage network.

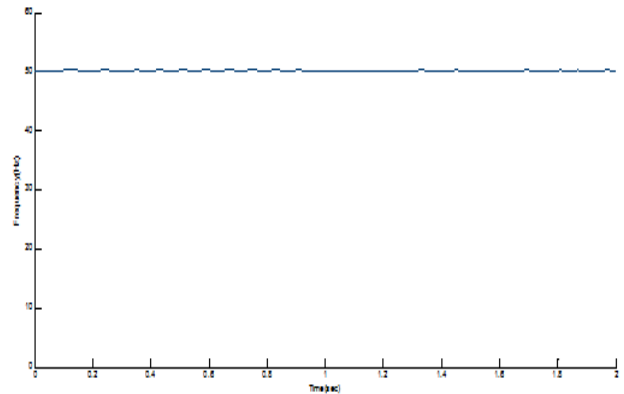


Fig.13. Stator Line Frequency

The stator line frequency is shown in figure 13. The line frequency waveform demonstrates the output frequency of the stator current and stable at 50 Hz with change of speed. The present sequence is fashion to achieved variable speed 50 Hz constant frequency.

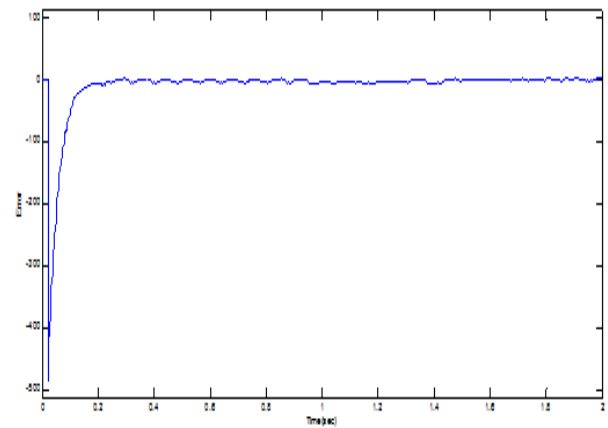


Fig. 14. The Error of Stator and Grid Voltage during Network Unbalance

The above figure 14 shows the stator and grid error voltage. The plot shows the error voltage of stator and grid voltage when DFIG in under unbalanced conditions. It can be seen that the error is zero.

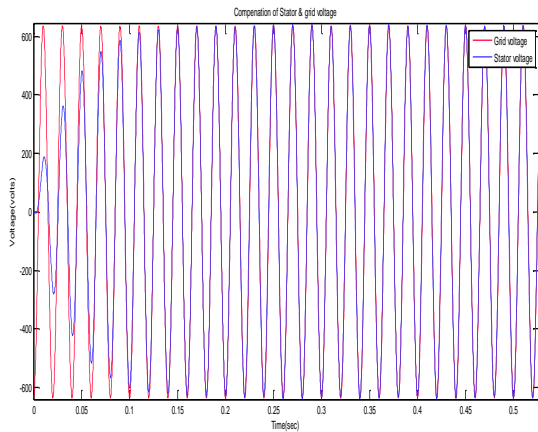


Fig. 15. Voltage Compensation of Stator and Grid

The above figure 15 shows voltage compensation of stator and grid under unbalanced grid voltage condition. The stator voltage convergence to the grid voltages after some adjustment when the balancing stator voltage is same as the grid voltage in volume, phase and frequency. Harmonic analysis of stator current and voltage is shown in figure 16, 17, 18 and 19. The total harmonic distortion of stator current and voltage are in two strategies, such as balanced and unbalanced voltages.

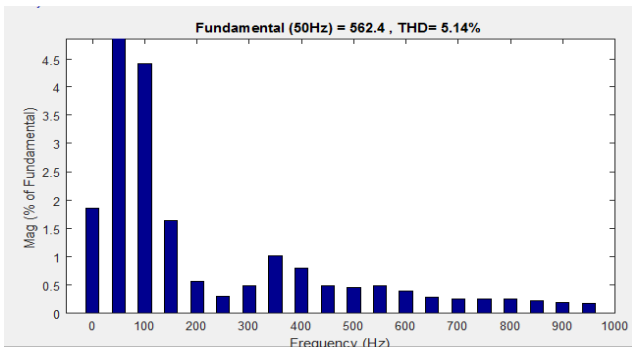


Fig. 16. THD in Stator Voltage during Network Unbalance

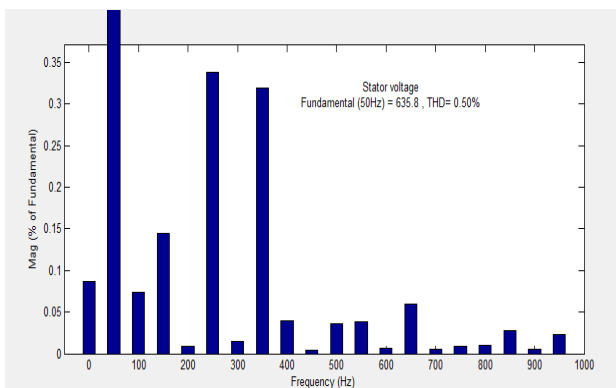


Fig. 17. THD in Stator Voltage during Network Balance

During balanced voltage strategy, harmonic content of stator voltage is quiet good for both PI and proposed control schemes when compared to the traditional method. The traditional THD of the stator voltage is 5.14 % and present THD is 0.50%. In this present technique THD is reduced by 4.64 % under balanced grid voltage strategy.

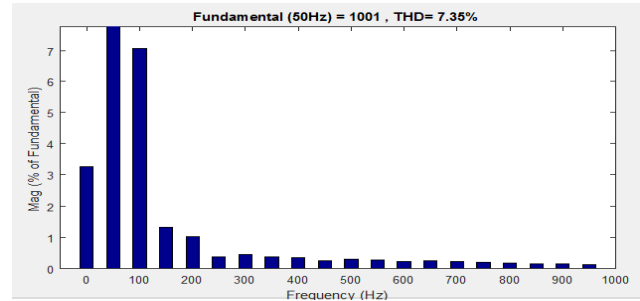


Fig. 18. THD in Stator Current during Network Balance

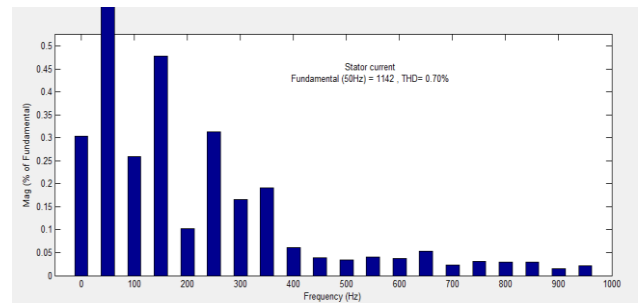


Fig. 19. THD in Stator Current during Network Balance

During balanced voltage strategy, harmonic content of stator current is quiet good for both PI and proposed control schemes when compared to the traditional method. The traditional THD of the stator current is 7.35%, present THD is 0.70%. In this present technique THD is reduced by 6.65% under balanced grid voltage strategy. Hence, the reduced THD improves the stator voltage and current. THD values are shown in table 1.

Table 1

THD Comparison for Balanced and Unbalanced Strategy

Parameter	THD (%)
Stator voltage with unbalance condition	5.14
Stator voltage with balance condition	0.50
Stator current with unbalance condition	7.35
Stator current with balance condition	0.70

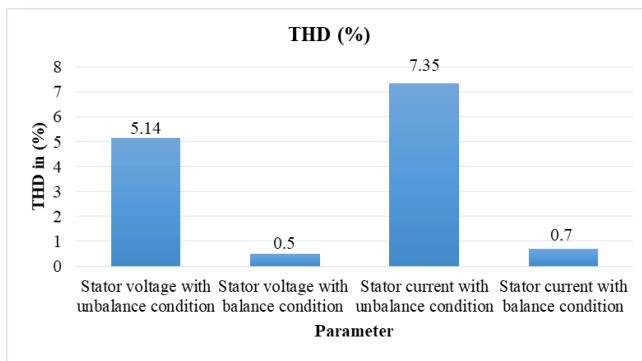


Fig. 20. THD Comparison for Balanced and Unbalanced Strategy

THD comparison for balanced and unbalanced strategy is shown in figure 20. The comparison result disclose the THD's stator voltage and current which is increased under unbalanced grid voltage condition and reduced under balanced grid voltage condition. Mostly grid or transmission lines pose serious issues to DFIG in the form of balanced or unbalanced low voltage faults or over voltage faults or recurring faults even with recent control techniques. When low voltage fault occurs, rotor speed increases, fault inrush current entering to rotor and stator terminal increases beyond 2 times. Voltage and frequency of stator and grid differ and hence synchronization to grid fails. This is not desired operation, hence sophisticated algorithm with a fast acting controller or additional external power source like a battery, FACTS devices are necessary. These will help in limiting the surge current to within 2 times rise, speed to remain constant, better stability margin. The control strategy with these fast controllers and FACTS devices helps in reaching normal state during and after fault for the DFIG parameters by allowing small surges at fault instant are desired. The impact of the large power system on grid connected DFIG during faults is high due to complex control of the system. Hence sophisticated control scheme with better FACTS device is necessary. A new control scheme and a new topology are required for overcoming all the issues because of faults is required. Based on the severity of fault, the high currents or voltages in the rotor circuit will damage the RSC semiconductor devices.

A number of fault ride through (FRT) systems for DFIG WTs have been developed in the literature to improve the transient stability. These techniques are briefly abridged as 1) basic control schemes with supplementary resistors to the WT system under grid fault; and 2) sophisticated control schemes operate by injecting series voltage to sustain the pre-fault voltage at the DFIG stator terminals using an extra voltage-source converter (VSC). One of the basic techniques is an application of a crowbar in the rotor circuit for protection the RSC from the fault surge currents by short circuiting rotor winding using an external

resistance. Few control schemes use series dynamic braking resistors (SDBRs) to limit the surge current in RSC and rotor of DFIG under the fault are proposed. However these FRT techniques cannot uplift the current scenario because of their inaptness with the modern FRT necessities conferred earlier. Alternatively, superior FRT techniques with an additional VSC as a (DVR) dynamic voltage restorer have been reported. These series VSCs can present the following merits: 1) better FRT; 2) effective for symmetrical or asymmetrical faults; 2) superior transient stability; and 4) preserve in electro-mechanical energy exchange under short time interruptions. But, extra full-rated series transformer and VSC are required to achieve these merits.

Hence, there is a requirement for effective control of real and reactive power under steady state and transient conditions. Effective extraction of real power, desired control of reactive power, smooth operation during any FRT issue is desired for grid connected DFIG.

6. Future Scope.

There is a large scope for research investigation for riding through under distorted and unbalanced grid and standalone load conditions which are having higher probability of occurrence in the power system.

1. Sufficient active and reactive power control schemes to balance completely the unbalanced voltage in the DFIG under unbalanced grid and weak grid operation.
2. Under a small unbalanced (asymmetrical) voltage dip large power oscillations in the torque and mechanical turbine system oscillations are still persisting with the present day technology.
3. The mechanical stress and reactive power effective control algorithms has a long scope for fault ride through and unbalanced grid operation for DFIG.
4. Complete elimination of mechanical crowbar with a good complete automatic power electronics converter and sophisticated control schemes are necessary for unbalanced and distorted load and grid operation.
5. Large flux components controlling is necessary during symmetrical faults and DFIG unbalanced voltage, because of this flux decay component, large emf is generated which leads to severe surge currents in the stator and rotor windings. This severe inrush surge currents will not only damage the RSC and GSC converters, will also damage considerably dc link capacitor, DFIG windings and also the mechanical system.

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