DIRECT TORQUE CONTROL FOR DFIG BASED WIND TURBINE WITHOUT CROWBAR PROTECTION UNDER VOLTAGE DIPS

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Abstract— **This paper focuses the analysis on the control of doubly fed induction generator (DFIG) based high-power wind turbines when they operate under presence of voltage dips. The main objective of the control strategy proposed for doubly fed induction generator based wind turbines is to eliminate the necessity of the crowbar protection when low-depth voltage dips occurs. A direct torque control strategy that provides fast dynamic response accompanies the overall control of the wind turbine. The proposed control does not totally eliminate the necessity of the typical crowbar protection for turbines it eliminates the activation of this protection during low depth voltage dips. Due to voltage dip in the wind turbine causes three main problems they are control difficulties, disturbance in the stator flux, increase of voltage and currents in the rotor of the machine. The DC bus voltage available in the back-to-back converter determines the voltage dips depth that can be kept under control. The modeling of the complete system is done in MATLAB-SIMULINK. Simulation results show the proposed control strategy that mitigates the necessity of the crowbar protection during low depth voltage dips.**

Index Terms— **The DTC offers excellent dynamic performance and gives good torque response than the field control.**

I. INTRODUCTION

1.1. Project synopsis

Wind power penetration levels have increased in electricity supply systems in a few countries in recent years; so have concerns about how to incorporate this significant amount of intermittent, uncontrolled and non-dispatch able generation without disrupting the finely-tuned balance that network systems demand. GRID-connected wind electricity generation is showing the highest rate of growth of any form of electricity generation, achieving global annual growth rates in the order of 20 - 25%. It is doubtful whether any other energy technology.

1.2. Problem statements

Grid integration issues are a challenge to the expansion of wind power in some countries. Measures such as aggregation of wind turbines, load and wind forecasting and simulation studies are expected to facilitate larger grid penetration of wind power.

In this paper simulation studies on grid connected wind electric generators (WEG) employing i) Squirrel Cage Induction Generator (SCIG) and ii) Doubly Fed Induction Generator (DFIG) has been carried separately. Their dynamic responses to disturbances such as variations in wind speed, occurrence of fault etc. have been studied, separately for each type of WEG

1.3. Power from wind

The power that can be captured from the wind with a wind energy converter with effective area A_r is given

$$P = \frac{1}{2}\rho_{air} C_p A v_w^3$$

by

Where P_{air} is the air mass density [kg/m^3], *vw* is the wind speed and *Cp* is the so-called power coefficient which depends on the specific design of the wind converter and its orientation to the wind direction. Its theoretical maximum value is 16/27 = 0.593 (Betz limit). For a wind turbine with given blades it can be shown that the power coefficient *Cp* basically depends only on tip speed ratio *l*, which equals the ratio of tip speed *vt* [m/s] over wind speed *vw* [m/s] and it is so-called blade pitch angle *q* [deg]. This pitch angle is defined as the angle between the cord of the blade and the plane of the wind rotor. So, for a wind rotor with radius *r*, (1) can be rewritten as:

$$P = \frac{1}{2}\rho_{air} C_p(\lambda,\theta)\pi r^2 v_w^3$$

As an example, Fig. 2 shows the dependency of the power coefficient *Cp* on the tip speed ratio *l* and the blade pitch angle *q* for a specific blade. For this blade maximum energy capture from the wind is obtained for *q* =0 and *l* just above 6. To keep *Cp* at its optimal value for varying wind speed, the rotor speed should be proportional to the wind speed. In practice both constant *l* (variable speed) and constant speed operation is applied.

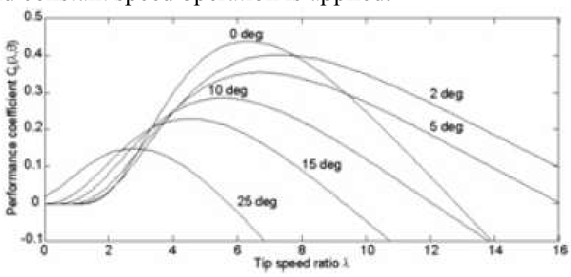


Fig: Power wind characteristics

For on shore turbines, the blades are designed such a way that the optimal tip speed is limited to roughly 70 m/s. This is done because the blade tips because excessive acoustical noise at higher tip speeds. For offshore turbines, this does not plays an important role that the higher speeds is used leading to slightly higher optimal values of *Cp*. The relation between wind speed and generated power is given by the power curve, as depicted in Fig. The power curve can be calculated, where the appropriate value of *l* and *q* should be applied. In the power curve, they can be distinguished, that the four operating regions can apply to both to constant speed and variable speed turbines:

1. No power generation due to the low energy content of the wind.
2. Less than rated power generation. In this region, optimal aerodynamic efficiency and energy capture is aimed at. The wind speed at the boundary of region 2 and 3 is called the rated wind speed and the variables of all the subscript rated refer to design values at this wind speed.
3. Because of Generation of rated power the energy content of the wind is enough. Because of this region, the aerodynamic efficiency must be reduced; otherwise the electrical system would become overloaded.
4. No power generation. Because of high wind speeds the turbine is closed down to prevent damage.

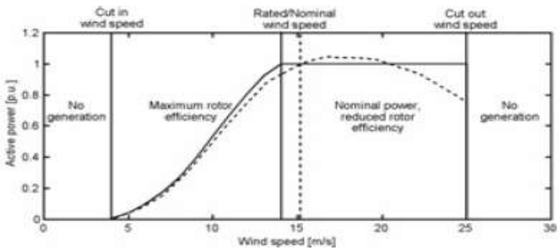
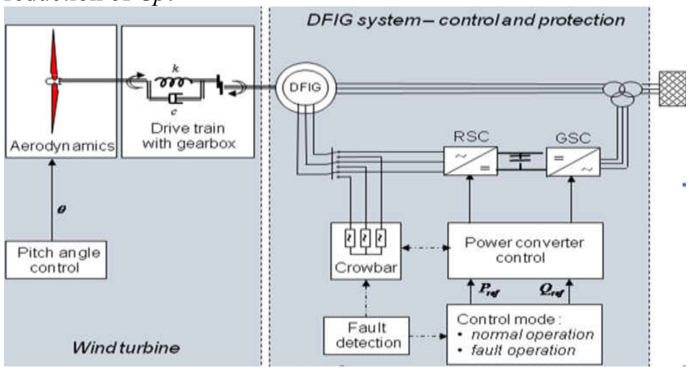


Fig.no.1.3.2. Typical power curve of a constant speed stall (dotted) and a variable speed pitch (solid) controlled wind turbine.

II. BLOCK DIAGRAM

2.1. Aerodynamic power control:

In region 3 (and 4) the shaft power should be less than the available power from wind to prevent overloading of components. The two main methods for limiting the aerodynamic efficiency are high wind speeds. With the first method one takes advantage of the aerodynamic stall effect. When the angle, at which the wind hits the blade ('angle of attack'), is gradually increased, then at a certain angle the airflow will no longer flow along the blade, but will become loose from the blade at the back side. Large eddy's will be formed that result in a drastic reduction of *Cp*. If a turbine is operated at constant speed and the wind speed increases, then automatically the angle of attack increases. At a certain wind speed the angle of attack will reach the value where stall occurs. Here it is assumed that the pitch angle *q* is not changed. Then it is called stall controlled turbines and the blade is designed such that the stall effect just starts at the rated wind speed. Due to the stall effect, for constant above rated wind speed the power is more or less, as indicated by the dotted curve in Fig. 3. No active control systems are used to achieve this, which also implies that the blade does not need to be pitch able. With variable speed (constant *l*) wind turbines the angle of attack is independent of the wind speed so that the stall effect does not occur. To reduce the power above the rated wind speed the blades are pitched towards the vane position by hydraulic or electric actuators resulting in a reduction of *Cp*.



2.2. Electrical system

As stated before two types of wind turbines can be distinguished namely variable speed and constant speed turbines. For constant speed turbines one applies induction generators that are directly connected to the grid. For variable speed turbines a variety of conversions systems is available.

2.2.1 Currently used generator systems

The three most commonly used generator systems applied in wind turbines are depicted in figure

1) Constant speed wind turbine with squirrel cage induction generator (CT)

Between the rotor and the generator, squirrel cage induction generator can be use there is a gearbox so that a standard (mostly 1500 rpm). The generator is directly connected to utility grid the power is limited using the classic stall principle: if the wind speed increases above the rated wind speed, the power coefficient will reduces, so that the power produced by the turbine stays near the rated power. Sometimes active stall is used: negative pitch angles are used to limit the power. There are a few variants:

1. pole changing generators with different numbers of pole pairs with two stator windings so that at two constant speeds the turbine can operate in order to increase energy yield and reduce audible noise, and
2. In order to reduce mechanical loads by making larger speed variations Generators with electronically variable rotor resistance is possible the semi variable speed wind turbine.

2) Variable speed wind turbine with doubly-fed (wound rotor) Induction generator (VTDI)

There is a gearbox so that a standard (mostly 1500 rpm) doubly-fed induction generator can be used between the rotor and the generator. The rotor is connected to a converter and the stator is directly connected to the utility grid. The synchronous speed falls in the middle (in this case at 85% of rated speed), the gearbox ratio is chosen such that then the lowest converter power rating is Obtained. When star-delta switching at the rotor winding is applied converter rating of roughly 35 % of the rated turbine power is sufficient, at above the rated wind speed, the power is reduced by pitching the blades.

3) Variable speed wind turbines with direct-drive synchronous generator (VTDD)

Standard generators can therefore not be used and generators have to be developed specifically for this application. These generators are very large because they have to produce a huge torque. The varying generator frequency to the constant grid frequency through a converter gives the total turbine power. The power is again reduced by pitching the blades.

2.3. Comparison of the three systems

1) Cost, size and weight

Squirrel cage induction generators are roughly 25% cheaper than doubly-fed (wound-rotor) induction generators. The converter for a doubly-fed induction machine is smaller and cheaper than for a direct-drive generator. Direct-drive generators are much more expensive because of large and heavy Direct-drive generators are much more expensive and have to be specially developed, so direct drive turbines not need a heavy gearbox.

2) Suitability for 50 and 60 Hz grid frequency

Turbines with generators are directly coupled to the grid (CT and VTDI) need different gearboxes for different grid frequencies. This is not the case when a converter decouples the two frequencies.

3) Audible noise from blades

In a well-designed wind turbine, the blades are the main sources of audible noise. In variable speed wind turbines, the rotor speed is low at low wind speeds, and so is the audible noise. This is not the case in constant speed wind turbines. At higher wind speed the noise from the blade tips drowns in the wind noise caused by obstacles more close to the observer. However mechanical resonance can also cause other audible noise, in a wind turbine that is not properly designed.

4) Energy yield

In order to capture the maximum energy from the wind, the rotor speed has to be proportional to the wind speed in region 2 of figure 3.. Especially in part load, gearboxes and power electronic converters have limited efficiencies. Therefore, the energy yield of variable speed wind turbines is larger than of constant speed wind turbines Direct-drive generators have lower efficiencies than standard induction machines.

5) Reliability and maintenance

The replacement and regular inspection should be made for Brushed synchronous generators and doubly-fed induction generators Permanent magnet (PM) and squirrel cage induction generators don't have this problem. Gearboxes are widely used, well-known components with many of applications.

In constant speed wind turbines, wind gusts immediately lead to torque variations, while in variable speed wind turbines, wind gusts lead to variations in the speed without large torque variations. Therefore, this may result a decrease in reliability and an increase in maintenance. Generally, more complex systems suffer from more failures than simple systems.

6) Power quality

Fig. 5 depicts measurements of wind speed sequences and the resulting rotor speeds, pitch angles and output powers for the three most used generator systems at wind speeds around the rated wind speed. It appears that the power output of variable speed wind turbines is much smoother (less 'flicker') than constant speed wind turbines because rapid changes in the power drawn from the wind are buffered in rotor inertia.

The fast power fluctuations in constant speed wind turbines are caused by variations in wind speed, but also by the tower shadow. If the converter rating is large variable speed wind turbines also can be used for voltage and frequency (V& f) control in the grid (within the limits posed by the actual wind speed), which is not possible with constant speed wind turbines.

Power electronic converters produce harmonics that may need to be filtered away.

7) Grid faults

The three concepts in case of a grid fault causing a voltage dip.

In case of a fault, constant speed wind turbines give the large fault currents, for activating the protection system. However, when the voltage comes back, they consume a lot of reactive power and thus impede the voltage restoration after the dip. In addition both the fault and the reconnection results in large torque excursions that may damage the gear box.

2.4. Alternatives and trends

A. Alternative generator systems

1) Variable speed with squirrel cage induction generator

A few manufacturers have produced variable-speed wind turbines with squirrel cage induction generators with a converter carrying the full power (VT/AGP in table I).

Compared to the doubly-fed induction generator this system has the following advantages

- The generator is cheaper
- The generator has no brushes,
- The system is often used as a standard industrial drive,
- It can be used both in 50 Hz and 60 Hz grids, and the following disadvantages
- The converter is larger and more expensive (100% of rated power instead of 35%)
- The losses in the converter are higher because all power is carried by the converter.

From the fact that this solution is known and rarely applied, it can be concluded that its disadvantages are more important than the advantages.

***2*) Variable speed with geared synchronous generator**

Recently, the Spanish manufacturer Made developed a geared wind turbine with a brushless synchronous generator and a full converter

Compared to the doubly-fed induction generator, this generator system has the following advantages

- The generator has a better efficiency,
- The generator is cheaper,
- The generator can be brushless,
- It can be used both in 50 Hz and 60 Hz grids, and the following disadvantages

- Larger, more expensive converter (100% of rated power instead of 35%)
- The losses in the converter are higher because all power is carried by the converter.

It is possible that the steady decrease in cost of power electronics (roughly a factor 10 over the past 10 years) will make this an attractive system in the near future.

B. Trends in geared generator systems

As appears from table I, the first trend to be mentioned is the fact that in recent years, many wind turbine manufacturers changed from constant speed to variable speed systems for the higher power levels for reasons mentioned in section 3.2.

The doubly -fed induction generator systems have been made suitable for grid fault ride-through. A next step might be than the turbine has to be made suitable to assist in the voltage and frequency (v & f) control of the grid, which is in theory possible, but should be implemented in practice.

C. Trends in direct-drive generator systems

Most of the current direct-drive generators are electrically excited synchronous generators (Enercon, Lagerwey). Some manufacturers work on permanent-magnet synchronous generators (Zephyros, Jeumont, Vensys). Enercon and Lagerwey started developing direct-drive generators in the early nineties, when permanent magnets were too expensive. Although magnet prices dropped by roughly a factor of 10 over the past 10 years, Enercon seems to stick to it successful, well-known and proven solution.

D. Trends in voltage levels

Until a few years ago, wind turbine manufacturers mainly used voltage levels of 400 V and 700 V. However, in the nineties of the last century, ABB came with the wind former, a medium voltage generator. In the past few years, a few wind\ turbines operating with higher voltage levels have been introduced: Vestas and Made use 1 kV, Zephyros uses 3 kV, and NEG-Micon even uses 6 kV for the stator winding.

III. PROJECT DESCRIPTION

The two most important reasons to situate wind energy offshore are especially in densely populated regions such as the Netherlands, there is hardly space for wind energy on shore. Offshore wind speeds are higher than on shore wind speeds, so that higher energy yields can be expected. The most important difference between the requirements for onshore and offshore wind energy is that for offshore wind turbines it is much more important that they are robust and maintenance-free. This is because it is extremely expensive and difficult and under certain weather conditions even impossible to do offshore maintenance and reparations. Further, an offshore environment is rather aggressive both for insulation materials that deteriorate and for steel and if applicable permanent magnets that may corrode. Therefore, special corrosion protection and the use of conditioned air should be considered. There are several facts that make permanent-magnet direct drive generators suitable for offshore wind turbines: they do not need maintenance requiring brushes and gearboxes and the large size is not a real disadvantage offshore. To improve the availability of offshore wind turbines, condition based maintenance and condition based control can be considered. However, this should be done in such a way that the turbine can remain in operation when the sensors fail.

3.1. Wind power:

Its existence in nature caused by uneven heating on the surface of the earth as well as the earth's rotation means that the wind resources will always be available. The conventional ways of generating electricity using non renewable resources such as coal, natural gas, oil and so on, have great impacts on the environment as it contributes vast quantities of carbon dioxide to the earth's atmosphere which in turn will cause the temperature of the earth's surface to increase, known as the green house effect. Hence, with the advances in science and technology, ways of generating electricity using renewable energy resources such as the wind are developed the demand of electricity produced by using non renewable energy is also increased accordingly.

3.2. Features of wind power:

Most wind power sites are in remote rural, island or marine areas. Energy requirements in such places are distinctive and do not require the high electrical power Rural grid systems are likely to be weak (low voltage 33 KV). There are always periods without wind. If supplies are to be maintained thus, WECS must be linked energy storage or parallel generating there are always periods without wind

3.3. Power from wind:

Kinetic energy from the wind is used to turn the generator inside the wind turbine to produce electricity. There are several factors that contribute to the efficiency of the wind turbine in extracting the power from the wind. The power produced from the wind turbine is a function of the cubed of the wind speed, the wind speed is one of the important factors in determining how much power can be extracted from the wind Thus, the power produced will be increased by eight times the original power if the wind speed if doubled. Then, location of the wind farm plays an important role in order for the wind turbine to extract the most available power form the wind. The next important factor of the wind turbine is the rotor blade. The rotor blades length of the wind turbine is one of the important aspects of the wind turbine since the power produced from the wind is also proportional to the swept area of the rotor blades i.e. the square of the diameter of the swept area.

But with the recent advances in fiberglass and carbon-fiber technology, the production of lightweight and strong rotor blades between 20 to 30 meters long is possible. Wind turbines with the size of these rotor blades are capable to produce up to 1 megawatt of power. The relationship between the powers produced by the wind source and the velocity of the wind and the rotor blades swept diameter is shown below.

$$P_{wind} = \frac{\pi}{8} dD^2 v_{wind}^3$$

Wind power has the following advantages over the traditional power plants.

- Improving price competitiveness
- Modular installation
- Rapid construction
- Complementary generation
- Improved system reliability
- Non-polluting.

3.4. Wind turbine:

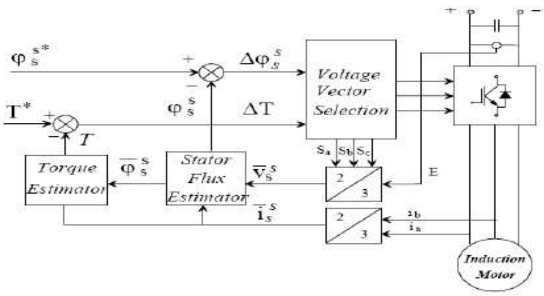
There are two types of wind turbine in relation to their rotor settings they are

- Horizontal-axis rotors
- Vertical-axis rotors.

The horizontal-axis wind turbine is designed so that the blades rotate in front of the tower with respect to the wind direction i.e. the axis of rotation are parallel to the wind direction. These are generally referred to as upwind rotors. Another type of horizontal axis wind turbine is called downwind rotors which has blades rotating in back of the tower. The main components of a wind turbine for electricity generation are the rotor, the transmission system, and the generator, and the yaw and control system. The following figures show the general layout of a typical horizontal-axis wind turbine, different parts of the grid-connected wind turbine, and cross-section view of a nacelle of a wind turbine (a) Main Components of Horizontal-axis Wind Turbine (b) Cross-section of a Typical Grid-connected Wind Turbine (c) Cross-section of a Nacelle in A Grid-connected turbine.

3.5. Direct torque control:

The Direct Torque Control method is basically a performance enhanced scalar control method. The advantages of DTC are minimal torque response time, absence of coordinate transformations which are required in vector controlled drive implementation and absence of separate voltage modulation block vector controlled drives. The disadvantages of Direct Torque Control are inherent torque and stator flux ripple and requirement for flux and torque estimators' simplifying the consequent parameters identification. The complete block diagram of DTC is shown in Figure.



There are two hysteresis control loops, one for the Torque control and the other for the Flux control.

3.6. Optimal switching logic:

In reality, there are only six active voltage vectors and two zero voltage vectors that a voltage-source inverter can produce [6, 8, 10].These are shown in Figure3.

By using switching functions S_a, S_b and S_c of which value is either 1 or 0, the primary voltage vector v is represented as

$$v = \sqrt{\frac{2}{3}} V_{dc}[S_a + S_b e^{j\frac{2\pi}{3}} + S_c e^{j\frac{4\pi}{3}}]$$

Where V_{dc} is dc link voltage.

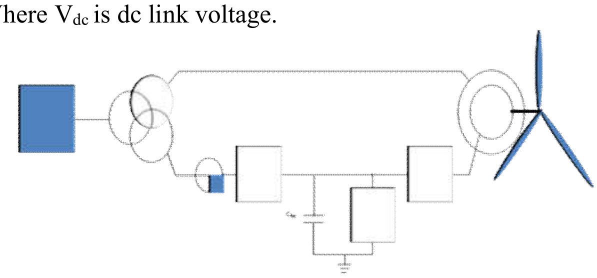


Fig: Optimal switching logic

IV. SIMULATIONS

The simulations are performed inMATLAB/Simulink.

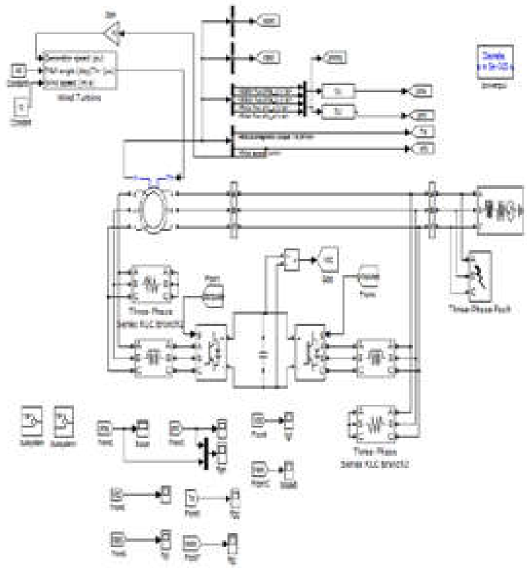


Figure: The SIMULINK diagram of direct torque control of DFIG without rotor flux reference.

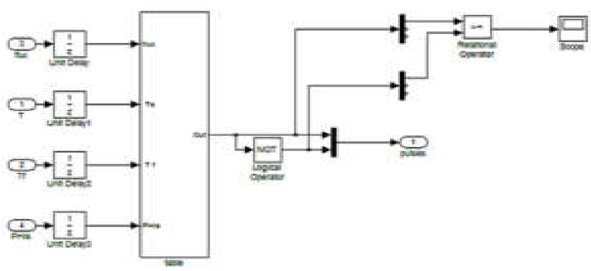


Figure: DTC without reference

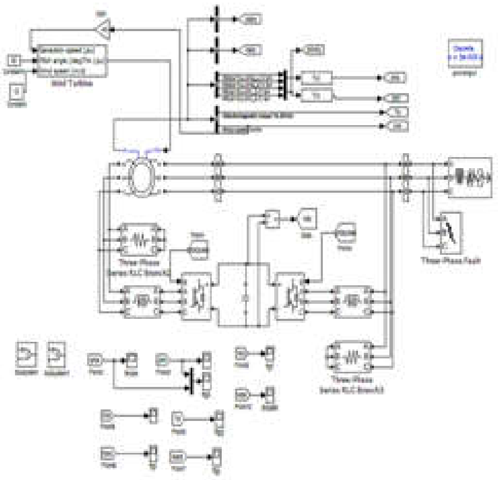


Figure: The SIMULINK diagram of direct torque control of DFIG with rotor flux reference.

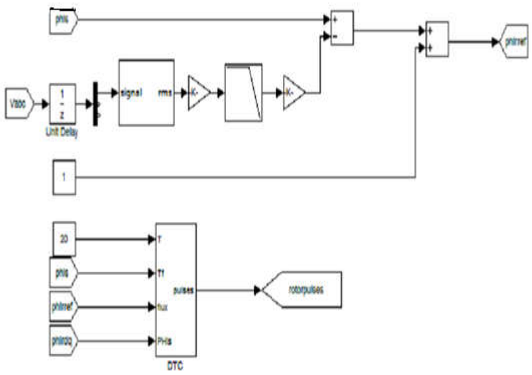


Figure: DTC block with rotor flux reference

V. REASULTS

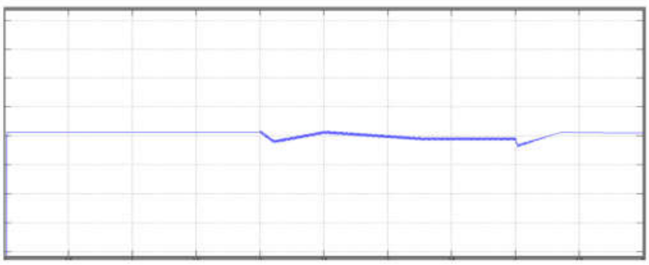


Fig: Speed of DFIG

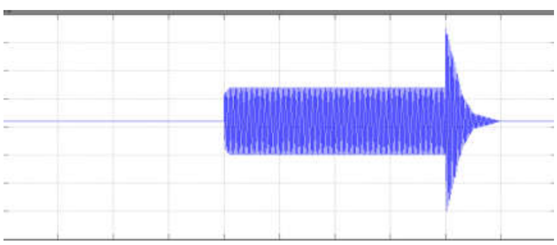


Fig: Torque for DFIG

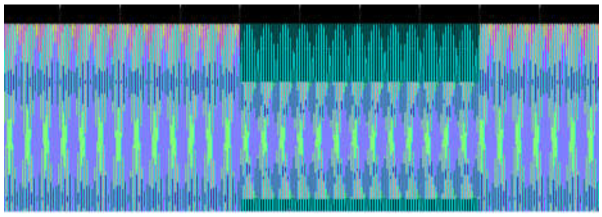


Fig: Grid voltage

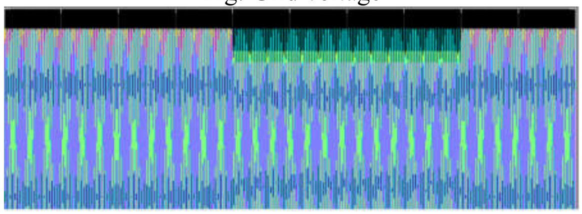


Fig: input converter voltage

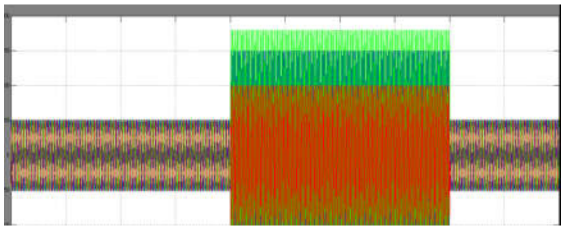


Fig: Inverter vabc voltage

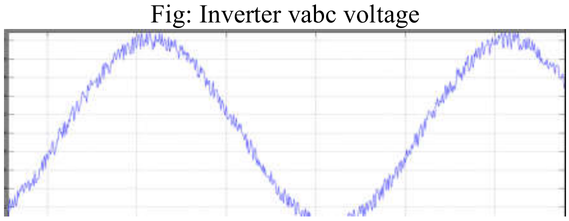


Fig: Line voltage of inverter output

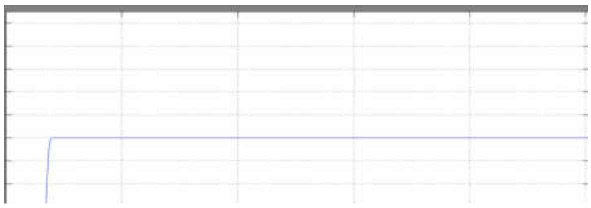


Fig: V_{dc} at converter output voltage

VI. CONCLUSION

The DTC of doubly fed induction machine is used to generate the required rotor pulses using the rotor flux generation strategy. The proposed syatem is used during the low depth voltage dips for higher voltage dips it is necessary to use crowbar protection. In steady state there is a ripple in the torque. This ripple depends on the switching frequency of the inverter which is determined by the torque and flux band. At the time of starting DTC draws high current control strategy is used during the low depth voltage dips for higher voltage dips it is necessary to use crowbar protection. In steady state there is a ripple in the torque. This ripple depends on the switching frequency of the inverter which is determined by the torque and flux band. At the time of starting Direct Torque Control draws high current. The switching frequency of the inverter varies over a wide range because of using hysteresis controllers. The stator flux magnitude can be maintained constant and several bright spots points where stator flux halts. In the transient state, and steady state the highest torque response can be obtained by selecting the fastest accelerating voltage vector to produce the maximum slip frequency. And the torque can be maintained constant, harmonic losses and acoustic noise of the machine may be decreased. Flux ripples are relatively small and minor loops are not observed in the locus Thus DTC offers excellent dynamic performance and gives good torque response than the field oriented control. It may be concluded that the DTC will be preferred control algorithm for A.C. drives in future because of its simplicity in control logic.

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