European Association for the
Development of Renewable Energies,
Environment and Power Quality

International Conference on Renewable Energies and Power Quality (ICREPQ'09)

Valencia (Spain), 15th to 17th April, 2009

Analysis of Shaft Voltage in a Doubly-fed Induction Generator

Jafar Adabi[1], Firuz Zare[1], Arindam Ghosh[1], Robert D. Lorenz[2]

[1] School of Electrical Engineering, Queensland University of Technology, GPO Box 2434, Brisbane, QLD, 4001, Australia
Email: adabi.jafar@student.qut.edu.au , f.zare@qut.edu.au , a.ghosh@qut.edu.au

[2] University of Wisconsin-Madison, Depts. of ME and ECE, 1513 University Avenue, Madison, WI 53706
Email: lorenz@engr.wisc.edu

Abstract. Fast switching transients and common mode voltage generated by pulse width modulated voltage in high frequency applications may cause many unwanted problems such as shaft voltage and resultant bearing currents. The main objective of this research work is to analyse shaft voltage generation in a doubly-fed induction generator (DFIG) with a back to back converter. A detailed high frequency model of the proposed system has been developed based on capacitive couplings between different objects of the machine. The proposed model can be used for shaft voltage calculations and finding parameters which have key effect on shaft voltage and resultant bearing currents. A discussion about the presented technique for shaft voltage elimination in existing literature is also presented based on mathematical analysis and simulations.

Keywords. DFIG, Wind turbine, Shaft voltage, PWM, Common mode voltage

Fig.1 shows a DFIG with a four-quadrant AC-DC-AC converter connected to the rotor windings which enables decoupled control of active and reactive power.

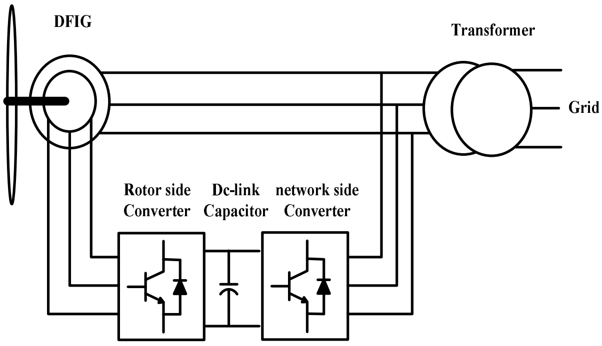


Fig.1. a DFIG with a four-quadrant AC-Dc-AC converter connected to the rotor windings

Power inverters are widely used in wind energy systems to convert AC output voltage of generators with variable frequency to an adjustable AC voltage for grid connection. On the contrary, there are many parasitic capacitive couplings between different parts of electric machine structure which may be neglected in low frequency analysis but the conditions are completely different in high frequencies. In fast switching converters, a low impedance path is created for the current to flow through these capacitors. Due to rapid developments of IGBT technology, switching frequency has dramatically increased. High dv/dt (fast switching transients) and common mode voltage generated by a power inverter in high frequency applications can cause unwanted problems such as: shaft voltage and resultant bearing currents, grounding current escaping to earth through stray capacitors inside a motor, conducted and radiated noises. Common mode voltage is known as a potential origin of shaft voltage.

Fig.2 shows the structures of a DFIG where the parasitic capacitive couplings exist between: the stator winding and rotor (C_{sr}), the stator winding and stator frame (C_{sf}), between the rotor and stator frames (C_{rf}), stator winding and rotor winding (C_{ws}), the rotor winding and rotor (C_{wr}), rotor winding and stator frame (C_{wf}) and ball bearing and outer and inner races (C_{b1}, C_{b2}).

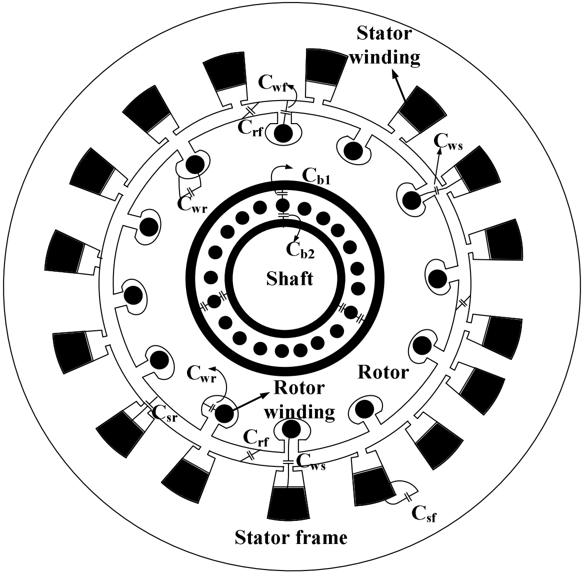


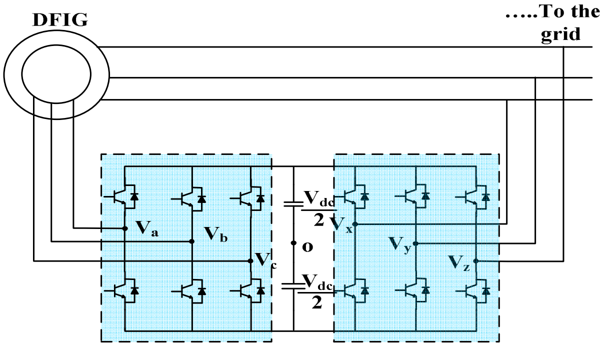
Fig.2. Capacitance coupling in a doubly fed induction machine

Fig.3 shows the arrangement of a DFIG with a back to back inverter. In this structure, neutral to ground zero sequence voltage of both stator and rotor windings act as common mode voltage sources. The common mode voltage of rotor side and stator side are given as:

$$V_{com,S} = \frac{V_{ao} + V_{bo} + V_{co}}{3} \quad (1)$$

$$V_{com,R} = \frac{V_{xo} + V_{yo} + V_{zo}}{3} \quad (2)$$

Where V_{ao}, V_{bo}, V_{co} & V_{xo}, V_{yo}, V_{zo} are the leg voltages of the converters connected to the stator and rotor, respectively. A high frequency model of the proposed doubly fed induction machine is shown in Fig.4.



Rotor side Converter **Dc-link Capacitor** **Stator side Converter**

Fig.3. a DFIG with a back to back inverter

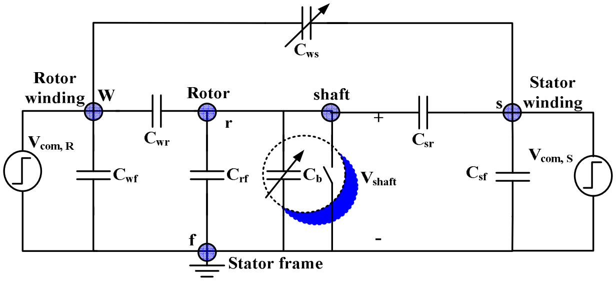


Fig.4. A high frequency model of a DFIG

According to Fig.5, Shaft voltage can be calculated as:

$$\left(V_{shaft} - V_{com,R}\right) \times C_{wr} + V_{shaft} \times \left(C_{rf} + C_b\right) + \left(V_{shaft} - V_{com,S}\right) \times C_{sr} = 0 \quad (3)$$

So, shaft voltage is:

$$V_{shaft} = \frac{V_{com,R} \times C_{wr} + V_{com,S} \times C_{sr}}{C_{wr} + C_{rf} + C_b + C_{sr}} \quad (4)$$

$$V_{shaft} = \frac{C_{wr}}{C_{wr} + C_{rf} + C_b + C_{sr}} \times V_{com,R} + \frac{C_{sr}}{C_{wr} + C_{rf} + C_b + C_{sr}} \times V_{com,S} \quad (5)$$

$$V_{shaft} = K_R \times V_{com,R} + K_S \times V_{com,S} \quad (6)$$

$V_{com,R}$ and $V_{com,S}$ are the common mode voltage generated by the converters connected to the rotor and the stator windings, respectively. K_R and K_S are defined as capacitance factors which are effective in total shaft voltage calculation.

Analysis of shaft voltage reduction in a DFIG with a back to back inverter was presented by A.M.Garcia and et al, 2006 with a pulse width modulation technique to fully remove the shaft voltage. According to that paper, if the switching states of machine side converter and line side converter are both odd, both even or the same zero states from both side converters, the common mode voltage can be forced to zero. In this case, switching vectors (1, 3, 5) or (2, 4, 6) are used with and without using zero states. The main concern is that this technique does not eliminate the shaft voltage and still we have the significant amount of voltage across the shaft which is affected by two sides' voltage sources (neutral points of stator and rotor winding to the ground). In other words, the voltage that is forced to be zero in proposed paper is not related to the shaft voltage.

To achieve a zero shaft voltage, both common mode voltage sources should be considered based on an accurate high frequency model of the system. Based on the Eq.5 and Fig.4, it is clear that by choosing a proper rotor common mode voltage (Eq.7), a zero shaft voltage will be achieved.

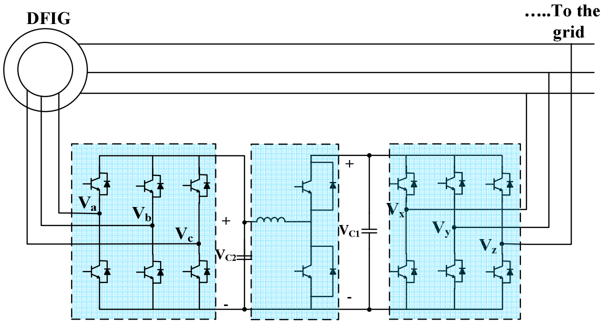
$$V_{com,R} = -\frac{C_{sr}}{C_{wr}} \times V_{com,S} \quad (7)$$

Table I shows the resultant shaft voltage by different switching states of both rotor and stator sides converters. Note that, rotor side common mode voltage has been decreased to $\frac{C_{sr}}{C_{wr}} \times V_{com,S}$ by a buck converter and shaft voltage is calculated based on Eq.5.

TABLE I. Different switching states and shaft voltage

		Rotor side converter			
		Vectors 1,3,5	Vectors 2,4,6	Vector 7	Vector 0
Network side converter	Vectors 1,3,5	$\frac{-K_S V_{dc}}{3}$	0	$\frac{K_S V_{dc}}{3}$	$\frac{-2K_S V_{dc}}{3}$
	Vectors 2,4,6	0	$\frac{K_S V_{dc}}{3}$	$\frac{2K_S V_{dc}}{3}$	$\frac{-K_S V_{dc}}{3}$
	Vector 7	$\frac{K_S V_{dc}}{3}$	$\frac{2K_S V_{dc}}{3}$	$K_S V_{dc}$	0
	Vector 0	$\frac{-2K_S V_{dc}}{3}$	$\frac{-K_S V_{dc}}{3}$	0	$-K_S V_{dc}$

To eliminate the shaft voltage completely, the condition of Eq.7 should be applied in the analysis. To meet these requirements, it is needed to apply odd switching vectors (1, 3, and 5) to one converter and even switching vectors (2, 4, and 6) to another converter. Also, switching V_0 from one side and V_7 from other side is conducted to generate zero shaft voltage. The presented PWM pattern can be used as an effective technique to reduce the shaft voltage. One of the issues regarding to this technique is that, a bidirectional buck converter should be employed to reduce the dc-link voltage (V_{c1}) to create a rotor side common mode voltage equal to $\frac{C_{sr}}{C_{wr}} \times V_{com,S}$ (see Fig.5).



Rotor side Converter **Bidirectional Buck converter** **network side Converter**

Fig.5. a new back-to-back inverters topology with a bidirectional buck converter and a DFIG

In this configuration, the limitation of the duty cycle of the buck converter should be considered. These conditions may affect the dynamic performance of the DFIG. Therefore, cancellation of the shaft voltage based on this topology should be mentioned in terms of practical barriers and dynamic analysis of the system which is beyond the scope of this paper.