Coordinated Control of DFIG under Grid Fault Condition in Wind Energy Conversion System

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Abstarct: - This paper proposes a coordinated control of rotor side converters (RSCs) and grid side converters (GSCs) of variable speed doubly-fed induction generator (DFIG) based wind generation systems under unbalanced voltage conditions. The control scheme uses stator flux-oriented control for the rotor side converter and grid voltage vector control for the grid side converter. System behaviours and operations of the RSC and GSC under unbalanced voltage are illustrated. The co-coordinated control schemes manage to restore the wind turbines normal operation after the clearance of fault. A complete simulation model is developed for the control of the active and reactive powers of the doubly fed generator under variable speed operation. Several studies are performed to test its operation under different wind conditions. The paper characterizes the control of a double-fed induction generator (DFIG) for variable speed wind power generation under grid fault condition. Detailed Models are used in Electromagnetic Transients Programs and capture both fast dynamics due to the electromagnetic transients and slow dynamics due to electromechanical transients. Simulation has been carried out for a detail model from Matlab & Simulink.

Key words: Doubly Fed Induction Generator (DFIG), Rotor Side converter (RSC), Grid Side converter (GSC), Vector oriented control (VOC), Stator Flux Orientation (SFO)

I.   INTRODUCTION

The global electrical energy consumption is rising and there is steady increase of the demand on power generation. So in addition to conventional power
generation units a large no. of renewable energy units is being integrated into the power system. It has been reported [1] that renewable energy will provide as much as 10% of the world's energy supply by 2020, and will increase to as much as 50% by 2050.
Among the other renewable energy sources, wind energy has proven to be one of the most promising technologies because they are cost competitive, environmental clean and safe renewable power sources, as compared to fossil fuel and nuclear power generation.

Nowadays, the most widely and extensively used wind turbine in high power wind Energy Conversion System (WECS) is based on doubly fed induction generator (DFIG) due to its noticeable advantages:

1)   Various speed generation
2)   Double output Generator feeds active and reactive power to the Grid via both stator   as well as rotor.
3)   Generates power more than rated without overheating.
4)   Decoupled control of active and reactive power
5)   Improve power quality.
6)   Mechanical stress reduction of turbine and acoustic noise reduction.

DFIG's ability to control rotor currents allows for reactive power control and variable speed operation, so it can operate at maximum efficiency over a wide range of wind speeds.
 However, wind turbines based on the DFIG are very sensitive to grid disturbance, especially to voltage dips, large negative and zero sequence components will appear in the stator flux causing excessive over current or voltage in rotor windings, which will damage the electronic devices in the converter. Electromagnetic torque and the active and reactive power start to oscillate with big amplitudes, which are harmful to the mechanical system of the wind turbine and the stability of the connected power network.
So it is very important to analyze the transient behavior of DFIG and to apply certain control strategy which will allow DFIG to stay connected to the grid under faulty conditions.

II.   DOUBLY FED INDUCTION GENERATOR (DFIG)

Doubly Fed Induction Generator (DFIG) is based on an induction generator whose rotor windings are connected back to the grid via an ac-ac voltage controller i.e. back to back Voltage Source Converters. The stator is directly connected to the AC mains, whilst the wound rotor is fed from the Power Electronics Converter via slip rings to allow DFIG to operate at a variety of speeds in response to changing wind speed. In a DFIG, both the stator and the rotor are able to supply active power, but the direction of this power flow through the rotor circuit is dependent on the wind speed and accordingly the generator speed. Below the synchronous speed, active power flows from the grid to the rotor side and rotor side converter (RSC) acts as the voltage source inverter while the grid side converter (GSC) acts as rectifier but above the synchronous speed, RSC acts as the rectifier, and GSC acts as the inverter. So the machine can be controlled as a generator or a motor in both super and sub-synchronous operating modes realizing four operating modes.

The slip power can flow in both the directions from rotor to grid or grid to rotor depending upon the mode of operation.
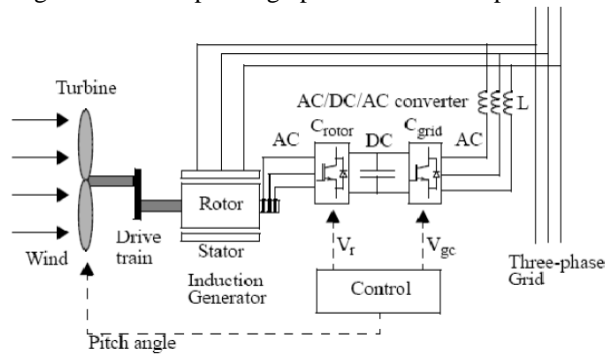

Fig 1: A typical wind energy system with Doubly Fed Induction Generator

In modern DFIG designs, the frequency converter is built by self-commutated PWM converters, a machine-side converter, with an intermediate DC voltage link.

• AC/DC/AC converter consists of an AC/DC converter connected to rotor winding called as rotor side converter (RSC) and another DC/AC converter connected to grid called as grid side converter(GSVC).

• RSC ensures the decoupled control of active and reactive power. GSC keeps the D.C. link voltage constant regardless of the direction and magnitude of rotor power.

The DC capacitor linking stator- and rotor-side converters allows the storage of power from induction generator for further generation. To achieve full control of grid current, the DC-link voltage must be boosted to a level higher than the amplitude of grid line-to-line voltage.

III.   UNBALANCE GRID VOLTAGE:

Reason:

It may be voltage dip i.e. a sudden reduction (between 10% and 90%) of the voltage at a point in the electrical system, and sudden change of load (dynamic load) .There can be many causes for a voltage dip:
1) Short circuits somewhere in the grid
2) Switching operations associated with a temporary disconnection of a supply
3) The flow of the heavy currents that are caused by the start of large motor loads, or large currents drawn by arc furnaces or by transformer saturation.

Consequence:

Unbalanced grid voltage cause many problems for Induction Generator
1) Torque pulsations.
2) Reactive power pulsations.
3) Unbalanced currents.

A voltage dip can cause high induced voltages or currents in the rotor circuit. The high currents might destroy the converter, if nothing is done to protect it. Voltage dips due to short-circuit faults cause the majority of equipment trip and therefore of most interest..

IV.   DOUBLE FED INDUCTION GENERATOR UNDER GRID FAULT CONDITION:

Consider DFIG in which, immediately after a 3-phase fault occurs, the stator voltage and flux reduces toward zero. The voltage drop depends, of course, on the location of the fault. The rotor current then increases to attempt to maintain the flux linkage within the rotor windings constant.

DFIG under fault can be shown in fig. 3. However, for a DFIG the increase in the rotor current immediately after a fault will be determined by two factors. The first is the change in the stator flux and the second is the change in the rotor injected voltage.
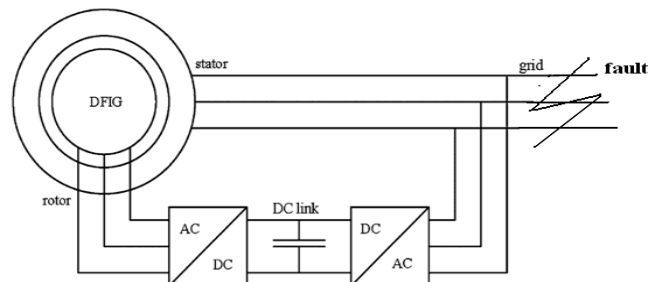

Fig 3: Block Diagram of DFIG with fault in Grid condition

A.   Operation of DFIG Under Unbalanced Condition:

Behavior immediately after the fault: In the fault instant, the voltage at the DFIG generator terminal drops and it leads to a corresponding decrease of the stator and rotor flux in the generator. This results in a reduction of the electromagnetic torque and active power. As the stator flux decreases, the magnetization that has been stored in the magnetic field has to be released. The generator starts thus its demagnetization over the stator by the reactive power peak in the moment of fault. In the fault moment, as the stator voltage decreases significantly, high current transients appear in the stator and rotor windings. In order to compensate for the increasing rotor current, the rotor side converter increases the rotor voltage reference, which implies a "rush" of power from the rotor terminals through the converter. On the other side, as the grid voltage has dropped immediately after the fault, the grid side converter is not able to

transfer the whole power from the rotor through the converter further.

 B.   Behavior at fault clearance:
During the fault, the stator voltage and rotor flux have been reduced, the injected rotor voltage has been changed and the rotor speed has been increased. Immediately after the fault is cleared the stator voltage is restored, and the demagnetized stator and rotor oppose this change in flux thus leading to an increase in the rotor and stator currents.

V.   CONTROL OF DFIG UNDER FAULT CONDITION:

The DFIG allows the stator to be connected directly to a constant frequency, three-phase grid even though the wind turbine, to which it is coupled, has a variable speed. Variable speed operation is indispensable for optimal wind power acquisition because the DFIG speed must track the changing optimal speed which is a function of the wind velocity as the wind fluctuates in time. Hence the control of DFIG plays a major role in achieving the variable speed operation. The DFIG is economical because when controlled by a Voltage-Source Converter connected to the rotor slip-ring terminals, its MVA rating is reduced by a factor ofS_{msx}, the maximum slip being $S_{msx}= 0.3$.
The vector control scheme is applied to GSC and Instantaneous Reactive Power Theory is applied to the RSC taking into account the two converters within a DFIG system. The control scheme uses stator flux-oriented control for the rotor side converter and grid voltage vector control for the grid side converter. The power converters are usually controlled utilizing vector control technique, which allows decoupled control of both active and reactive power. The co-coordinated control schemes manage to restore the wind turbines normal operation after the clearance of fault. To provide enhanced operation, the RSC is controlled to eliminate the torque oscillations at double supply frequency under unbalanced stator supply. The oscillation of the stator output active power is then cancelled by the active power output from the GSC, to ensure constant active power output from the overall DFIG generation system.
There are different types of control method for DFIG, which are as follows:

A. Scalar control
Scalar control is due to magnitude variation of the control variables only, and disregarding the coupling effect in the machine. For example, the voltage of the machine can be controlled to control the flux, and the frequency and slip can be controlled to control the torque. Scalar controlled drives are easily implementable and hence widely used in industry. However their importance has diminished recently because of the superior performance of vector controlled drives, which is demanded in many applications.

B. Vector control or field oriented control:

For Scalar control the inherent coupling effect i.e. both torque and flux are functions of voltage or current and frequency gives the sluggish response and the system is easily prone to instability because of high order system harmonics. If the torque is increased by incrementing the slip, the flux tends to decrease. The flux variation is then compensated by the sluggish flux control loop, feeding additional voltage. This temporary dipping of flux reduces the torque sensitivity with slip and lengthens the system response time.

These foregoing problems can be solved by vector control or field oriented control where an induction generator can be controlled like a separately excited DC motor, brought a renaissance in the high performance control of AC drives. Because of DC machine like performance, vector control is known as decoupling, orthogonal, or Trans vector control. Vector control is applicable to both induction and synchronous motor drives. Vector control and the corresponding feedback signal processing, particularly for modern sensor less vector control, are complex and the use of powerful microcomputer or DSP is mandatory. Because of the above mentioned advantages over scalar control, vector control will be accepted as the industry standard control for AC drives.

 C.   Decoupled Control of Active and reactive power
     It can be achieved by d-q model. After converting a-b-c axes of 3 phase voltage to d-q axis and then converting it to compensating terms and addition of the compensating terms to the uncompensated voltage terms makes it possible to achieve decoupled performance of the rotor side converter.

A current regulated PWM scheme is used where q and d axes currents are used to regulate DC-link voltage and related power respectively.
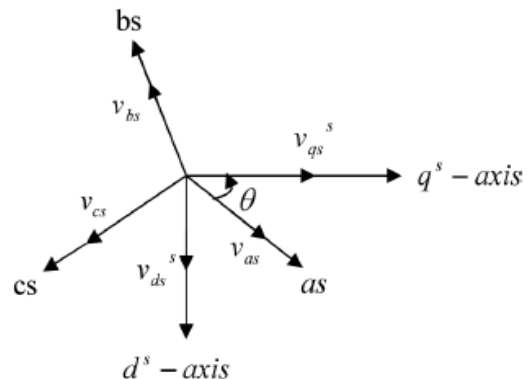

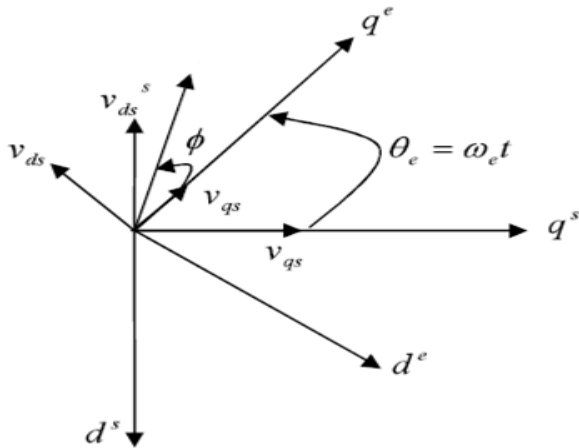Fig 4: Stationary frame a-b-c to d^s-q^s axes transformation

Fig 5: Stationary frame d^s-q^s to synchronous rotating frame d^e-q^e

Fig 6: DFIG rotor side controller

Rotor Side Converter

Rotor side converter, ensures decoupled control of active and reactive power. The reference frame used here is also the synchronously rotating frame i.e. SFO or SVO control scheme is used. The rotor side converter provides the actuation and the control requires rotor and stator currents, stator voltage and rotor position. Analysis of d-q currents and voltages outlines the control scheme for the converter.

Starter-side converter

Keep the DC Link voltage constant regardless of the direction and magnitude of rotor power. The 3-phase AC variables are referred to synchronously rotating frame using Park's Transformation which converts them into two DC variables at quadrature with each other, namely the direct component and quadrature component. The converter is current regulated, with direct component used to regulate DC Link voltage and quadrature component to regulate reactive power.

Generator control of DFIG wind turbine

Basically the speed control of a DFIG is achieved by controlling the power. The rotor-side convertor is responsible for power control which is a two-stage controller comprising of a real and reactive power controller [8-11]. Stator-flux oriented frame has been the most commonly utilized frame for the design and analysis of DFIG [8-9, 10-13]. In this frame the q-axis and d-axis components of the rotor currents are used for active and reactive power control respectively (Fig.6) [8,11]. In order to operate converters at same constant frequency, the current control strategy is implemented through a voltage regulated PWM converter. The d-q control signals are generated by comparing the d-q current set values with the actual d and q components of the rotor current. The two-stage rotor side converter controller structure is shown in the fig. below:
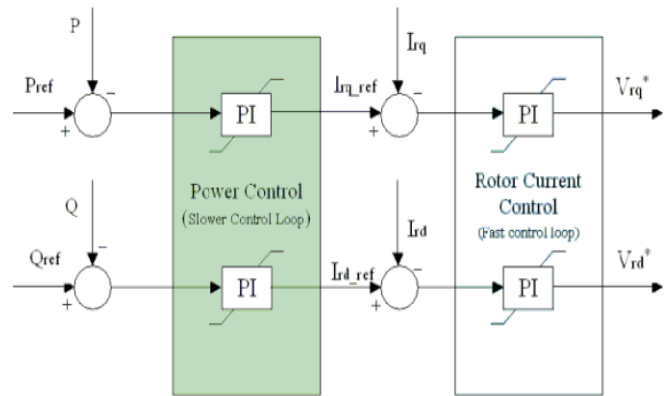
The transformation of d-q signals to three-phase sinusoidal signals for the rotor side converter can be achieved by the technique as shown in Fig. 7. The two signals v_{rd}^* and v_{rq}^* represent the d and q reference voltage control signals respectively, generated by the controller. The α and β stationary reference frame voltages, v_α^* and v_β^* are obtained through a suitable vector transformation of $e^{j(\theta s - \theta r)}$, where θ_s is the position of the stator-voltage space vector and θ_r is the position of the rotor. Then by applying by Park's vector transformation, the stationary reference frame voltages, v_α^* and v_β^* are used to generate a three-phase pulse width modulated sinusoidal reference voltage, v_a^*, v_b^* and v_c^* to control the rotor-side converter. The three-phase sinusoidal voltage v_a, v_b, v_c injected into the grid by the converter is directly proportional to the three-phase reference voltage signals, v_a^*, v_b^* and v_c^* in the converter linear modulation mode. The gain factor between the two quantities is given by $k_{pwm} = {v_{dc}}/{v_{tri}}$ where v_{dc} is the capacitor DC-link voltage and v_{tri} is the amplitude of the bipolar triangular reference carrier signal waveform.
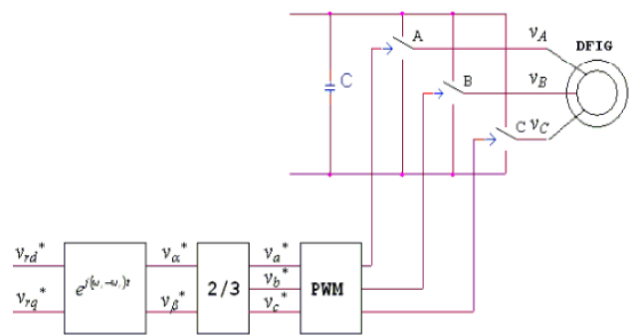

Fig.7: Decoupled d-q vector control structure for DFIG rotor-side converter

Simulation:

A detail model of 9 MW wind farm connected to three bus-B120, B25 and B575 has been simulated to analyze the results. Detailed Models are used in Electromagnetic Transients Programs and capture both fast dynamics due to the electromagnetic transients and slow dynamics due to electromechanical transients. This model includes detailed representation of power electronic IGBT converters. This model is well suited for observing harmonics and control system dynamic performance over relatively short periods of times (typically hundreds of milliseconds to one second).
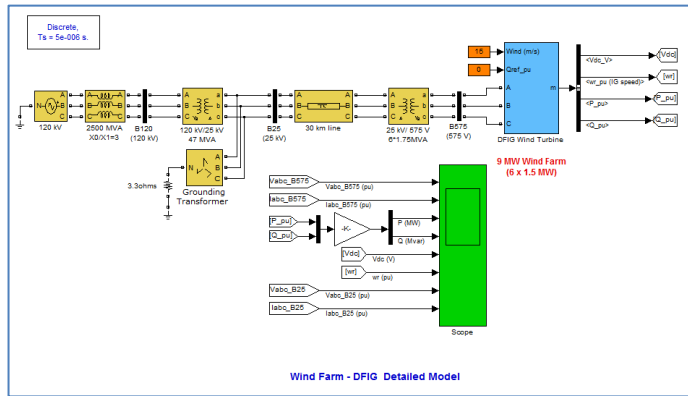

Fig 8: The Detailed Model of DFIG in WECS

Initially the DFIG wind farm produces 9 MW. The corresponding turbine speed is 1.2 pu of generator synchronous speed. The DC voltage is regulated at 1150 V and reactive power is kept at 0 Mvar. At t=0.03 s the positive-sequence voltage suddenly drops to 0.5 p.u. causing an oscillation on the DC bus voltage and on the DFIG output power. During the voltage sag the control system tries to regulate DC voltage and reactive power at their set points (1150 V, 0 Mvar). The system recovers in approximately 6 cycles at t=0.13 s
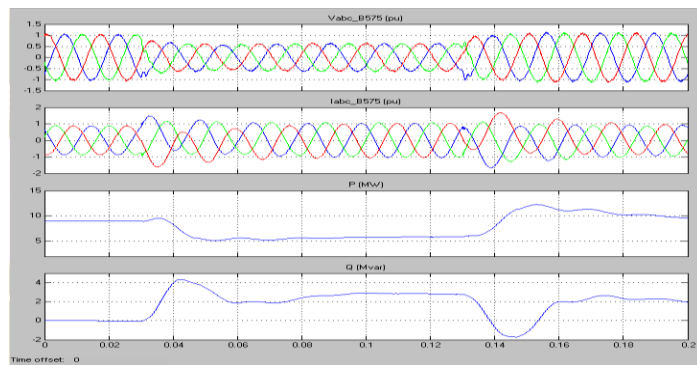

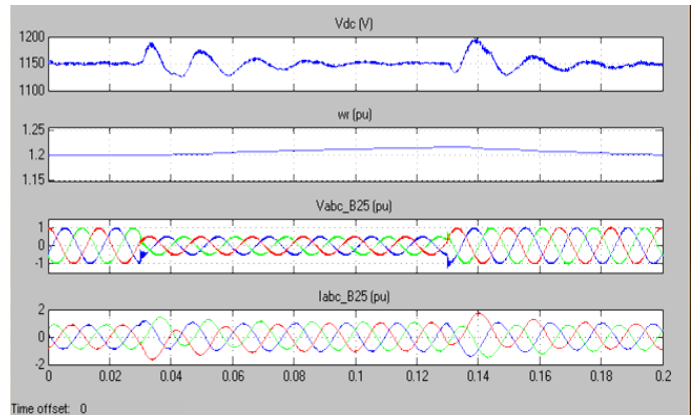Fig. 9: Simulation result at bus B575 due to the fault (voltage sag) in the 120kv motor-load

Fig:10 Simulation result at bus B25due to the fault(voltage sag)in the 120kv motor-load.

VI. CONCLUSION

The DFIG considered in this analysis is a wound rotor induction generator with slip rings. The stator is directly connected to the grid and the rotor is interface via a back to back partial scale power converter (VSC). Power converter are usually controlled utilizing vector control techniques which allow the decoupled control of both active and reactive power flow to the grid. In the present investigation, the transient response of DFIG is presented for both normal and abnormal grid conditions. The control performance of DFIG is satisfactory in normal grid conditions and it is found that, both active and reactive power maintains a study pattern in spite of fluctuating wind speed and net electrical power supplied to grid is maintained constant. During grid disturbance, considerable torque pulsation of DFIG system has been observed.

In view of that, future scope aims to develop a controller, which can effectively improve the dynamic stability, transient response of the system during faulty grid conditions.

To develop a protection system for power converter and DFIG for large disturbances like 3-phase fault of little cycle duration as the power converter is very sensitive to grid disturbance.

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