DFIG MODELLING AND THE RELEVANCE OF MODEL SIMPLIFICATION

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SUMMARY

There has been a fast growing demand for the application of doubly fed induction generators (DFIG) in wind power plants in recent years. They have in particular dominated the market in the last two years. DFIG is an ideal candidate to satisfy the requirements of the recently proposed challenging grid codes. However, many uncertainties still exist or at least there are no published reports regarding validated comprehensive DFIG models. This paper attempts to clarify the existing ambiguities in modelling of DFIG under various operating conditions. The paper deals with detailed modelling of DFIG in stator-flux oriented reference frame using vector control algorithm. The model includes the current controllers for the rotor-side and grid-side converter. It investigates the influence of various subsystems (including model simplifications) on DFIG simulation results using the power system analysis package DIgSILENT PowerFactory. It also suggests appropriate control strategies for a selected set of network operating conditions and topologies.

DFIG SYSTEM MODELLING

The network shown in Fig. 1 is built in DIgSILENT in order to analyse various aspects of DFIG modelling and operation. It consists of a single 1.5MW DFIG generator connected to the external 20 kV grid through a transmission line.

The DFIG generator model is a full built-in model [1, 2] which integrates the induction machine and rotor-side converter (RSC). A generic control scheme is employed as shown in Fig. 2. DFIG and RSC are modelled in rotor reference frame (RRF) rotating at generator speed. However the RSC controller operates in a stator flux oriented reference frame (SFRF) rotating at grid synchronous speed so d-q axis rotor voltages (or PWM indices) and currents are transformed accordingly.

RSC control modifies the stator active (P) and reactive (Q) power by regulating the q- and d-axis rotor currents, respectively. The active power reference is obtained from a look-up table (provided by the wind plant operator) representing the maximum power tracking algorithm. The reactive power reference can be obtained from a voltage or power factor controller. In this study however, unity power factor operation is considered. Non-windup PI controllers are used to define the current and voltage set-points and rotor voltages are applied by defining the PWM indices. Grid-side converter (GSC) controller operates in grid ac voltage reference frame (GCVRF) and regulates the dc-link voltage regardless of the direction of the rotor power flow. GSC has to be synchronised with the ac voltage and a phased-locked loop (PLL) is used to determine the ac voltage angle. Current and voltage limits of the converters are considered in all controllers [3].

MODEL SIMPLIFICATIONS

The DFIG system can be simplified in order to save computational time or to eliminate hard-to-obtain data. The influences of these simplifications have been tackled in some published reports in the past [2, 4] however, some of the uncertainties still exist and those will be discussed in this paper.
Representation of aerodynamic rotor

For the state-of-the-art modelling of the rotor, blade element theory should be used. However, this requires very detailed information and computations become complicated and lengthy [3]. To overcome this, an algebraic relationship between a wind speed and extracted mechanical power is assumed and described by the aerodynamic efficiency, \( C_p \). In transient stability simulations it is usually the wind speed that is assumed to be constant and not the mechanical power nor the mechanical torque. Mechanical power and torque depend not only on wind speed but on the generator speed as well. In other words, they depend on the tip-speed ratio, \( \lambda \), as long as pitch angle is constant. During large disturbances when the generator speed deviates from the pre-fault value, \( C_p \) changes. \( C_p \) characteristic is not properly represented with constant power (or torque) assumption. Results of simulations with a constant wind speed and a constant wind power are compared in Fig.3 following a 3-phase short-circuit applied on transmission line close to a 5MW DFIG. It can be seen from these results that the \( C_p \) characteristic should be included in the model if disturbances resulting in high generator speed deviation (>10%) are to be simulated and if the wind speed is assumed to be constant. If the wind power or mechanical torque are constant then \( C_p \) characteristic can be neglected.

Fig.3 Effect of including \( C_p \) characteristic. Solid – \( C_p \) neglected, Dashed – \( C_p \) included. (a) Wind power (MW), (b) Mechanical torque (Nm), (c) Stator \( P \) (MW), (d) Speed (p.u)

Fig.4 shows the comparison of DFIG responses for different shaft stiffness values. At \( t=3s \) a 300 ms, 3-phase short-circuit is applied and at 3.5s crowbar is removed and RSC is re-started. The original shaft stiffness (\( K_{turb} \)) of the turbine is 2.1p.u/el.rad. However if the shaft is softer (e.g. 0.3p.u/el.rad. [4]), the oscillations have lower frequency and the acceleration is higher as seen in the figure.

Because Q control is decoupled from P control it is not affected significantly by shaft dynamics. Speed oscillations however lead to P oscillations and depending on R/X ratio of the network, voltage may fluctuate as well. These oscillations may further excite the synchronous generator oscillations [4]. Multi-mass model requires more data and is more complex than the lumped mass model. However, the results of simulations show that when the shaft system is relatively stiff (shaft stiffness, \( K_s \geq 3.0 \) p.u), lumped mass model can be applied without loss of accuracy.

Machine model order

DIgSILENT allows simulation of both 3\textsuperscript{rd} and 5\textsuperscript{th} order induction machine models. Fig.5 compares the difference in DFIG response when different machine models are used. A 350ms 3-phase short-circuit is applied at 0s and crowbar is removed at 0.5s. Stator flux transients (50Hz oscillations) in current, \( P \) and \( Q \) traces are clearly visible if 5\textsuperscript{th} order model is used. The observed difference in speed responses can be explained by examining the rotor current response. In case of 5\textsuperscript{th} order model rotor current decay is longer and the ‘first torque swing’ is positive resulting in a drop in speed at the instant of fault. Higher rotor currents are observed with the 5\textsuperscript{th} order model. These currents may activate the crowbar protection. By using the 3\textsuperscript{rd} order model of DFIG one may fail to appropriately account for the operation of crowbar protection. During the simulations however, it was observed that the critical voltage value for crowbar insertion was 0.5 p.u if the 3\textsuperscript{rd} order model is used and 0.52 p.u if the 5\textsuperscript{th} order model is use. The simulations with the full model may provide better resolution but the computation time is

\[ J_{lumped} = \frac{J_{turb}}{n^2} + J_{gen} \]  

\( n \) is the gear-box ratio.
significantly longer. For transient analysis of power systems with DFIG a 3rd order model can be safely used in spite of these small differences in results obtained with different models.

![Graphs showing transient analysis results](image)

**Converter representation**

There is a close relationship between the machine model used and the converter detail to be included. For example it will not be necessary to include semiconductor switching devices if the 1st or 3rd order model of a DFIG is used. Similarly if a 5th order machine model is used the dc-link capacitor should be modelled together with fast current controllers. Switching devices can be represented either as ideal or non-ideal (switching losses, finite modulation frequency, etc. included).

The non-ideal representation will result in high frequency ripple in the dc-link which does not influence transient stability calculations. However, modulation and current limits should be taken into account in order to represent the capability of power electronics correctly.

**Detailed modelling of the converter, current controllers and machine requires small integration steps. Large time (integration) steps can be used without any loss of accuracy when operating in steady-state and the time step only needs to be reduced during large transient disturbances when rotor currents deviate significantly from the reference values. Employing variable time step therefore, will represent the system behaviour correctly without slowing down the simulation.**

**TRANSIENT SIMULATION RESULTS**

Several case studies have been carried out to demonstrate the adequacy of the developed models of DFIG system.

**Operation throughout the wind speed range**

In order to illustrate the converter and controller performance,
an artificial wind series is generated (using BLAED software) which covers the whole operating region of DFIG as shown in Fig.7. Tower shadow and turbulence are also taken into account. DFIG is operated at unity power factor.

![Figure 7 Performance of DFIG for a wind series covering the operating region. (a) Wind speed (m/s), (b) Stator P (p.u), (c) Speed (p.u), Pitch angle (deg)]](image)

The turbine acts as an energy buffer and wind speed variations are not observed in speed response resulting in a smooth power profile. The controllers act accordingly with the changing speed such that maximum power is extracted from the wind. When the wind speed exceeds the rated value, pitch controller increases the pitch angle and reduces C_p such that wind power is limited to rated value (i.e. 1 p.u). However pitch control is not very fast (±7°/sec in this case) and cannot manage sudden increases or decreases in wind speed as seen at t=55s.

**Influence of crowbar protection**

When the stator voltage reduces suddenly to low values, high rotor currents are induced. Even though they last for a quite short period of time, they may damage or even destroy the RSC. In order to prevent this, crowbar protection is activated where RSC is blocked and bypassed and rotor is short-circuited through some resistance. Under such conditions the turbine is no longer DFIG but an ordinary induction generator which has no control over P or Q. Therefore, crowbar protection is of vital importance to DFIG systems.

**Effect of crowbar impedance.** Fig.8 shows DFIG response to a 350ms 3-phase short-circuit for different crowbar resistance values. Three cases are simulated; no resistance, 2×Rotor resistance (2R_r) and 20×R_r. RSC is re-started 500ms after the disturbance. Without any crowbar impedance the rotor current shows oscillatory response during the fault and even if the RSC is re-started the system voltage collapses. However, when a resistance 2R_r is inserted, oscillations are sufficiently damped and the machine remains stable. The machine behaves like an over-speeding induction machine and consumes large amount of reactive power while the crowbar protection is active.

On the other hand when the RSC is re-started 200ms after the fault clearance, another transient occurs and RSC is blocked again if crowbar impedance is not big enough. For example with an extra impedance of 2R_r, RSC can not re-start due to the high rotor transients occurring at each re-start attempt. It tries to re-synchronise every 500ms (e.g. at 1s and 1.5s), but hardly achieves this at the third attempt at ~1.5s. During this period very high currents flow in the rotor and stator circuits which might degrade the life-time of the insulation. Moreover, voltage tends to stay low due to high Q consumption by DFIG which may further cause voltage instability in networks with high motor load.

![Figure 8 Response of DFIG to a short-circuit for different crowbar impedances (Solid — no crowbar impedance, Dashed — 2R_r, Dotted — 20R_r)](image)

If the crowbar impedance is sufficiently big (20R_r in this example) current oscillations are damped and kept low during the disturbance and the DFIG recovers and RSC re-starts successfully. For the network considered in this study it is found that the crowbar resistances higher than 10R_r always result in satisfactory recovery. Further increase of crowbar resistance would result in very low rotor currents leading to unnecessary electrical torque reduction and over-speeding of the turbine during the disturbance.

**Effect of RSC re-start.** Up till now DFIG was disconnected from the network as soon as the crowbar protection was activated. However new grid codes require low-voltage ride-through. Therefore RSC is re-started safely once the sub-transient period is over. Fig.9 shows DFIG response to different RSC re-start times. Same disturbance as in the previous case is applied. Three cases are simulated; RSC is re-started, (i) when the initial transient after the disturbance is sufficiently decayed (e.g. 200ms later) (ii) ~50ms after the fault clearance when the voltage has recovered to a safe value (e.g. 0.8p.u) (iii) few hundred ms after the fault clearance transient has decayed and voltage has stabilised at a safe value.

It can be seen from Fig.9 that when the RSC is re-started after the initial transient, it improves voltage by ~5% since the control over P and Q is resumed. If re-start procedure is delayed after the fault clearance then DFIG operates as an induction machine during this period and degrades the performance. Therefore the RSC should be re-started as soon as the currents decay to a safe value.
Fig. 9 DFIG response to a short-circuit for different RSC re-start times

CONCLUSIONS

Based on the simulations performed, the paper clearly shows the distinction between constant wind speed and constant wind power (torque) operation of the DFIG. It demonstrates that shaft dynamics may substantially influence the transient recovery of the DFIG depending on the shaft stiffness. It is also shown that the reduction/simplification of the model of converter and induction machine does not notably influence DFIG transient response. Finally, the rotor side converter blocking (crowbar protection) and re-starting schemes should be chosen cautiously as the DFIG may operate as a motor or generator for a short period of time depending on the pre-disturbance speed. The voltage recovery is also affected immensely by the RSC blocking and re-starting schemes.

REFERENCES


