Analysis of Shaft Voltage in a Doubly-fed Induction Generator

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Abstract. Fast switching transients and common mode voltage generated by pulse width modulated voltage in high frequency applications may cause 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](image1)

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 (Cₜ), the stator winding and stator frame (Cₛₒ), between the rotor and stator frames (Cₛᵣ), stator winding and rotor winding (Cₛₘᵣ), the rotor winding and rotor (Cₘᵣ), rotor winding and stator frame (Cₘₛ) and ball bearing and outer and inner races (Cₜ₁, Cₜ₂).

![Fig.2. Capacitance coupling in a doubly fed induction machine](image2)

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:

\[ V_{com,S} = \frac{V_{zo} + V_{hs} + V_{co}}{3} \]  \hspace{1cm} (1)

\[ V_{com,R} = \frac{V_{xo} + V_{yo} + V_{zo}}{3} \]  \hspace{1cm} (2)
Where $V_{co}, V_{bo}, V_{co}, V_{yt}$, and $V_{zo}$ 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.

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

$$V_{shaft} = V_{com.R}C_{wr} + V_{shaft}C_{cf} + C_{b} + V_{shaft}C_{cm} = 0$$

(3)

So, shaft voltage is:

$$V_{shaft} = \frac{V_{com.R} + V_{com.S}C_{wr}}{C_{wr} + C_{cf} + C_{b} + C_{cm}}$$

(4)

$$V_{shaft} = \frac{C_{cm}}{C_{wr} + C_{cf} + C_{b} + C_{cm}} V_{com.S}$$

(5)

$$V_{shaft} = K_R V_{com.R} + K_S V_{com.S}$$

(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.

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 $\frac{C_{wr}}{C_{wr}} V_{com.S}$ by a buck converter and shaft voltage is calculated based on Eq. 5.

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 ($V_{cl}$) to create a rotor side common mode voltage equal to $\frac{C_{wr}}{C_{wr}} V_{com.S}$ (see Fig. 5).

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.