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Analysis, Calculation and Reduction of Shaft Voltage in Induction Generators

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Abstract. This paper presents analysis of shaft voltage in different configurations of a Doubly Fed Induction Generator (DFIG) and a stator fed Induction Generator (IG) with a back-to-back inverter in wind turbine applications. Detailed high frequency model of the proposed systems have been developed based on existing capacitive couplings in IG & DFIG structures and common mode voltage sources. Placements of an LC line filter in different locations and its effects on shaft voltage elimination are studied with mathematical analysis and simulations.

Shaft voltage generated by converters in a stator-fed induction generator

Fig.1.a shows the structures of an IG 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}), and ball bearing and outer and inner races (C_{b1}, C_{b2}). Fig.1.b shows an induction generator wind turbine structure in which a power converter is connected between the generator and the grid. A simple high frequency model of a motor drive is shown in Fig.1.c and shaft voltage can be calculated as:

$$V_{shaft} = \frac{C_{sr}}{C_b + C_{rf} + C_{sr}} \times V_{com} \tag{1}$$

Fig.1.d shows a view of a stator slot, a rotor and winding where g_1 is the air gap, g_2 is the gap between winding and stator and g_{in} is the thickness of insulation. d is the length of slot tooth and ρ is the height of the stator slot. W and W′ are the width of winding at the top and bottom respectively. h_W is the length of the stator winding at both the right and the left side of winding. Different capacitive couplings in a single stator slot can be approximately calculated as:

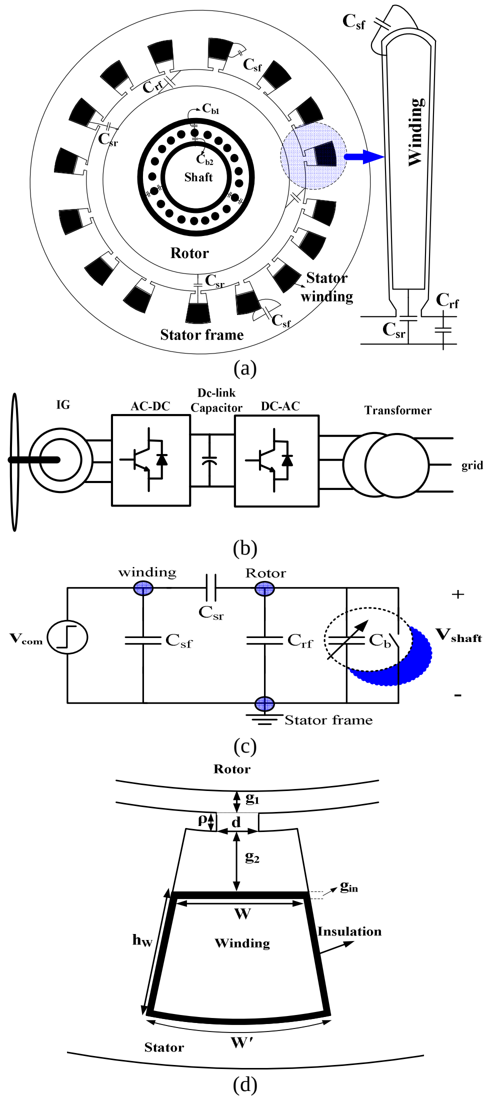
$$\begin{cases} C_{rf} \approx \dfrac{\varepsilon_0 (\frac{2\pi r}{n} - d) \times L_r}{g_1} \\ C_{sf} \approx \left(\dfrac{\varepsilon_0 \varepsilon_r (W' + 2 \times h_W)}{g_{in}} + \dfrac{\varepsilon_0 \varepsilon_{r1} \varepsilon_{r2} (W - d)}{g_2 \varepsilon_{r1} + g_{in} \varepsilon_{r2}} \right) \times L_r \\ C_{sr} \approx \varepsilon_0 \dfrac{d - \rho}{\rho + g_1 + g_2} \end{cases} \tag{2}$$

Where r is the rotor radius and g_1 is the air gap, L_r is the rotor length. ε_0 is the permittivity of free space and ε_{r1}, ε_{r2} are the permittivity of the insulation and the slot wedge materials. By substituting of Eq.2 in Eq.1, the ratio between shaft voltage and common mode voltage is:

$$\frac{V_{shaft}}{V_{com}} \approx \frac{g_1 (d - \rho)}{g_1 (1 + x)(d - \rho) + (\rho + g_1 + g_2)(\frac{2\pi r}{n} - d)} \quad , d > \rho \tag{3}$$

Where x is the ratio between bearing capacitance and C_{sr}. According to calculation analysis in different parameters:

- ● Csr is an important capacitance in case of shaft voltage generation because it can be changed by variation of the design parameters while other capacitances have not such a freedom to change. As shown Eq.3, the effective parameters on shaft voltage are d, ρ, g_1 and g_2
- ● An increment of stator slot tooth increases the shaft voltage while increasing the gap between the slot tooth and winding decreasing the shaft voltage. This information can be taken into account in the design procedure of the motor structure and the motor designer can choose design parameters which are a trade off between shaft voltage issue and other electromechanical considerations.



(a)

(b)

(c)

(d)

Fig.1. (a) Structure of a stator fed induction generator with different parasitic capacitive couplings (b) with an AC-DC-AC converter (c) high frequency model (d) a stator slot and different design factors

Shaft voltage generated by converters in a doubly-fed induction generator

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}).

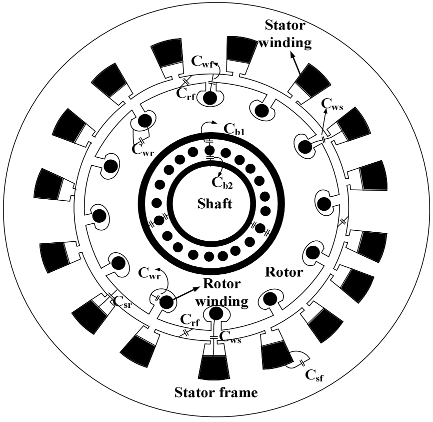


Fig.2. A view of a doubly fed induction generator with different parasitic capacitive couplings

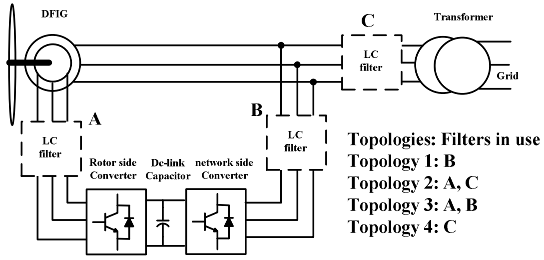


Fig.3. different placements of L-C filters in wind turbine applications in a DFIG with a back to back converter

Different topologies of a DFIG with a four-quadrant AC-DC-AC converter connected and different placements of LC filters in both rotor and stator sides, and a line filter has been investigated (see Fig.3). Shaft voltage (V_{shaft}) is calculated in each topology.

Topology1: the network side converter is connected to the grid through a line LC filter which is used to damp the higher order harmonics generated by the switching of semiconductors switches.

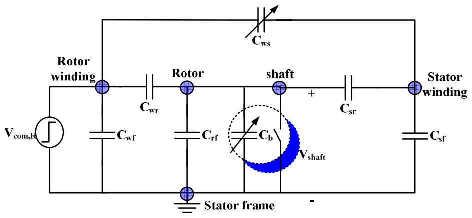


Fig.4. High frequency model a DFIG with Topology1

$$\begin{cases} V_{shaft} = \dfrac{C_{wr}\times(C_{sf}+C_{sr}+C_{ws})+C_{ws}\times C_{sr}}{(C_{wr}+C_{rf}+C_{b}+C_{sr})\times(C_{sf}+C_{sr}+C_{ws})-C_{sr}^{2}}\times V_{comR} \\ V_{shaft} \approx \dfrac{C_{wr}}{(C_{wr}+C_{rf}+C_{b}+C_{sr})}\times V_{comR} \end{cases} \quad (4)$$

Topopolgy2*:* A filter is placed in the rotor side converter and the voltage from the rotor side has fewer harmonics.

$$\begin{cases} V_{shaft} = \dfrac{C_{sr}\times(C_{wr}+C_{wf}+C_{ws})+C_{ws}\times C_{wr}}{(C_{wr}+C_{rf}+C_{b}+C_{sr})\times(C_{ws}+C_{wr}+C_{wf})-C_{wr}^{2}}\times V_{com,S} \\ \quad \approx \dfrac{C_{sr}}{(C_{rf}+C_{b}+C_{sr})}\times V_{com,S} \end{cases} \quad (5)$$

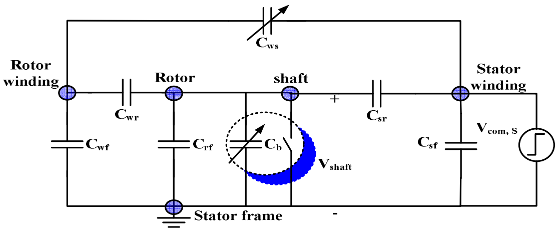


Fig.5. high frequency model of a DFIG with Topology2

Topology3: LC filters in the both rotor and stator sides are used to damp the higher order harmonics. In this case, there is no any common mode voltage from both sides.

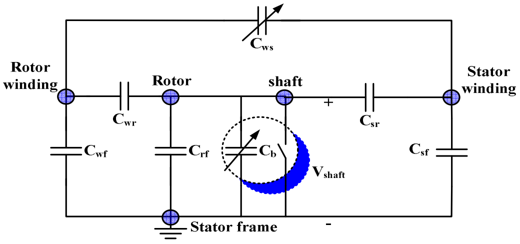


Fig.6. high frequency model of a DFIG with Topology3

Topology4: there is no LC filter in both converters sides.

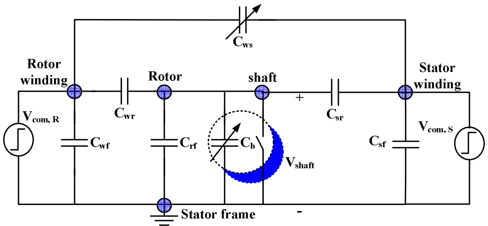


Fig.7. high frequency model of a DFIG with Topology4

$$V_{shaft} = \frac{C_{wr}}{C_{wr}+C_{rf}+C_{b}+C_{sr}}\times V_{com,R} + \frac{C_{sr}}{C_{wr}+C_{rf}+C_{b}+C_{sr}}\times V_{com,S} \quad (6)$$
$$= K_R \times V_{com,R} + K_S \times V_{com,S}$$

KR and KS are defined as capacitance factors which are effective in total shaft voltage generation.

$$K_R = \frac{C_{wr}}{C_{wr}+C_{rf}+C_{b}+C_{sr}} \text{ and } K_S = \frac{C_{sr}}{C_{wr}+C_{rf}+C_{b}+C_{sr}} \quad (7)$$

The system configuration in Topology 1 can not remove the shaft voltage because the common mode voltage from the rotor still exists. This voltage has a major impact on the shaft voltage. In this case by removing stator side common mode voltage, a small part of shaft voltage will be removed. Removing the rotor side common mode voltage (Topology2) by filtering the rotor side converter will remove major part of the shaft voltage but there is a considerable amount of shaft voltage from the stator side. Removing zero switching vectors from stator side converter can reduce the common mode voltage and as a result a reduced shaft voltage can be achieved. In these two topologies (1&2), the price for filtering is paid but there is still a considerable amount of shaft voltage. Furthermore, it is obvious that the configuration of Topology3, because of filtering in both sides, will remove both sides' common mode voltages and will not generate shaft voltage significantly.

In Topology4, to achieve a zero shaft voltage, both common mode voltage sources should be considered based on Eq.6 and Fig.7. It is clear that by choosing the rotor common mode voltage as follow, zero shaft voltage can be achieved.

$$V_{com,R} = -\frac{C_{sr}}{C_{wr}}\times V_{com,S} \quad (8)$$