Stator and Rotor Current Harmonics in Doubly Fed Machine with Cycloconverter in Rotor Circuit

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Abstract. The stator and rotor currents of a doubly fed machine (DFM) with a 12-pulse cycloconverter in the rotor circuit for different operating states are analyzed. It is shown that the stator as well as the rotor currents contain harmonic spectra dependent on the machine operating state, especially on the mutual relation of fundamental component frequencies of both the currents.

Key words

Doubly fed machine, harmonic analysis, cycloconverter, stator and rotor currents, operating states.

1. Introduction

Speed of doubly fed machines can be controlled easily by means of changes of rotor current frequency. This fact represents a considerable advantage in comparison with synchronous machines operating only at synchronous speed. Doubly fed machines resembling induction machines with wound rotors as far as their construction is concerned, can be utilized for example at pumped storage plants.

Pumped storage plants with doubly fed machines (DFM) have significantly better properties in comparison to those with synchronous machines. The application of doubly fed machines enables variable-speed operation, which improves the turbine efficiency, particularly at lower load [1, 2]. The erosion damage of the turbine blades can also be substantially reduced by adjusting the optimal speed. Independent changes in speed and rotor voltage provide more freedom in control of the active and reactive power outputs of the machine both in motor and generator operation. Moreover, this system is especially suitable for maintaining the stability of the power network, owing to the faster control in comparison to the systems with synchronous generators [3]. For these reasons some manufacturers plan the production of such units for power outputs of up to 500 MW.

For these outputs and for control of speed in ranges about 5% above and under synchronous speed it is suitable to feed the rotor winding from a cycloconverter. In order that the stator and rotor windings can be designed, we need to know the content of harmonics in currents that arise as a consequence of non-sinusoidal feeding from the cycloconverter (for different operating states). These harmonics can influence unfavorably the power grid.

2. System under consideration

The scheme of an adjustable-speed power unit is shown in Fig. 1. The stator of the DFM is connected to the power network through a block transformer. The rotor is driven by an adjustable-blade turbine and fed from a twelve-pulse cycloconverter with a three-winding transformer.
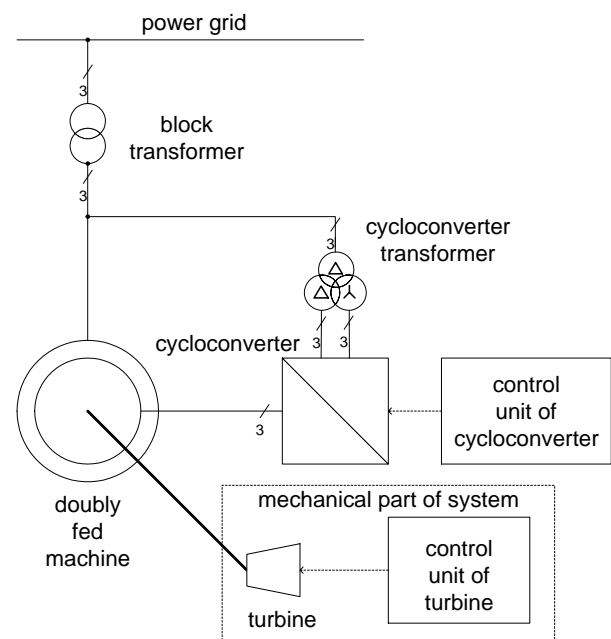

Fig. 1. Adjustable-speed power unit

The control circuitry is included in the system. At a given speed the rotor voltage (its amplitude and phase) should

be controlled so that the demanded active and reactive power outputs are reached, but neither stator nor rotor currents exceed permissible values given by the design of the machine. The phasors of the rotor voltage that meet these conditions define the working regions of the DFM.

The operation of the unit can be analysed by means of a mathematical model. The model of the system consits of the model of the DFM with the mechanical part of the system, based on the space phasor theory, the model of the 12-pulse cycloconverter with the transformer, which has been developed under the assumption of ideal switches and the model of the control unit [4,5]. A 12-pulse cycloconverter without circulating currents with the topology as depicted in Fig. 2 has been considered in the model. The model of the cycloconverter has been developed under the assumption of ideal electric switches and the effect of snubber and other auxiliary circuits has been neglected in the model.
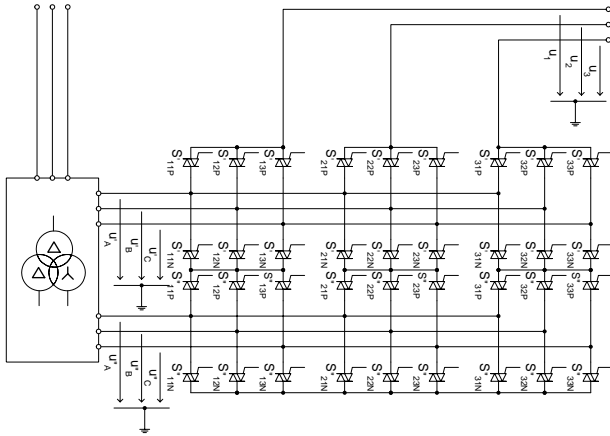

Fig. 2. Scheme of cycloconverter

The cycloconverter represents a system of three electric potentials from the point of view of the machine. The instantaneous values of these potentials are given by the voltages at the input side of the cycloconverter together with the current configuration of the active elements of the cycloconverter. This can be expressed by

$$\mathbf{U} = \left(\mathbf{S}'_{\mathbf{P}} - \mathbf{S}'_{\mathbf{N}}\right)\mathbf{U}' + \left(\mathbf{S}''_{\mathbf{P}} - \mathbf{S}''_{\mathbf{N}}\right)\mathbf{U}'' \qquad (1)$$

where

$$\mathbf{U} = \begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix}, \quad \mathbf{U}' = \begin{bmatrix} u'_A \\ u'_B \\ u'_C \end{bmatrix}, \text{ and } \mathbf{U}'' = \begin{bmatrix} u''_A \\ u''_B \\ u''_C \end{bmatrix} \qquad (2)$$

The meaning of the individual potentials and voltages in (8) is apparent from Fig. 2. Symbols $\mathbf{S}'_{\mathbf{P}}$, $\mathbf{S}'_{\mathbf{N}}$, $\mathbf{S}''_{\mathbf{P}}$, and $\mathbf{S}''_{\mathbf{N}}$ represent the switching matrices that bear the information on the current configuration of the active elements in the cycloconverter. The control unit of the cycloconverter triggers the sequential changes of the switching matrices in dependence on the demanded

instantaneous values of the output voltages according to a particular control strategy.

A cycloconverter transformer with two delta and lambda connected secondary windings and one primary delta connected winding is used to obtain two mutually independent three-phase voltage systems. From the secondary windings of the cycloconverter transformer the cycloconverter draws the following currents

$$\mathbf{I}' = \left(\mathbf{S}'_{\mathbf{P}} - \mathbf{S}'_{\mathbf{N}}\right)^T \mathbf{I} \qquad (3)$$

$$\mathbf{I}'' = \left(\mathbf{S}''_{\mathbf{P}} - \mathbf{S}''_{\mathbf{N}}\right)^T \mathbf{I} \qquad (4)$$

where

$$\mathbf{I} = \begin{bmatrix} i_1 \\ i_2 \\ i_3 \end{bmatrix}, \quad \mathbf{I}' = \begin{bmatrix} i'_A \\ i'_B \\ i'_C \end{bmatrix}, \text{ and } \mathbf{I}'' = \begin{bmatrix} i''_A \\ i''_B \\ i''_C \end{bmatrix} \qquad (5)$$

are the column matrices of the currents on the output and input sides of the cycloconverter corresponding to the similarly denoted potentials. The currents in matrix $\mathbf{I}$ are given by the rotor currents of the DFM. The overall current consumed or generated by the unit is given by the sum of the stator currents and the primary current of the cycloconverter transformer.

3. Resuts of numerical simulation

The following figures hold true for a machine with the output 320 MW operating at the slip $s = 5\%$. In Fig. 3 are time courses of rotor voltage u_{Rd} and current i_{Rd} in the axis d, the current in the stator phase $i_{S\alpha}$ and the torque in the air gap for the operating point P_{max} that means for a regime when the machine is operating with maximum active output. Torque course contains pulsation of frequency defined as six fold of the basic harmonic of the feeding voltage and pulsations of higher frequencies.
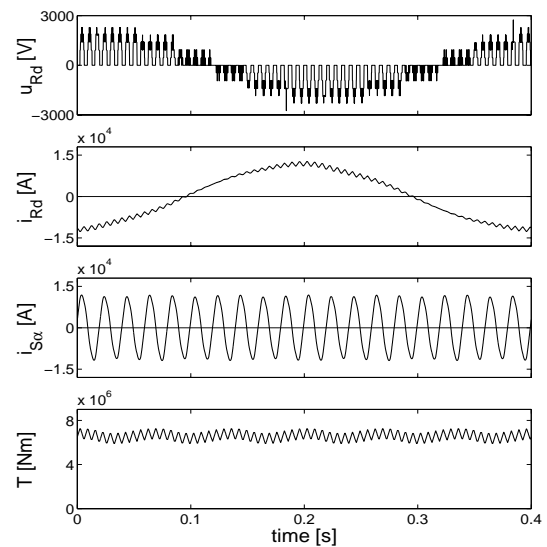

Fig. 3. Rotor voltage and current, stator current and electromagnetic torque for $s = 5\%$ and P_{max}
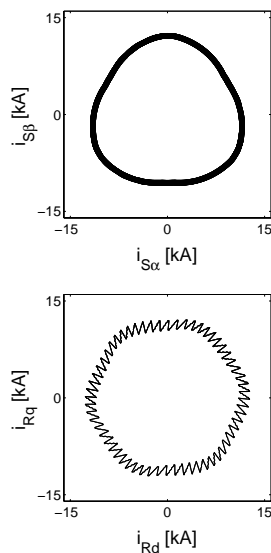
Fig. 4. Loci of stator and rotor current phasors for $s = 5\%$ and P_{max}
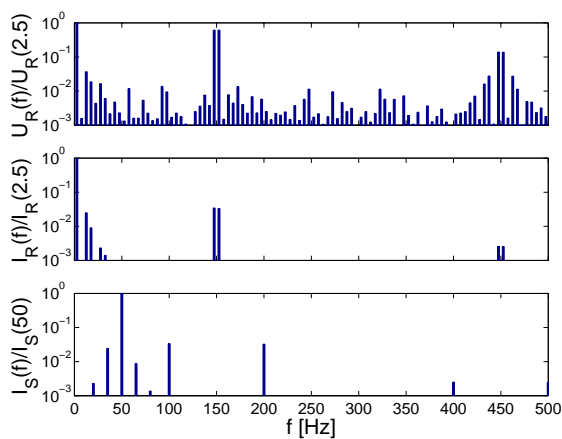

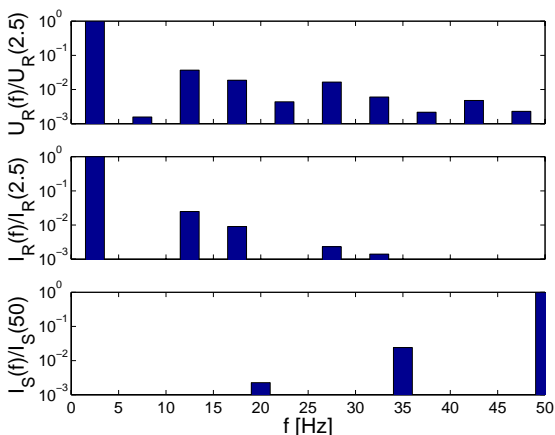Fig. 5. Frequency analysis of rotor voltage and current, and stator current for $s = 5\%$ and P_{max}

Fig. 6. Frequency analysis of rotor voltage and current, and stator current for $s = 5\%$ and P_{max}

Trajectories of stator and rotor current phasors for this case are in Fig. 4. Harmonic analyses of one phase of the rotor voltage as well as stator and rotor phase currents were carried out. The results are depicted in Fig. 5. The amplitudes U_R of rotor harmonic voltages are related to the amplitude of fundamental harmonic which is 2.5 Hz in this case. All the waves up to the frequency 500 Hz were observed. In a similar way proportional values of amplitudes of individual harmonics in rotor currents I_R related to its fundamental harmonic amplitude are depicted. Amplitudes of the stator currents I_S are related to the amplitude of the basic harmonic of frequency 50 Hz. Similar proportional values as in the Fig. 5 but only for waves of frequencies up to 50 Hz are in Fig. 6. It is evident that the rotor voltage contains a wide range of harmonics. Besides the fundamental one, other very strong waves are those of orders 5 and 7. The strongest orders, however, are 59 and 61 or rather 179 and 181. In effect the harmonics 5 and 7 are only observable in rotor currents. Due to the growing reactance with the frequency, the influence of higher wave orders is smaller in currents than in voltage. Due to the rotor influence, orders both lower and higher than the basic harmonic order arise in the stator current. Besides the basic wave of 50 Hz, the waves of frequencies 35, 65, 100 and 200 Hz are most considerable. As it follows from the operating state at the point P_{min} when the machine works with minimum active output, almost the same ranges of harmonics as at the operating point P_{max} are in focus. Courses of the same quantities as in Figs. 3 to 6 but for the operating point Q_{max}, when the machine generates the maximal reactive power, are in Figs. 7 to 10.
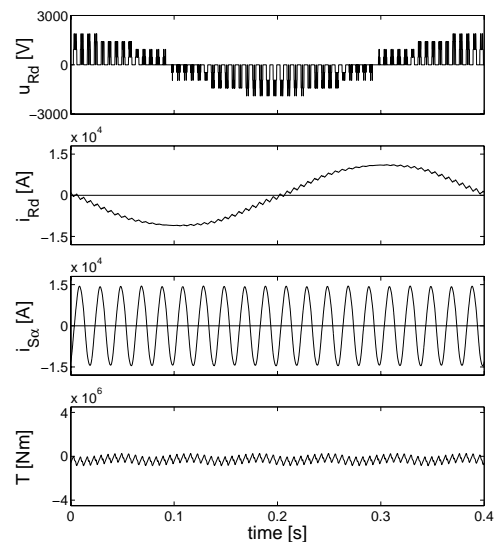

Fig. 7. Rotor voltage and current, stator current, and electromagnetic torque for $s = 5\%$ and Q_{max}
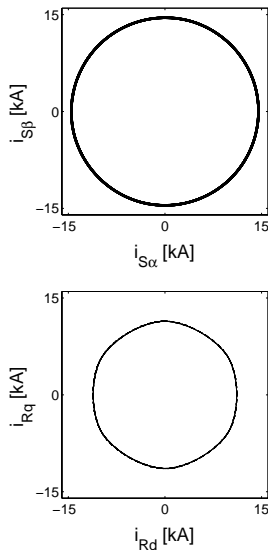
Fig. 8. Loci of stator and rotor current
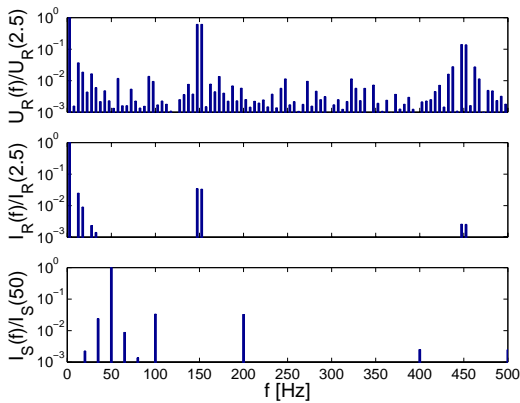phasors for $s = 5\%$ and Q_{max}

Fig. 9. Frequency analysis of rotor voltage and
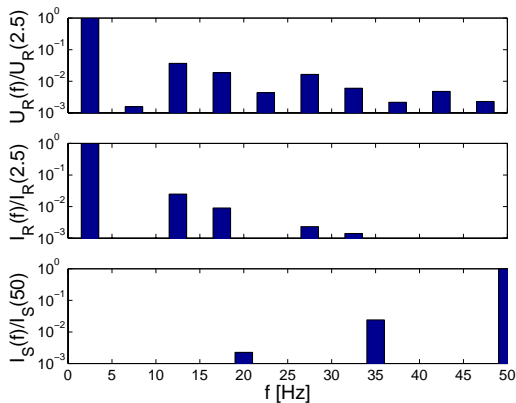current, and stator current for $s = 5\%$ and Q_{max}

Fig.10. Frequency analysis of rotor voltage and
current, and stator current for $s = 5\%$ and Q_{max}

The contents of harmonics in individual quantities for the operating point Q_{min} do not differ from the state in the point Q_{max} significantly. Courses of the focused quantities for unloaded machine are in Figs. 11-14. Due to the fact that the first harmonic of the stator current almost equals zero, the course of stator current trajectory in Fig. 2 is distorted considerably by higher harmonics. The distortion is also significant in rotor current trajectories. That is illustrated in Fig. 4 which shows that the amplitudes of some harmonics especially in stator current are near the fundamental wave amplitude.
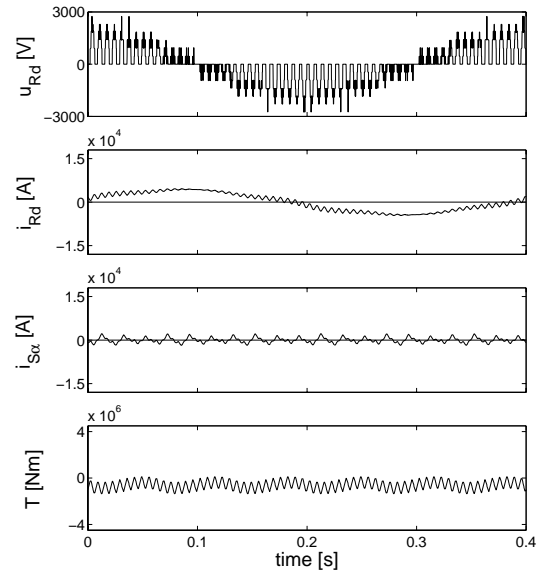

Fig.11. Rotor voltage and current, stator current,
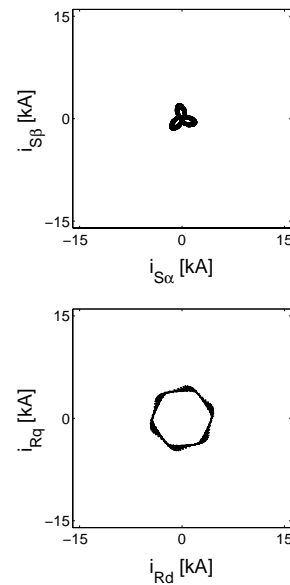and electromagnetic torque for $s = 5\%$ and P=0, Q=0

Fig.12. Loci of stator and rotor current
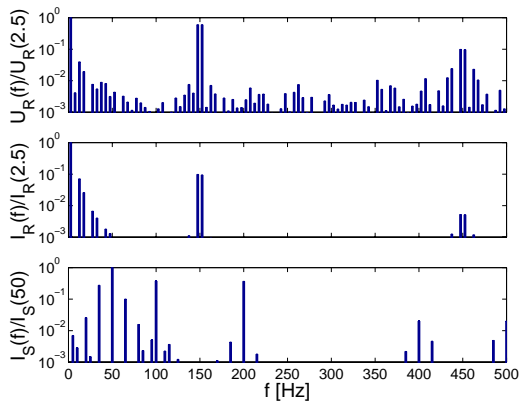phasors for $s = 5\%$ and $P = 0$, $Q = 0$

Fig. 13. Frequency analysis of rotor voltage
and current, and stator current for *s* = 5%
and *P* = 0, *Q* = 0

Fig. 14. Frequency analysis of rotor voltage,
and and current stator current for *s* = 5%
and *P* = 0, *Q* = 0

Fig.15. Rotor voltage and current, stator current,
and electromagnetic torque for *s* = 4.2%

Fig. 16. Frequency analysis of rotor voltage
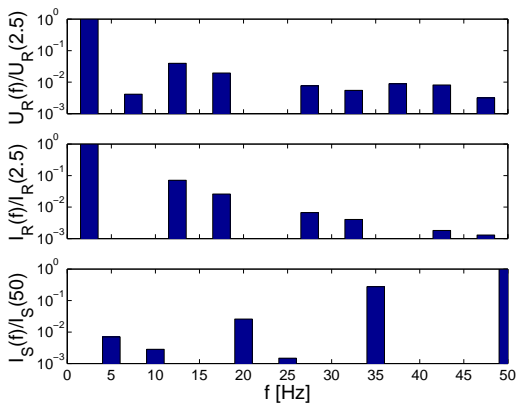and current, and stator current for *s* = 5%
and *P* = 0, *Q* = 0

Fig. 17. Frequency analysis of rotor voltage,
and and current stator current for *s* = 5%
and *P* = 0, *Q* = 0

The content of the harmonics in the voltages and currents of the machine in the case, when the stator frequency is not an integer multiple of the fundamental rotor frequency was also analysed. The same quantities as in Figs. 7, 9, and 10 but for slip 4.2% and generated active power P=-125,6 MW and reactive power Q=-198 MVAr are in Figs. 15-17. The spectrum of harmonics in the rotor voltage seems to be continuous. The magnitudes of the harmonics with frequency of about 150 Hz reach comparable value to the fundamental harmonic. Significant harmonics of the same frequencies occur in the rotor currents. The stator current contains also harmonics with frequencies lower then 50 Hz. The magnitudes of these harmonics considerably increase with their order.
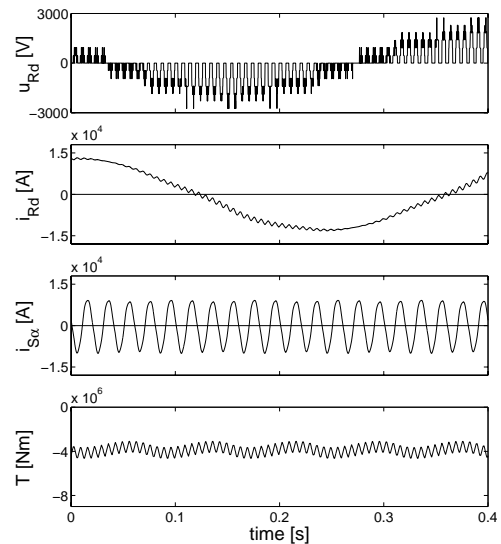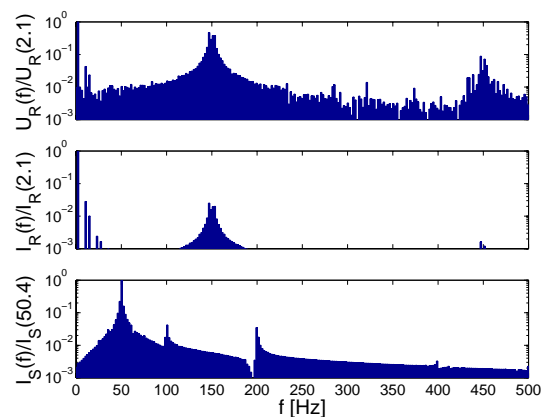
4. Conclusions

In the design of the winding of doubly fed machines with cycloconverters in the rotor winding, it is necessary to take into consideration the fact that both the stator and the rotor currents contain a spectrum of harmonics. These harmonics cause additional losses in the machine as well as its torque pulsations. Another disadvantage are their detrimental effects on the feeding network. The broadest spectrum occurs when stator frequency is not an integer multiple of the fundamental rotor frequency. By the introduced mathematical modelling method, the orders of harmonics both in the rotor voltage and in the rotor and stator currents can be specified for a given range of speed and for demanded loads.

Acknowledgement

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