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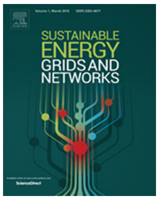

High frequency wind energy conversion system for offshore DC collection grid — Part II: Efficiency improvements

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ABSTRACT

This is the second part of a two-part paper dealing with a high frequency wind energy conversion system for series-connected DC wind turbines. In part I, the efficiency of the AC–AC converter and high frequency transformer was assessed and compared for three different converter topologies: the matrix converter, indirect matrix converter and back-to-back converter. The conversion system with matrix converter presented the highest efficiency, however the three converters had comparable efficiencies. In this part II paper, improvements are presented in order to increase the operating frequency of the transformer without deteriorating the efficiency of the system. The loss analysis methods presented in part I are used to evaluate the benefits of the suggested modifications. Two modulations adapted for the considered high frequency conversion system are explained which keep the efficiency high while allowing for a significant increase in the transformer operating frequency. Using the most efficient modulation, the comparison of the three AC–AC converters is extended to wind speeds below nominal. The results show that the gap between the efficiency of the matrix-type converter and the back-to-back increases when the wind speed decreases. A multi-winding transformer design is suggested in order to reduce the volume and losses.

1. Introduction

This paper is the sequel to a first paper where a Wind Energy Conversion System (WECS) was evaluated in terms of efficiency considering three different converter topologies; the back-to-back converter (B2B), the matrix converter (MC) and the indirect matrix converter (IMC) [1]. The considered conversion system is suggested for a wind park with series-connected turbines shown in Fig. 1. The conversion system itself is shown in the inset of Fig. 1 and is composed of a Permanent Magnet Synchronous Machine (PMSM), an AC–AC converter, a High Frequency Transformer (HFT) and a Diode Bridge Rectifier (DBR). In [1], the results showed that the MC and IMC led to most efficient conversion systems, with the MC slightly superior to the IMC. The transformer frequency was however only 1 kHz to limit the switching frequency in the converter. In this paper two modulations, are therefore suggested in an effort to raise the operating frequency of the transformer to 10 kHz without increasing the switching losses to an unacceptable level. The transformer frequency of 10 kHz is approaching but still below other cutting edge concepts suggested in the literature for high frequency links in [2] or [3]. The first modulation is adapted to the considered conversion system and the second one appropriate for high frequency operation. Both modulations are presented in Section 2. Since the transformer is the bulkiest element of the conversion system, an investigation has been done in Section 3 to reduce the size as well as loss of the transformer. Hence, a multi-winding transformer concept is introduced and compared with conventional 3-phase transformers. In Section 4, the efficiency and functionality of the proposed topology improvements are assessed and compared with the conventional conversion system introduced in part I of the paper [1].

2. Adapted modulation for the HF conversion system in a series-connected park

In this section, 2 modulations which are modified versions of the conventional Indirect Space Vector Modulation (ISVM) [4] are presented for the MC and IMC. These are also described in [5].

Two modifications characterize these modulations. The first modification is related to the choice of (I)MC parameters to control. Usually the (I)MC parameters that are independently controlled are the output voltage amplitude, frequency and phase angle as

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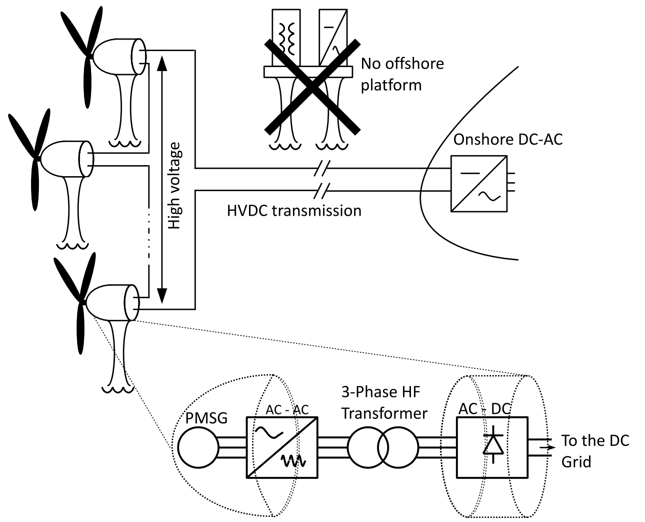

Fig. 1. Series connection of wind turbines and the suggested wind energy conversion system inside the turbine.

well as the input current phase angle and frequency which is almost always set to the mains frequency. This is the maximum number of parameters that can be independently controlled in an (I)MC due to the input and output power equality. In conventional applications such as motor drives connected to the grid or in WECS connected in parallel to a stiff voltage grid, it is easier to connect the current source side of the (I)MC to the grid and control the electric machine with the (I)MC voltage source side. Thus the above-mentioned parameters are the most convenient to use.

In the considered wind park topology however, the turbines are connected in series and the DC current in the series-connection is controlled by an onshore converter. Thus the DC grid represents a stiff current source and the (I)MC should therefore interface the transformer with its voltage source side. The current source side of the converter will control the generator speed for maximum power point tracking. For this application, it is more convenient to control a different set of (I)MC parameters: the input current amplitude, frequency and phase angle as well as the output voltage frequency and phase angle. The authors could not find any examples in the (I)MC literature where this set of parameters are used instead of the conventional ones, however the modifications needed to the ISVM are described in [4].

The second modification is new and can take advantage of the specific WECS topology considered in this paper so as to increase the current ratio of the converter. This modulation that will be called Modified Indirect Space Vector Modulation (MISVM) will be explained in the next section. It can be further modified into a High Frequency modulation, called HF MISVM, more suited for the application in a high frequency conversion system.

2.1. The MISVM

To present the MISVM, the circuit in Fig. 2 is considered. The three phase HFT has a delta-wye connection and $N = \frac{N_{HV}}{N_{LV}}$ is the turn ratio. The leakage inductance, resistance and parasitic capacitance are omitted as well as the input (I)MC filter and the output DC filters. The MISVM is applicable to both the conventional MC and the IMC, as the converters have the same properties from the input/output perspective. The modulation will be explained using the IMC as it provides a better understanding of the internal mechanisms of the modulation. It enables separation into the space vector modulation of the Current Source Rectifier (CSR) in Fig. 3(a) and the space vector modulation of the Voltage Source Inverter (VSI) in Fig. 3(b).

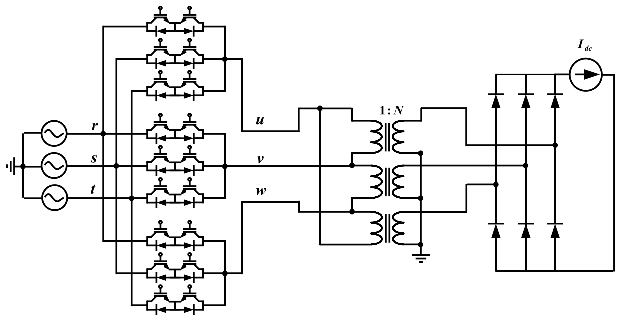

Fig. 2. The considered WECS.

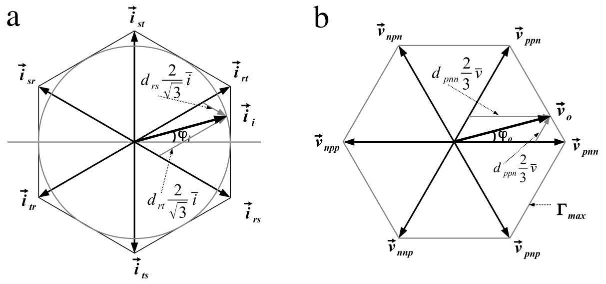

Fig. 3. The modified indirect space vector modulation separated into (a) the current source space vector modulation and (b) the voltage source space vector modulation.

The input current and the output voltage shown in Fig. 3 are defined in complex form as

$$\vec{i}_i = \hat{I}_i e^{j\omega_i t} = \hat{I}_i e^{j\varphi_i} \tag{1}$$

$$\vec{v}_o = \hat{V}_o e^{j\omega_o t} = \hat{V}_o e^{j\varphi_o}. \tag{2}$$

The developed modulation should enable independent control of the input current amplitude rather than the output voltage amplitude as is the norm. Therefore, an input/output current transfer ratio is defined as $q_I = \frac{\hat{I}_i}{\hat{I}_o}$ instead of a voltage transfer ratio. The output voltage is not controlled and is thus set to its maximum. In the space vector modulation of the VSI, this leads to the application of only active vectors and no zero vectors such that the following is true at all times:

$$d_{pnn} + d_{ppn} = 1 \tag{3}$$

with d_{pnn} and d_{ppn} the duty ratios for the application of the active vectors adjacent to the output voltage reference $\vec{v}_o$ in Fig. 3(b). Graphically (3) translates into $\vec{v}_o$ following the hexagonal trajectory $\Gamma_{\max}$ shown in Fig. 3(b). The expression for these duty ratios are found to be

$$\begin{aligned} d_{pnn} &= \sqrt{3}\frac{\hat{V}_o}{\bar{v}} \sin\left(\frac{\pi}{3} - \varphi_o\right) \\ d_{ppn} &= \sqrt{3}\frac{\hat{V}_o}{\bar{v}} \sin\left(\varphi_o\right) \end{aligned} \tag{4}$$

where $\bar{v}$ is the average DC link voltage over a modulation period. If $\vec{v}_o$ is located in a different sector than the first sector $\left[\vec{v}_{pnn}; \vec{v}_{ppn}\right]$ as shown in Fig. 3(b), (4) can still be used by rotating $\vec{v}_o$ back to the first sector.

$\hat{V}_o$ and $\bar{v}$ still need to be determined. To do that, the current source modulation of the MISVM must be analyzed. Fig. 4(a)–(d) shows the current in the WECS during a commutation in the VSI of the IMC from $\vec{v}_{pnn}$ to $\vec{v}_{ppn}$. The sequence in Fig. 4(a)–(d) is part of the switching pattern of the MISVM shown in Fig. 5 for half a modulation period. The switching pattern is valid for the case shown in Fig. 3 where both the current and voltage space vector