PHASE-TO-GROUND VOLTAGE ESTIMATION AT WIND TURBINE GENERATOR TERMINALS

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INTRODUCTION

The demand for high efficiency from wind turbines makes permanent magnet generators (PMGs) the optimum choice for wind turbine manufacturers. The capacity factor of wind turbines is normally in the range of 0.4 in the best operating locations, and therefore wind turbines mainly operate at partial loads, where PMG technology is the best choice [1]. Other technologies, such as the doubly-fed induction generator (DFIG) and squirrel cage induction generators (SCG) also exist on the market.

In many applications the generator interfaces with the grid by means of a back-to-back converter as shown in Fig. 1. In the case of low voltage (< 1000 VAC), the back-to-back converter comprises two three-phase IGB-transistor bridges, generating pulse-width modulation (PWM) sequences, which are usually filtered to improve the generator terminal or grid supply voltage harmonic spectra. Structurally, PMG, DFIG and SCG (designed for operation in variable speed wind turbines) drives resemble each other [1, 2, 3]: they contain a back-to-back converter, which is connected either to the stator winding (PMG, SCG) or to the rotor winding via slip rings (DFIG).

Taking into account this similarity, let us further consider the PMG drive as an example, remembering, however, that the considerations and outcomes of this paper are also applicable to other drives containing frequency converters with some modifications.

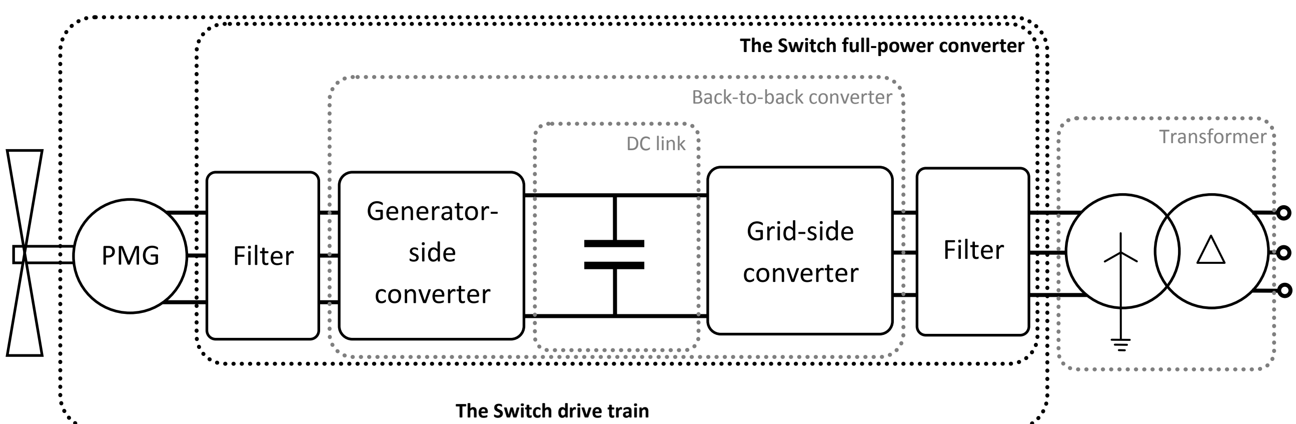

Figure 1: A block diagram of the full-power converter for a wind turbine based on a permanent magnet generator (PMG). The generator transforms the wind energy into electrical energy. The energy flow is controlled by a back-to-back converter that contains two IGB-transistor bridges. The filters clean the electrical signal from noises harmful for the PMG and a grid load, connected to the system through a transformer.

EQUIVALENT ELECTRICAL CIRCUIT

Typically, the low-voltage side of the three-phase transformer is star-connected with a galvanically grounded star point. This potential is, therefore, the reference potential of the whole drive train. All the other potentials of the drive train are connected to this basic potential through different impedances. As follows from Fig. 1, the back-to-back converter comprises two frequency converters. A frequency converter generates common-mode noise, which can cause failures in the electrical machine winding and bearings [4]. The common-mode noise, generated by the frequency converter, can appear either at the phase terminals, if the system is grounded on its DC side, or in the DC link potentials, if the system is grounded on its AC side, when measured versus electrical ground.

Electrical filters are very effective in common-mode noise prevention in single-converter systems [5, 6]. However, in the back-to-back converter, common-mode noise is generated by two sources, one of which produced by the grid-side converter is the reference for the other one produced by the generator-side converter [7]. This is illustrated in Fig. 2 for one phase of the three-phase system. In Fig. 2 u_{cm_gr} is the common-mode voltage of the grid-side converter, u_{conv_gen} is the generator converter one phase voltage, u_{cm_gen} is the common-mode voltage part produced by other two phases of the three-phase generator converter, e_{gen_ph} is the back-electromotive force in the PMG's phase, $L_{f\&cab}$ is the sum of filter and cable inductance, and L_{ph} is the PMG's phase inductance. Filter capacitances and resistances are neglected in Fig. 2 for simplicity. However, they are usually needed to provide the best possible high-frequency attenuation. Fig. 2 indicates that the generator filter cannot affect the common-mode voltage generated by the grid-side converter. This means that the back-to-back converter can place stress on the PMG winding and bearings more than single converters do. It is worth mentioning that the grid-side and generator-side converters are usually working at a different base and, often, switching frequencies, which indicates a variety of switching combinations that exist in phase-to-ground voltages at the PMG terminals. Thus, it is reasonable to estimate that phase-to-ground voltage is at the maximum level possible at least once in a period, corresponding to the lowest nominal base frequency of the back-to-back converter.

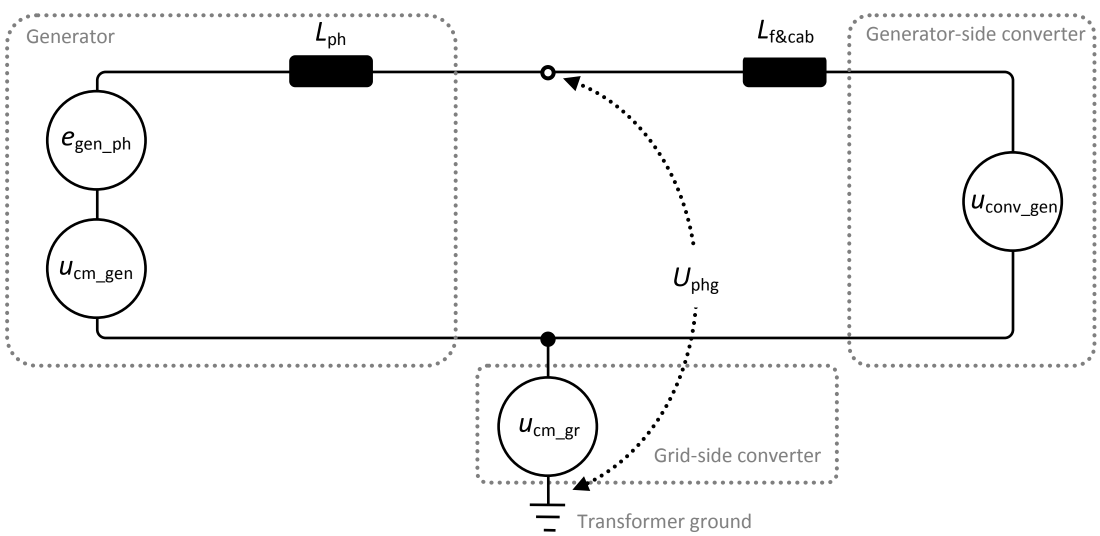

Figure 2: A simplified electrical circuit of the back-to-back converter system, which describes the phase-to-ground voltage generation in a full-power converter. The phase-to-ground voltage is thus a combination of the back-to-back converter voltages, which depend on the relation between the generator inductance L_{ph} and the sum of the generator-side filter and cable inductances $L_{f\&cab}$.

Special PWM techniques have been invented to minimize the common-mode emission of the frequency converters. They can be successfully implemented in the back-to-back converter, however, a risk of winding insulation damage for badly insulated PMGs can still be high.

That is why the estimation of possible phase-to-ground voltage applied at generator terminals is important in the generator selection procedure.

GENERATOR TERMINAL VOLTAGES ESTIMATION

Let us consider a typical case when the generator phase inductance L_{ph} is much more than the sum inductance of the cable and the filter $L_{f\&cab}$, i.e. $L_{ph} >> L_{f\&cab}$. In this case, as follows from Fig. 2, the peak voltage applied at the generator terminals can be described as:

$$U_{phg.m} = U_{cm\_gr.m} + U_{conv\_gen.m}, \quad (1)$$

where m indicates peak values.

Let us consider some practical data. Common-mode voltage, generated by the grid-side frequency converter, can be seen, for example, in the DC link potentials measured versus earth. The shape of this voltage is shown in Fig. 3.

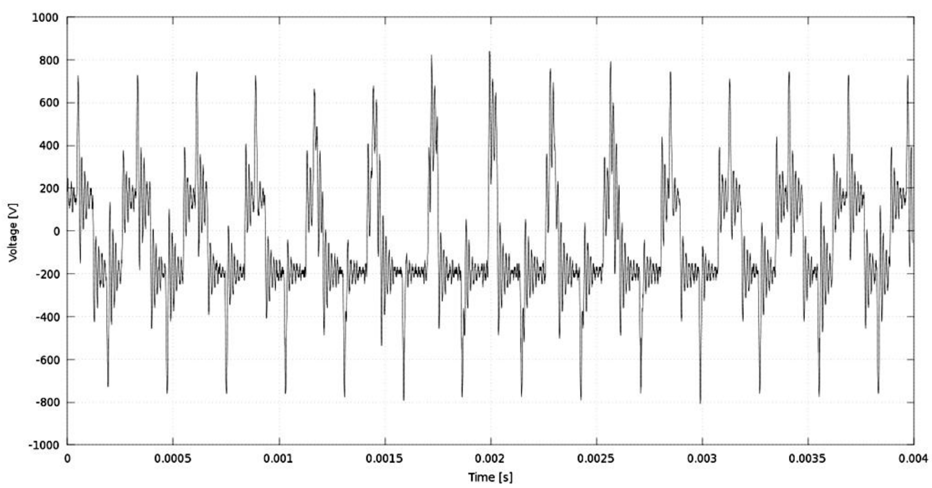

Figure 3: Common-mode voltage generated by the grid-side converter, which affects the generator phase-to-ground voltage. This voltage is highly oscillatory because of the *LC* resonances between phase inductances and stray capacitances present in a generator and, if not taken into account during system design, can cause unexpected generator failures.

It is worth observing that the grid-side common-mode voltage, presented in Fig. 3, is highly oscillatory. Usually, these oscillations are hardly possible to prevent: they can be explained by the *LC* resonances between the phase inductances and stray capacitances present in a generator. The resistances of the stray paths are rather low, which explains the hard oscillations presented in the common-mode voltage. Therefore, peak common-mode voltage in the DC link can be estimated as follows:

$$U_{cm\_gr.m} = 1.67 \cdot U_{DC}/2, \quad (2)$$

where U_{DC} is the voltage between the DC link potentials.

Furthermore, the generator converter voltage is typically filtered by a d*u*/d*t* filter, which is usually an *LCR* circuit, providing a certain voltage overshoot σ (in per cent).

$$U_{conv\_gen.m} = (100+\sigma)/100 \cdot U_{DC}/2 = k_\sigma \cdot U_{DC}/2. \quad (3)$$

Finally, we can see that, in accordance with (1),

$$U_{phg.m} = U_{cm\_gr.m} + U_{conv\_gen.m} = U_{DC} \cdot (0.835 + k_\sigma/2). \quad (4)$$

Since the common-mode voltage is practically the same for all three phases, it is not visible in the phase-to-phase voltages. Thus the peak phase-to-phase voltage can be expressed as

$$U_{phph.m} = k_\sigma \cdot U_{DC}. \quad (5)$$

For example, if U_{DC} = 1050 V and the voltage overshoot after filtering is 10 %, an expected peak voltage applied to the generator terminals, calculated with (4), is 1454 V. The peak phase-to-phase voltage at the generator terminals is equal to 1155 V. Calculated values should be taken into account during the system design.

With the help of (4) and (5), we can derive that

$$U_{phg.m}/U_{phph.m} = 0.5 + 0.835/k_\sigma. \quad (6)$$

Thus, if $k_\sigma < 1.7$, (i.e. overshoot after generator filter is lower than 70 %, which is a typical case), phase-to-ground voltage spikes $U_{phg.m}$ represent a dominating threat for the PMG's winding insulation.

CONCLUSION

This paper proposes a way to estimate the generator terminal voltages. It is shown that phase-to-ground voltages typically represent the dominating threat for the generator windings. This is explained by the fact that the back-to-back converter generates two common-mode voltages. Estimations presented in the paper are recommended for the system design procedure in order to agree on generator voltage levels between the wind turbine, wind generator and power converter manufacturers. The analysis presented in this paper is applicable for both doubly fed induction generator and permanent magnet generator drives, as well as for other systems containing back-to-back converters.

ACKNOWLEDGEMENT

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that both the converters and PMGs are designed to achieve the best performance and reliability for the sake of lowering the cost of energy and improving the end customer's profit.

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