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PERFORMANCE OF A VARIABLE SPEED DOUBLE-FED INDUCTION GENERATOR WIND TURBINE DURING NETWORK VOLTAGE UNBALANCE CONDITIONS

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ABSTRACT

The issues of the negative performance of DFIG's due to supply network voltage unbalance are outlined in this paper. The paper shows the effects that voltage unbalance can have on a DFIG, using the power simulation program DigSilent. The results from simulations show that voltage unbalance affects the both the induction generator and the rotor converter, due to the high unbalanced currents generated. The ability to modify the control strategy of a DFIG to compensate for voltage unbalance is outlined and a proposal to build a test-rig suitable to implement such a system is suggested.

Keywords: Power Quality, Wind Power, Voltage Unbalance, DFIG

INTRODUCTION

Usually the most productive sites for the development of wind turbines and wind farms are in rural remote areas where distribution networks can be weak and voltage unbalance can be a common feature. This is certainly the case in Ireland where the majority of the wind energy developments have been on the north and west coast of the island [1]. This is also the region in which the transmission and distribution network is weakest.

Problems of power quality can arise with regard to the connection of embedded generation, including wind generation. On weak networks, the connection of wind generation can give rise to voltage fluctuations, including flicker and voltage control [2]. At the same time, power quality problems inherent to the network can cause difficulties with regard to the connection of wind generation. In the event of voltage depressions in the vicinity of system faults, wind generators can experience difficulties in remaining connected; the voltage ride-through problems [2]. Voltage unbalance can also give rise to excessive unbalanced stator currents in wind generators, causing generators to trip out. The authors have monitored the voltage unbalance at a small wind farm in County Cavan in the Republic of Ireland over an extended period and have gained an insight into the extent and variability of voltage unbalance experienced by wind generation.

This paper looks specifically at the behaviour of a double-fed induction generator (DFIG) in response to a voltage unbalance introduced into the network to which it is connected. The simulation study is conducted with the DigSilent software package and the behaviour of the induction generator and the grid/rotor converters in investigated.

SIMULATION STUDY

Induction generators subjected to network voltage unbalance can overheat due to the excessive currents, and mechanical stress can occur due to torque pulsations. The rotor converter in a DFIG is also susceptible to high currents during periods of voltage unbalance.

The DFIG wind turbine in this study is modelled in the dynamic power system simulation program DigSilent [3] to analyse the behaviour of both the induction generator and rotor converter to grid network voltage unbalance. The rotor converter in particular is analysed during network voltage unbalance conditions. The system under investigation is shown in Fig. 1. The model used is a built-in example in DigSilent . The network to which the DFIG is connected is represented by a constant voltage and a distribution line with a length of 10 km. The line series resistance is 0.015 Ω/km and the reactance is 0.3 Ω/km. The distribution line is operated at a voltage of 30kV. The fault level at Bus A in Figure 1 is 150 MVA. The DFIG is connected via a 30kV/690V three-winding transformer. The generator rotor is connected to the grid side via a rotor converter, a dc bus [1.15 kV] , a grid side converter and the tertiary windings of the three-winding transformer. The DFIG has a total rating of 5MVA, and the rotor converter has a rating of 2 MVA. With a 30% speed range, when maximum power is being supplied by the system the stator can supply 3.5 MVA and the rotor converter
1.5 MVA.

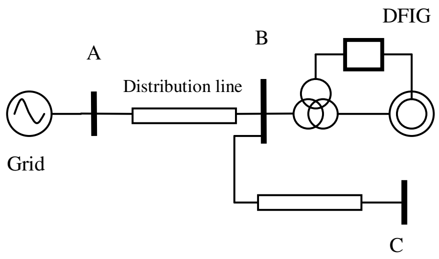

Figure 1 DFIG and Network Model [To be modified]

As shown in Fig. 1, a second line has been added to the original system and a load of 4 MVA is supplied. The line series resistance is 0.015 Ω/km and the reactance is 0.3 Ω/km and thus a fault level of 100 MVA is established at Bus C. The voltage unbalance is simulated by single phase fault at bus C with a fault resistance of 50 Ω. This fault introduces a voltage unbalance of 3.2 % at the transformer connections. The voltage unbalance is expressed as the ratio of the negative sequence voltage to the positive sequence voltage [4].

SIMULATION OF VOLTAGE UNBALANCE

Initially the effect of the voltage unbalance on the stator of the generator is considered. Under network voltage unbalance conditions a negative phase sequence component occurs. Fig. 2 shows the instantaneous stator current predicted by the DigSilent software when the voltage unbalance occurs at 2 seconds. Clearly, the stator current is significantly unbalanced after this time. The faulted phase current is shown in green.

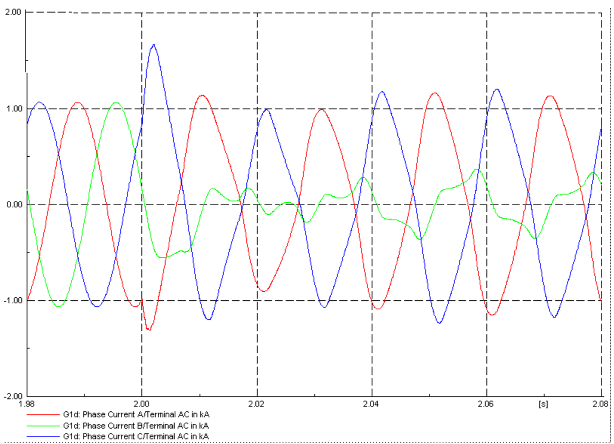

Figure 2 Stator Current

Although the voltage unbalance factor is low, (3.2% in this case) the accompanying negative sequence current factor is 18.3%, see figure 3. As described in [4], this is because the negative sequence impedance of an induction generator is considerably lower than the positive sequence impedance at normal operating slip speeds.

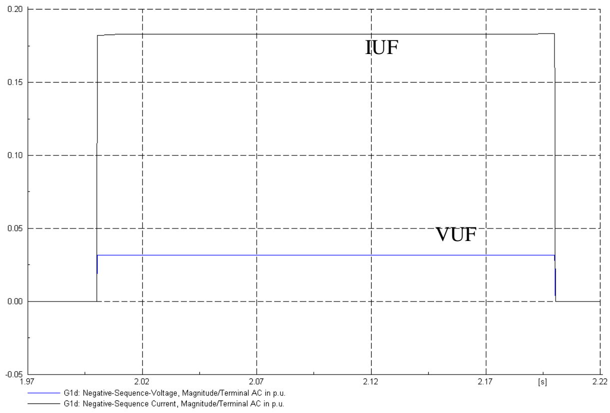

Figure 3 Stator Voltage and Current Unbalance

The effect of voltage unbalance on the converter can be clearly observed in figure 4. With the voltage unbalance factor at 3.2% the grid-side converter has a current unbalance of nearly 20 %.

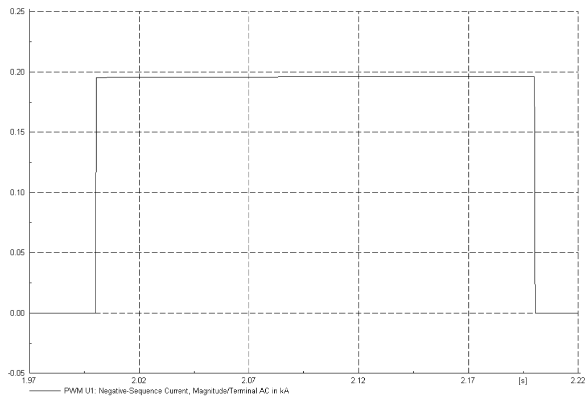

Figure 4 Grid-Side Converter Current Unbalance

Investigations into voltage unbalance and sag conditions in a variable speed drive incorporating a PWM converter was evaluated by [9]. Some of the conclusions reached are that current unbalance can up to 100% for an input voltage unbalance of only 5%.

ANALYSIS OF EFFECTS OF INDUCTION MACHINE PERFORMANCE

This section deals with the effect of network voltage unbalance on the induction generator itself. The persistence or lingering of an unbalanced voltage condition presents serious problems to induction generators. Under network voltage unbalance conditions a negative phase sequence occurs, which can result in power and torque oscillations. Figure 5 shows the results of the DigSilent simulation on the 5 MW DFIG with voltage unbalance occurring after 2 seconds. Power pulsations can clearly be observed in a DFIG due to network voltage unbalance of 3.2%.

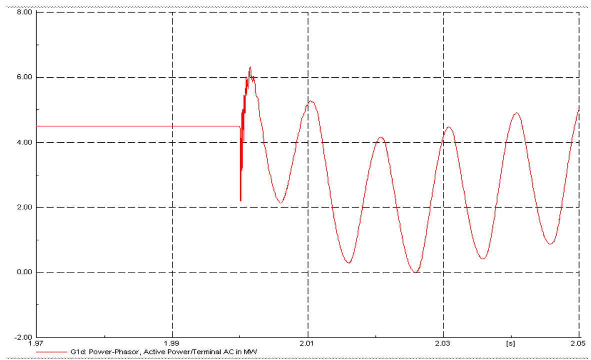

Figure 5 Power Pulsations on DFIG Due to Network Voltage Unbalance

When using symmetrical components, a separate equivalent circuit can be obtained for positive and negative sequence components, shown in figures 6 and 7 [4].

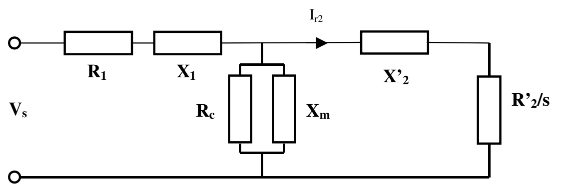

Figure 6 Positive Sequence Equivalent Circuit of Induction Machine

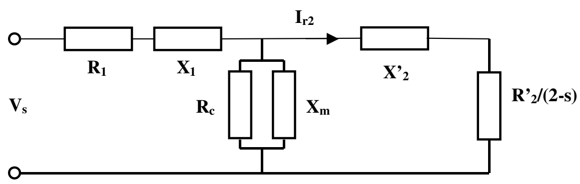

Figure 7 Negative Sequence Equivalent Circuit of Induction Machine

The developed power P_e of an induction machine consists of the positive (P_1) and the negative (P_2) sequence power components [10,11]:

$$P_e = P_1 + P_2 \tag{1}$$

Where

$$P_1 = 3\, I_{1r}^2 \frac{(1-s)}{s} R_r' \tag{2}$$

$$P_2 = 3\, I_{2r}^2 \frac{(s-1)}{(2-s)} R_r' \tag{3}$$

And for values of slip less than zero, (generating) P_1 is negative and P_2 is negative.

The positive and negative sequence torques are:

$$T_1 = \frac{P_1}{\omega_m} = \frac{P_1}{\omega_s(1-s)} = \frac{3 I_{1r}{}^2 R_r}{s\,\omega_s} \tag{4}$$

$$T_2 = \frac{P_2}{\omega_m} = \frac{P_2}{\omega_s(1-s)} = \frac{3 I_{2r}{}^2 R_r}{(2-s)\omega_s} \tag{5}$$

The developed torque is:

$$\begin{aligned} T &= T_1 + T_2 \\ &= \frac{3R_r}{\omega_s}\left(\frac{I_{1r}{}^2}{s} + \frac{I_{2r}{}^2}{(2-s)}\right) \end{aligned} \tag{6}$$

The positive and negative sequence currents are functions of their sequence voltages, machine parameters and the slip s. There is introduced an oscillating torque at twice the supply frequency as a result of the negative sequence currents.

The power in terms of positive and negative sequence components is:

$$P_{in} = \text{Real}\,[3*(V_1 I_1^* + V_2 I_2^*)] \tag{7}$$

EFFECTS OF VOLTAGE UNBALANCE ON A DFIG CONVERTER

This section of the study deals with the effects that network voltage unbalance has on the rotor converter. Voltage unbalance can cause voltage harmonics on the dc bus of a DFIG, and lead to current harmonics. Positive and negative sequence components can be used to analyse the effects of voltage unbalance on converters. The cross product of positive and negative sequence components of voltage and current generate a (2-ω) frequency power ripple (where ω is the rotational speed) causing dc link voltage and current ripple [5]. Increased current harmonics on the dc link can shorten the life of the capacitor, or lead to capacitor failure. The bus ripple voltage can also lead to the generation of pulsating torques at the second line harmonic, similar to the effects on the induction generator shown in the previous section.

Fig. 8 shows the results of a simulation in DigSilent of the of the dc link current pulsations in the converter of a DFIG due to the effect of 3.2% unbalanced terminal voltage.

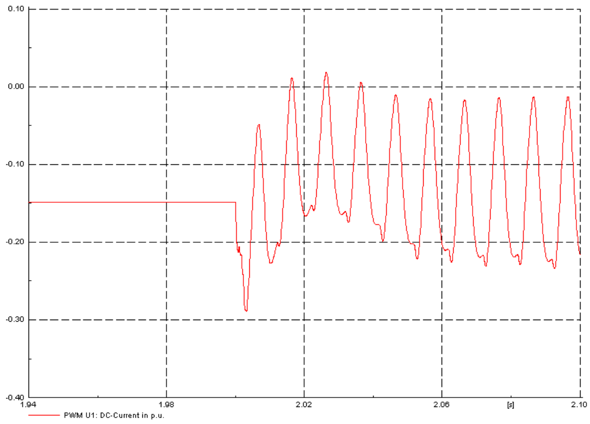

Figure 8 DFIG DC link Current Pulsations with Network Voltage Unbalance of 3.2%

Positive and negative sequence components can be used to analyse the effects of voltage unbalance on converters. The cross product of positive and negative sequence components of voltage and current generate a 2-ω frequency power ripple causing dc link voltage ripple [7,12,13].

ALLEVIATION OF THE EFFECTS OF NETWORK VOLTAGE UNBALANCE

The issues associated with the connection of wind turbines and DFIG's to network grids with voltage unbalance, have been investigated [6,7]. In a DFIG the grid-side converter, dc link capacitor and transformer may function as a STATCOM. [6] uses this approach to design a control system to alleviate the problems on the DFIG as a result of unbalance voltage in the supply grid. [7] presents a novel controller design for a DFIG that provides adjustable speed and reactive power control and also reducing torque pulsations due to supply voltage unbalance. This design is based on using the stator and rotor I_d and I_q current components to compensate for the torque pulsations. The torque equation of a DFIG is given by [7]

$$T_{em} = p/2\, L_m\, (i_{sq}\, i_{rd} - i_{sd}\, i_{rq}) \qquad (8)$$

Where L_m is the magnetising inductance, i_{sd} is the stator direct component, i_{sq} is the stator quadrature component, *isd* the rotor direct component and i_{rq} is the rotor quadrature component.

From the appropriate induction machine q and d equivalent circuits the magnetising current is defined as

$$i_{msd} = i_{sd} + i_{rd} \qquad (9)$$

$$i_{msq} = i_{sq} + i_r$$

The torque equation can now be expressed as

$$T_{em} = p/2\, L_m\, (i_{msq}\, i_{rd} - i_{msd}\, i_{rq}) \qquad (10)$$

When the dq frame is synchronously rotating, the stator voltages are balanced, and the generator is in steady-state, all dq quantities are dc. The torque equation is

$$T_{em} = p/2\, L_m\, (I_{msq}\, I_{rd} - I_{msd}\, I_{rq}) \qquad (11)$$

With $I_{msq}\, I_{rd\ and}\, I_{msd\ Irq}$ constant the torque will also be constant. However when voltage unbalance occurs in the supply network, this will cause perturbations in i_{msq} and i_{msd} at twice the synchronous frequency. The torque equation for unbalanced network voltage is

$$T_{em} = p/2\, L_m\, ((I_{msq} + i_{msq})\, (I_{rd} + I_{rdcomp}) - (I_{m,sd} + i_{msq})(I_{r\,q} + I_{rq\,comp}) \qquad (12)$$

I_{rdcomp} and I_{rqcomp} are compensating currents which can be added to the rotor converter control currents to cancel the effects of the oscillating i_{msd} and i_{msq}.

To alleviate the effects of voltage unbalance on DFIG's it is proposed to concentrate on the current controllers in both the rotor side and grid side converters. This will be necessary as the power flow direction through a DFIG converter changes when it is operating in the subsynchronous and supersynchronous regions. It is proposed to build a test-rig incorporating a dc and ac coupled machine-set and implement the control system using DSP.

CONCLUSION

The effects of voltage unbalance on a DFIG were investigated. Software simulations showed that voltage unbalance when applied to a DFIG results in large current oscillation in both the induction generator and converter. Research in this area has proposed some solutions and a method to implement one solution is suggested.

REFERENCES

1. M. F. Conlon, M. Basu, N. G. Jayanti, and K. Gaughan, "A Survey of the Installed Wind Generation Capacity in Ireland", 2nd International Conference of Renewable Energy in Maritime Island Climates, 26-28 April 2006, Dublin, Ireland, pp. 55-60
2. A larson,. "Power Quality of Wind Energy generating System and Their interaction with the grid," Ref.
3. DigSilent PowerFactory, WWW.digsilent.de
4. M.F. Conlon and J. Kearney, "Negative Sequence Analysis of Induction Machines" 40th Universities Power Engineering Conference (UPEC), Cork, Ireland, 6th - 9th September 2005
5. S. D. Rubira and M. D. McCullagh, "Control of Double Fed Generators connected to the Grid by Asymmetric Transmission Lines", 33rd Annual IEEE Industry Applications Conference, 12th-15th Oct.1998
6. Bjarne Idsoe Naess, Tore M. Undeland, Terje Gjengedal "Methods for Reduction of Voltage Unbalance in Weak Grids Connected to Wind Plants", IEEE Workshop on Wind Power, Oslo 17.-18. June 2002
7. Ted Brekken, Ned Mohan, "A Novel Doubly-fed Induction Wind Generator Control Scheme for Reactive Power Control and Torque Pulsation Compensation Under Unbalanced Grid Voltage Conditions", in 34thAnnualPower Electronics Specialist Conference, 2003. PESC '03. 2003 IEEE Vol. 2, 15-19 June 2003, pp. 760 – 764
8. E. Muljadi, T. Baten D. Yildirim, C.P. Butterfield "Understanding the Unbalanced-Voltage Problem in Wind Turbine Generation", National Renewable Energy Laboratory
9. Kevin Lee, Eaton Electrical, Giri Venkataramanan and Thomas M M Jahans University of Wisconsin-Madison. "Modelling Effects of Voltage Unbalances in Industrial Distribution Systems with Adjustable Speed Drives". Industry Applications Conference, 2004, 39th IAS Annual Meeting, Conference Record of the 2004 IEEE, Volume 4, 3-7 Oct. 2004 pp. 2579 – 2586.
10. Jawad Faiz, Hamid Ebrahimpour, and Pragasen Pillay, "Influence of Unbalanced Voltage on the Steady-State Performance of a Three-Phase Squirrel-Cage Induction Motor", IEEE Transactions on Energy Conversion, Vol. 19, No. 4, Dec. '04
11. Pragasen Pillay, Peter Hofmann, Marubini Manyage. "Derating of Induction Motors Operating With a Combination of Unbalanced Voltages and Over or Undervoltages", IEEE Trasactions on Energy Conversion, Vol. 17, No. 4, Dec. 2002
12. Jun-Koo Kang, Sueng-Ki Sul. School of Electrical Engineering, Seoul National University. "Control of Unbalanced Voltage PWM Converter Using Instantaneous Ripple Power Feedback", PESC '97 Record., 28th Annual IEEE Power Electronics Specialists Conference, 1997Volume 1, 22-27 June 1997 Page(s):503 - 508.
13. D Vincenti, P.D. Ziogas, and R V Patel, Dept. of Electrical and Computer Engineering, Concordia University, Montreal, Quebec, "An Analysis and Design of a Force Commutated Three-Phase Ac Controller with Input Unbalance Correction Capability," *in Proc. Seventh Annual Applied Power Electronics Conference and Exposition APEC 23rd-27thFeb. 1992*, pp. 487 – 493.

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