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INFLUX OF PWM-MODULATION UPON TORQUE HARMONICS OF INDUCTION MACHINES

Smooth torque is required for PWM-VSI-fed drives in various applications. Torque harmonics may lead to mechanical oscillations in the drive train, which are often harmful for the connected loads and may distort the technological process. These oscillations may damage drive gears. Furthermore audible noise may arise.

Low order torque harmonics are especially dangerous; they may excite the mechanical resonance oscillations during the steady state operation or during the start up of the drive train.

Cases of occurrence of the first, second and sixth torque harmonics in PWM-VSI-fed drives are reported in the literature [1], [2], whereby the sixth torque harmonic is normally the dominating one [3-5]. Not all reasons for these torque oscillations have been investigated yet. In the Fig.1 measured torque spectrum of a 220 kW-asynchronous drive is shown [5], it can be seen, that the sixth torque harmonic is strongly dominating.

Torque harmonics may arise also by an ideally sinusoidal power supply caused by the properties of an electrical machine itself, by its control technique or by the load properties. This investigation focuses however solely on torque harmonics due to the PWM-supply in kHz range.

Investigation of current- and torque-harmonics for PWM-supply with small switching frequencies can be found in the literature [6-10].

The first torque harmonic may be of a mechanical origin, it arises for instance due to an eccentric bearing of the rotating masses in a drive train. In the case of PWM-VSI-fed drives the first torque harmonic may arise due to the dc component in the phase currents of a drive [5], [11-14].

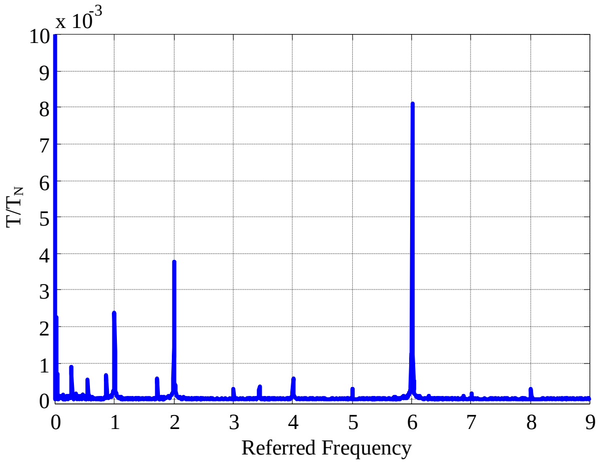

Fig. 1. Torque spectrum of a 220kW-asynchronous drive [1,5]

The dc current offset may result from an offset in current measurement for drives with closed loop current control. Such offset is normally rather small and may not lead to high current offsets. For open loop controlled drives the reason may lie in the parameter dispersion of the control circuits and of power switches or in the malfunction of the dead time compensation because of an offset in a current measurement. The dead time compensation malfunction leads even at a very small measurement offset level to a very high dc current offset [14]. The compensation reference voltage is switched dependent on the load current polarity. Even very small offset in the current measurement leads to the faulty polarity detection of the load current and thus to an unbalance in positive and negative half-waves of the compensation voltage: A DC offset in the resulting compensation reference appears.

The unbalance depends upon the time, during which the current polarity is detected wrongly. Obviously, the current slope and consequently the current amplitude at a given frequency are decisive. That means an operation with low current amplitude (for instance in the field-weakening region at idle load) may lead to a to a high DC voltage and current offsets. For instance the measurement in [14] showed a DC current offset of 23% in the field weakening area caused by merely 0.8% DC offset in the current measurement (Fig. 2).

The second current harmonic in the negative phase sequence leads also to the first torque harmonic. When the dead time voltage is not compensated, the second harmonic arises in the presence of a dc current offset, which leads to an asymmetry of the dead time voltage [1] and consequently to the second harmonic component in its spectrum. Whereby the fundamental component of the dead time voltage will decrease with a stronger asymmetry.

So if the dead time voltage is not compensated, then the dc current component in the phase currents of a machine will lead not only to the first torque harmonic, as known before, but also to the second torque harmonic.

The fifth and seventh current harmonic, resulting from an uncompensated dead time voltage, lead to the sixth torque harmonic. The amplitude of the dead time voltage remains constant at a constant switching frequency and dc-link voltage. That is why the magnitude of the sixth torque harmonic caused by the dead time voltage increases with decreasing output frequency of the inverter.

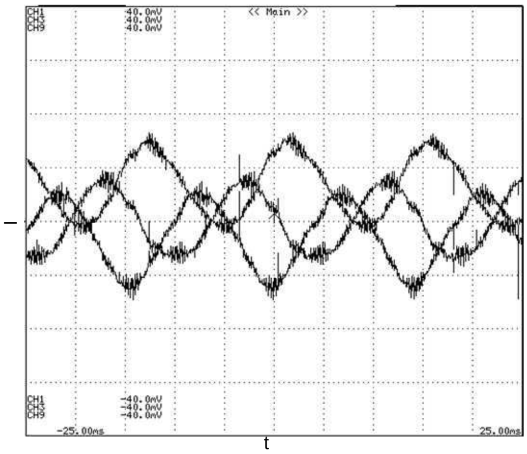

Fig. 2. Measured phase currents of a 2.2kW induction machine at no load and activated dead time compensation at 70 Hz [14]

The sixth torque harmonic due to the dead time effect can be avoided by implementing dead time compensation or by implementing the PWM without dead time generation, as described in [1]. The main obstacle for implementation of both these methods lies in the precise determination of current zero crossing, whereby for the PWM operation multiple current zero crossings are possible because of the current ripple.

A three-phase, two-level voltage inverter offers eight switching states. Six of them correspond to possible voltage space phasors, and another two form a zero phasor, when all phases are switched to the same conductor. Using combinations of the eight possible space phasors, other phasors can be realized by PWM. Note, that without utilizing zero phasors, a hexagon is obtained in the space plane. Since a circular trajectory is desired, the difference area between hexagon and circle will be compensated by applying zero-phasors. In the neighbourhood of space phasors $\vec{U}_{1\div 6}$ the zero phasor time intervals will increase, and in the middle of each sector they will decrease. Hence the ratio of "on" and "off" states will vary six times in one period. This variation causes torque harmonic pulsation of sixth order. Such torque pulsation cannot be measured at the drive shaft, because the carrier frequency (the switching frequency) will be absorbed by the inertia masses of the machines rotor.

In the case of the machine operation above the so-called "knee" of a magnetization curve, the positive and negative half-waves will be distorted, not compensating each other in the average any more. With increasing amplitude of the oscillation the non-zero average decreases. Thus the pulsation at this operation point will show maxima at $n \cdot 60°$ ($n = 0; \pm 1...$). The sixth torque harmonic results from this non-linearity. The sharper the knee of the magnetization characteristic, the larger the amplitude of the sixth torque harmonic will appear.

With decreasing magnitude of the average space phasor, the zero phasor duration will increase and its relative variation will decrease. That is why the amplitude of the sixth torque harmonic will decrease with the decreasing output voltage of the inverter.

In the most cases the torque harmonics resulting from the PWM operation may be compensated by the changes in the control software. To compensate the first and second torque harmonics, the appearance of the dc offset in the machines phase currents must be avoided. The compensation of the sixth torque harmonic component due to the variation of the zero-phasor duration by operation at the "knee" of the magnetization characteristic can be performed by means of torque reference values in phase opposition to the sixth harmonic. Magnitude and phase of torque reference values for the torque control loop are to be stored for various working points of a drive in a look-up table in the controller memory. Such feed-forward compensation method would not diminish dynamic properties of a drive [1].

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