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Reducing the losses of electrical machines under torsional vibration

Antero Arkkio, Eemeli Mölsä, Timo P. Holopainen

Abstract – **Electric drivetrains have an almost rigid-body torsional vibration mode at a low natural frequency. If a torsional excitation occurs close to this frequency, the vibration amplitude may grow large, and the losses of the electrical machine may significantly increase. The possibilities to reduce or eliminate these additional losses are studied. When the machine is connected directly to the grid, the possibilities for vibration control mainly come from mechanical solutions. If the machine is fed from a frequency converter, there are several potential ways to suppress the additional losses. The torsional vibration control of electric drivetrains is studied from loss minimization point of view. This is the novelty of the paper.**

Index Terms—**electrical machines, torsional vibrations, electromagnetic losses, finite-element analysis.**

I. Introduction

THIS paper studies the possibilities of reducing the losses of electrical machines under large torsional oscillations.

Such oscillations may occur, for instance, in electric drivetrains for reciprocating compressors, particularly, if the load causes torsional excitations at a frequency close to the natural frequency of the torsional rigid-body mode [1, 2]. To be exact, this mode is not a rigid-body mode due to the minor torsional deformation, but in this paper this mode is systematically referred as the rigid-body mode. In the rigid-body mode, the electromagnetic field of the motor acts as a torsional spring and the rotating mass of the whole drivetrain oscillates under this spring action. The natural frequency of the rigid-body mode is typically some Hertz for large-power drives and some tens of Hertz for smaller ones. At such a rigid-body resonance, the electrical machine may suffer from significant additional losses [3].

To avoid the additional losses, the excitation frequency and the natural frequency of the vibration mode should be pushed away from each other. If the electrical machine is directly connected to the grid, not much can be done electrically. The change of the main flux of the machine would change the resonance frequency but as the machine has to provide the rated torque without overheating, the flux cannot be changed significantly.

Usually, the torsional stiffness of drivetrain components, as coupling, is adjusted to control the natural frequencies of the drivetrain. However, with the rigid-body mode the adjustment of stiffness is ineffective. An alternative approach is to adjust the inertia of the drivetrain. The decrease is difficult, but the increase of inertia by a flywheel is probably the most common approach to avoid the torsional resonance of the rigid-body mode. This decreases the natural frequency and also attenuates the vibration excitations.

Torsional vibration at frequency f_v induces two additional harmonics in the stator current. They appear at frequencies $f_s \pm f_v$, where f_s is the supply frequency. These two harmonics are later called the vibration harmonics. If the machine is supplied from a power-electronic converter, we may have the possibility to control the vibration harmonics of the current and thus significantly affect the torsional behavior of the drivetrain. For instance, we can eliminate the first rigid-body mode or we can force the amplitude of torsional vibration to be zero.

Suppressing torsional vibration of an electric drivetrain by proper control is not a new topic. See for instance [4-9]. In the present paper, we are interested in the losses of electrical machines and we study how different ways of vibration control affect these losses. Time-discretized finite-element analysis (FEA) is used for loss computation. In the simulations, the machine is supplied from a voltage source having such harmonic contents that lead to the wanted vibration characteristics. The exact details on how to generate the required voltage from a power-electronic converter are left out of this paper. We just want to see the gains in energy efficiency if a properly controllable voltage source were available.

In this paper, the alternative strategies of vibration control are considered focusing on the electromagnetic losses. The results will show that there is an optimal solution combining both the vibration and loss suppression. This is the main finding and novelty of the paper.

II. Methods of Analysis

In FEA, the magnetic field in the core region of the motor is assumed two-dimensional. End-winding impedances are added to the circuit equations of the windings to approximately model the 3D end-winding fields. The trapezoidal rule is used for time-discretization. The field and circuit equations are discretized and solved together [10]. Moving-band technique in the air gap of the machine allows rotating the rotor [11]. The torque is obtained using Coulomb's method [12] and the equation of motion of the rotor is solved within the time-stepping process.

The resistive losses of the windings are included in the model when solving the field equations within FEA. The eddy-current losses in the core sheets are also included in the FE solution using the simple method presented by Knight et al. [13]. The hysteresis losses are obtained in post-

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processing. Thus, their effect is not included in the field solution.

The task is to eliminate certain harmonics from the stator current and/or rotation speed. Adding proper harmonics to the supply voltage provides the means for the elimination. A numerical Newton's iteration was built up to search for the harmonics. The machine was first simulated with slightly varying supply voltages. The results were Fourier analyzed and the Jacobian of Newton's method was constructed to get the next voltage harmonics. This was repeated for so long that the unwanted harmonics vanished from the current and/or speed.

The simulated period had to be longer than one second to get a frequency resolution of 1 Hz from the Fourier analysis. In the time-discretization, one period of supply frequency was typically divided into 400 time steps. Second-order finite elements were used. The 2D finite element meshes included 3800 – 6400 nodal values.

Two complex-valued vibration harmonics of the rotation speed and/or stator current were eliminated using the numerical Newton's method. This means that the Jacobian was a 4x4 matrix. The iteration typically converged within four iteration steps. Each iteration step required five time-stepping simulations to build up the Jacobian matrix.

III. Results

Two electrical machines are used as test samples. They are a 37 kW four-pole cage induction motor and a 6 MW synchronous motor having twenty salient poles. Table I includes the main parameters of the machines. The induction machine is small for compressor applications. It is included as it was earlier tested under torsional vibration to validate the loss computation methods [3]. The synchronous motor was specially designed for a compressor drive.

TABLE I
Test Machines

	Induction motor	Synchronous motor
Rated power [kW]	37	6000
Number of poles	4	20
Supply frequency [Hz]	50	60
Air-gap diameter [mm]	200	2120
Core length [mm]	249	850
Inertia of rotor [kgm^2]	0.256	9713

For shorter presentation, the different ways of dealing with the harmonics are called Cases 0 … 5. They are defined below. In all of the Cases, the constant rated torque acts at the shaft of the motor. Most of the Cases also include a harmonic excitation torque with amplitude equal to half the rated torque. This relatively large oscillating torque was chosen as standard shaft couplings are able to transmit this amount of oscillating torque [14].

Case 0 – The motor operates at the rated voltage and load. There is no harmonic torsional excitation and the motor is fed from a purely sinusoidal voltage source. This gives the lowest electromagnetic loss of the cases studied. It is used as a reference when discussing the losses and currents obtained for the other cases. The excitation is zero only in this Case, and thus, it is marked as Case 0.

Case 1 – The amplitude of torsional excitation at the shaft is equal to half the rated torque. The machine is fed from a sinusoidal voltage source. The variation of the rotation speed follows the equation of motion of the rotor. The maximum vibration amplitude occurs at the rigid-body resonance. The speed variation induces the two vibration harmonics in the stator current and there is no control of them.

Case 2 – The amplitude of torsional excitation is equal to half the rated torque. Two voltage harmonics at frequencies $f_s \pm f_v$ are added to the supply voltage. They are used as control variables to suppress the corresponding current harmonics to zero. This eliminates the "first" rigid-body resonance. However, higher-order vibration harmonics remain in the current and they cause a "second" rigid-body resonance at a lower natural frequency.

Case 3 – The amplitude of torsional excitation is equal to half the rated torque. The voltage harmonics are changed to suppress the torsional vibration and the lower vibration harmonic $f_s - f_v$ of the current to zero.

Case 4 – The amplitude of torsional excitation is equal to half the rated torque. The voltage harmonics are changed to force the harmonic in the rotation speed and the upper vibration harmonic $f_s + f_v$ of the current to zero.

Case 5 – The amplitude of the torsional excitation is equal to half of the rated torque. Both the voltage harmonics are adjusted. Such a combination of harmonic currents is searched for that gives the minimum of total electromagnetic loss and forces the harmonic of the rotation speed to zero.

A. Cage induction motor

Figure 1 shows the total electromagnetic loss computed for the 37 kW motor in the different Cases as functions of the torsional excitation frequency.

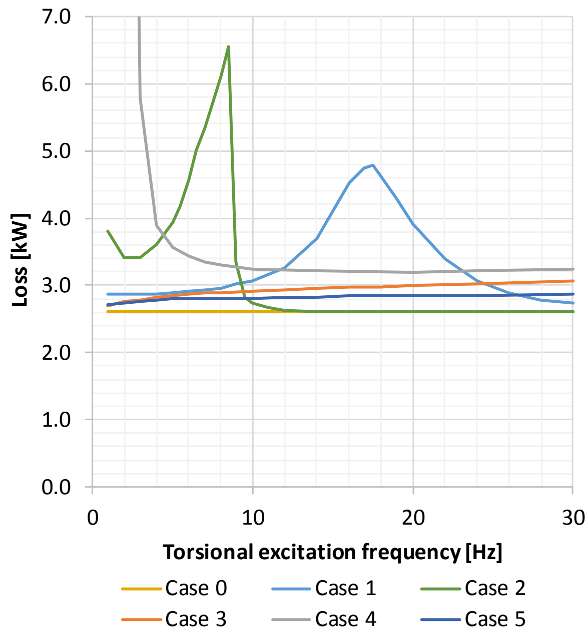

Fig. 1. Total electromagnetic loss of the 37 kW motor as a function of excitation frequency under different control modes of the harmonics. Cases 0 … 5 are defined in the main text.

The loss curve for Case 1 indicates that the natural frequency of the rigid-body mode of the 37 kW motor is 17.5 Hz. However, it should be noted that the only rotating mass of inertia included in the simulations was that of the induction motor itself. Including all the inertia of the drivetrain would reduce the natural frequency.

When forcing the first-order vibration harmonics of the current to zero (Case 2), the rigid-body resonance at the first natural frequency vanishes and the losses stay small. However, higher-order vibration harmonics remain in the current and cause a second resonance peak at 8.5 Hz.

When only the upper vibration harmonic $f_s + f_v$ is used to suppress the torsional vibration (Case 3), the losses stay reasonable. The magnetic field associated with this harmonic rotates faster than the rotor and produces a small positive torque. The control current helps to rotate the rotor.

The loss curve for Case 4 shows bad behavior. There are problems particularly at lower excitation frequencies when the frequency of the lower vibration harmonic $f_s - f_v$ is only some Hertz smaller than the supply frequency. The magnetic field associated with the current harmonic rotates slightly slower than the rotor. The slip is small and the magnetic coupling between the rotor cage and the harmonic field is strong. This produces a significant retarding torque. The machine takes a larger fundamental current to react the retarding torque. This interaction significantly increases the losses of the machine.

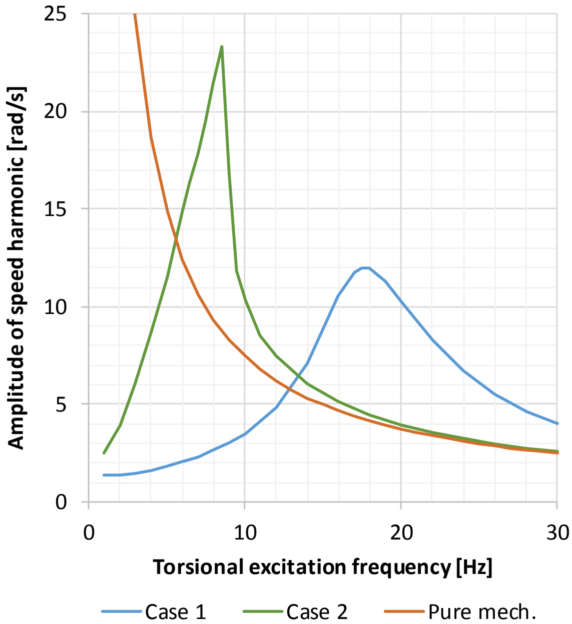

Fig. 2. Amplitudes of vibration harmonic in the rotation speed of the 37 kW motor for Cases 1 and 2. The third curve presents the amplitude obtained from the equation of motion when neglecting the electromagnetic effects.

Finally, the blue curve (Case 5) is obtained by forcing the torsional vibration to zero by changing simultaneously both the harmonics $f_s \pm f_v$ and by searching for such a combination of them that leads to a loss minimum. At larger vibration frequencies, the minimum loss is obtained when the harmonic currents have roughly equal amplitudes. However, due to the strong coupling between the rotor cage and the lower vibration harmonic as discussed above, the vibration suppression at the low vibration frequencies has to be done using mainly the upper vibration harmonic $f_s + f_v$.

It should be noted that the amplitude of torsional vibration is different from case to case. The harmonic amplitudes of rotation speed are shown in Fig. 2 for Cases 1 and 2.

In Cases 1 and 2, particularly at the resonance frequencies, the amplitudes are very large. In the other Cases, the vibration is either forced to zero or stays otherwise very small. The third curve in Fig. 3 shows the amplitude of speed harmonic in a purely mechanical case in which the torsional excitation is present but all the electromagnetic effects are put to zero.

The results of Fig. 1 imply that significant savings could be obtained in the losses of the electrical machine if a properly controllable voltage source were available. To see more clearly what is required from such a power-electronic converter, Fig. 3 shows the peak values of the terminal currents of the machine in Cases 0 … 5.

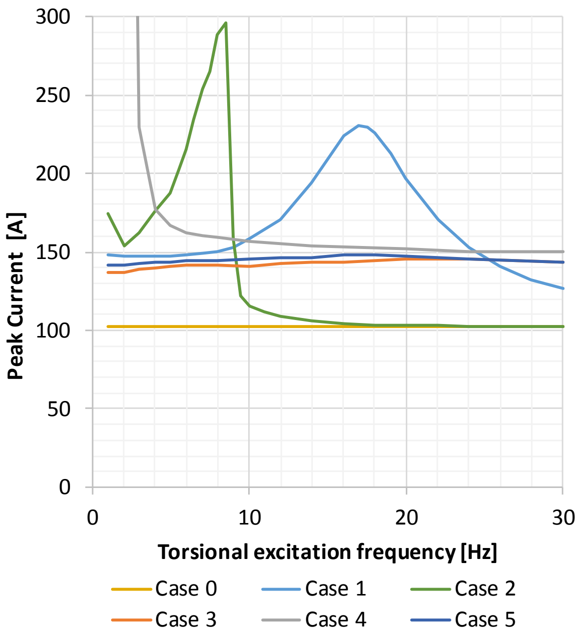

Fig. 3. Peak values of the terminal currents of the 37 kW motor for the different Cases studied.

When there is a large torsional excitation, the power supply has to provide significantly larger peak currents than in case of a constant load torque. Case 2, in which the first-order vibration harmonics $f_s \pm f_v$ were eliminated from the current, behaves very well at higher vibration frequencies. However, the higher-order vibration harmonics of the current strongly increase at frequencies smaller than 10 Hz.

Case 5 gave the minimum loss of the cases in which the torsional vibration was suppressed. It does not give the minimum of peak current.

The amplitudes of the control variables, i.e. the harmonic voltages for Cases 2 … 5 are shown in Figs. 4 … 7. They are scaled to the rated voltage of the motor. Symbol U– refers to the lower vibration harmonic at frequency $f_s - f_v$, symbol U+ to the upper vibration harmonic at frequency $f_s + f_v$.

Eliminating the first-order vibration harmonics from the current (Case 2) reduces the electromagnetic torsional damping significantly leaving the inertia of the rotor the main constraint of torsional vibration. This can keep the vibration amplitude reasonably small at excitation frequencies larger than 10 Hz (Fig. 4). Close to the second-order rigid-body resonance at 8.5 Hz, the vibration amplitude is very large (Fig. 2) and so are harmonic voltages needed to eliminate the first-order vibration harmonics from the current.

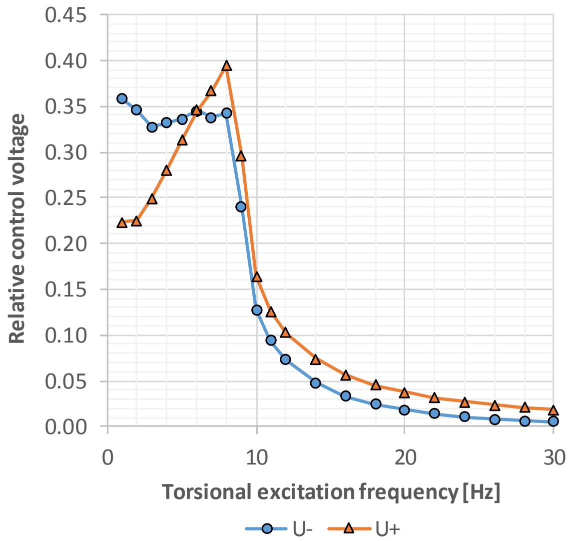

Fig. 4. Amplitudes of voltage harmonics needed to suppress the first-order vibration harmonics from the stator current of the 37 kW motor (Case 2).

Figure 5 shows the voltage harmonics for Case 3. They stay reasonably small at frequencies larger than 3 Hz.

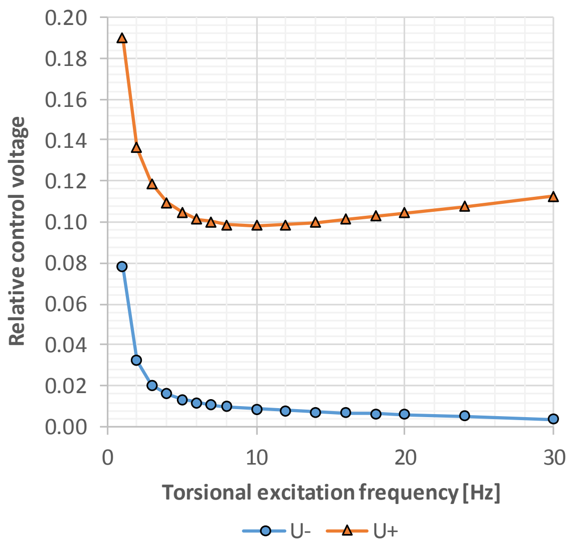

Fig. 5. Amplitudes of voltage harmonics needed to suppress the torsional vibration and lower current harmonic of the 37 kW motor (Case 3).

The retarding torque associated with the lower vibration harmonic of current causes problems in Case 4. From the harmonic voltage point of view, the method would be valid at frequencies larger than 5 Hz (Fig. 6).

When both the current harmonics are used to suppress the vibration, a minimum in losses can be found and the voltage harmonics remain relatively small (Fig. 7). However, the peak values of the terminal current (Fig. 3) are still clearly larger than the ones in case of no torsional excitation.

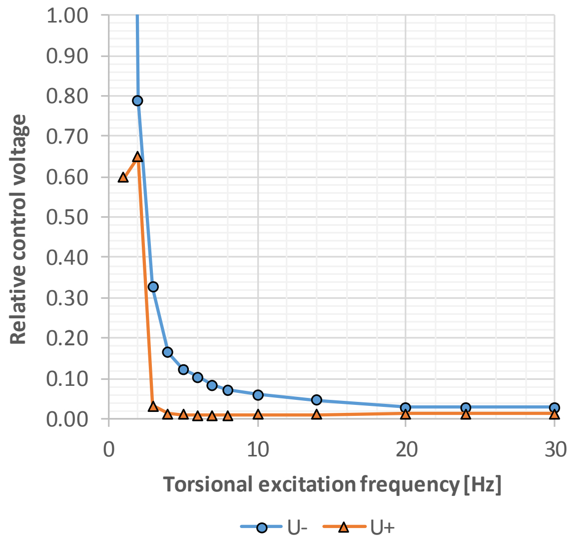

Fig. 6. Amplitudes of voltage harmonics needed to suppress the torsional vibration and upper current harmonic of the 37 kW motor (Case 4).

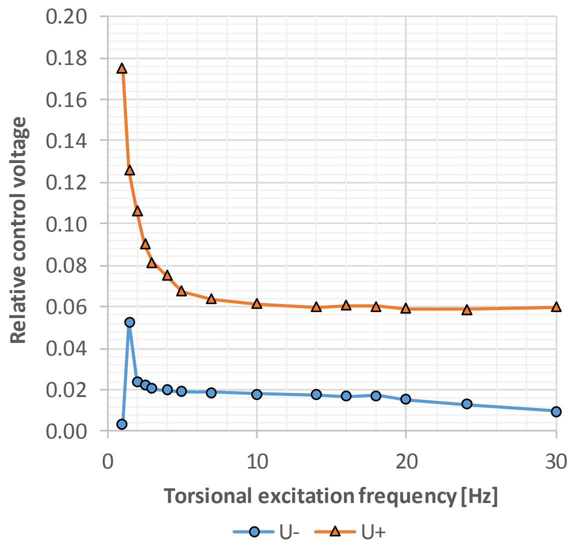

Fig. 7. Amplitudes of voltage harmonics that suppress the torsional vibration and give the minimum electromagnetic loss for the 37 kW motor (Case 5).

B. Salient-pole synchronous motor

Figure 8 shows the total electromagnetic losses obtained for the 6 MW synchronous motor as functions of the torsional excitation frequency in the different Cases.

The synchronous machine follows similar lines in its torsional behavior as was earlier shown for the induction motor, only the resonance frequencies are lower for the larger machine. The natural frequency of the rigid-body mode of the 6 MW motor is 2.75 Hz. The amplitudes of vibration harmonic in the speed for Cases 1 and 2 are shown in Fig. 9. In Cases 3 … 5, the amplitude of mechanical vibration was forced to zero.

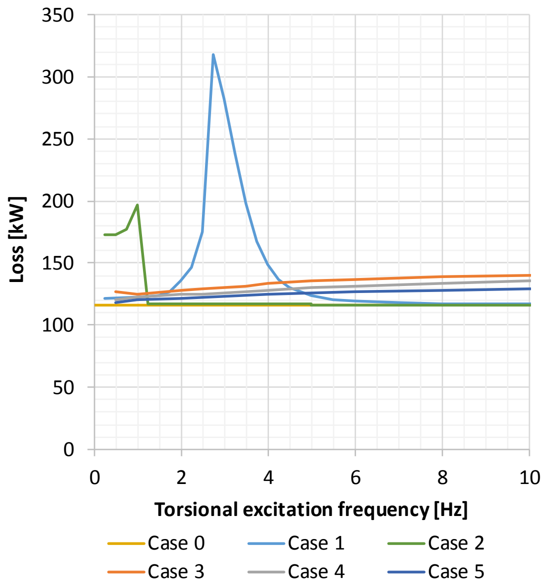

Fig. 8. Total electromagnetic loss of the 6 MW synchronous motor as a function of excitation frequency under different control modes of harmonics. The Cases are defined on the second page of this text.

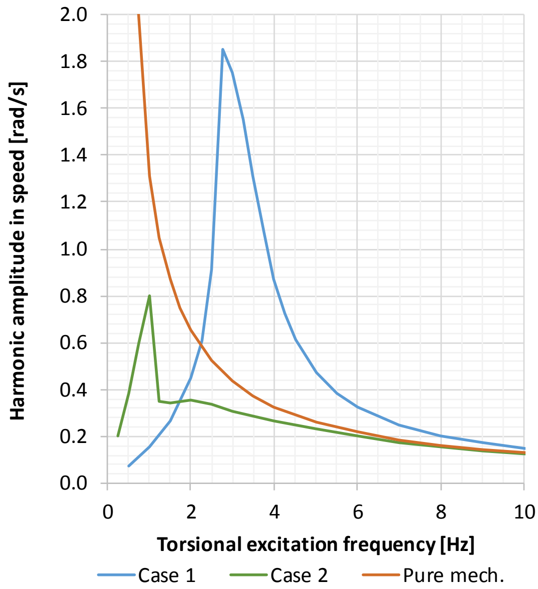

Fig. 9. Amplitudes of vibration harmonic in the rotation speed of the 6 MW motor for Cases 1 and 2. The third curve presents the amplitude obtained from the equation of motion when neglecting the electromagnetic effects.

The peak values of terminal current for the 6 MW motor in the different Cases are shown in Fig. 10.

The large synchronous motor requires larger relative control voltages (Figs. 11 … 14) than the small cage induction motor. The electromagnetic coupling between the lower control harmonic and the damper winding is weak and there is not such a large retarding torque as in the case of the induction motor. However, such an effect might appear at the mHz range of frequencies. The turning of the curves in Figs. 13 and 14 hint to this direction. Studying torsional vibrations within the mHz range would require very long simulations. They are left out from this paper.

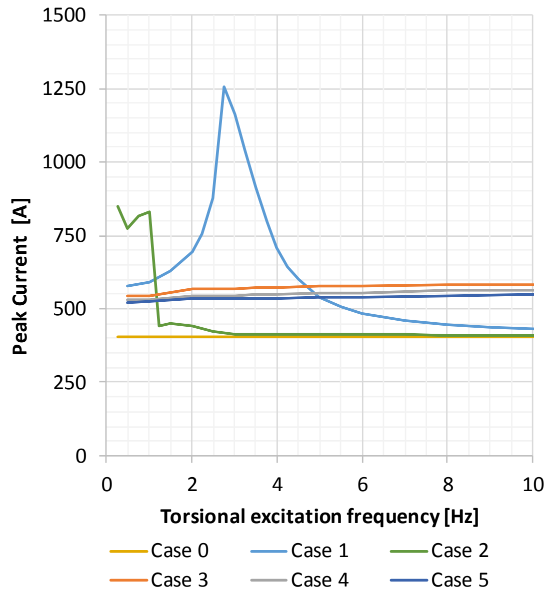

Fig. 10. Peak values of terminal currents of the 6 MW motor for the different Cases studied.

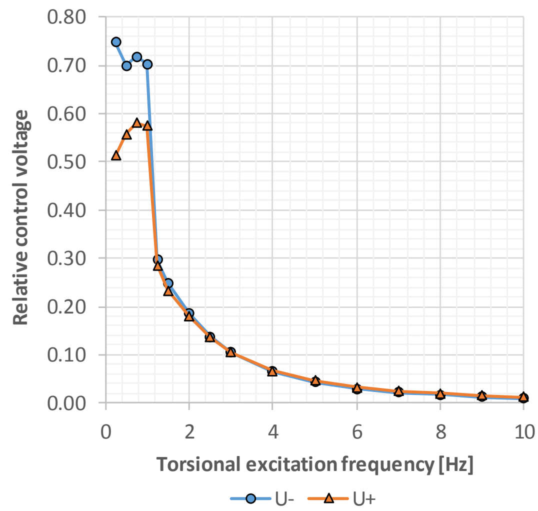

Fig. 11. Amplitudes of voltage harmonics needed to suppress the first-order vibration harmonics from the stator current of the 6 MW motor (Case 2).

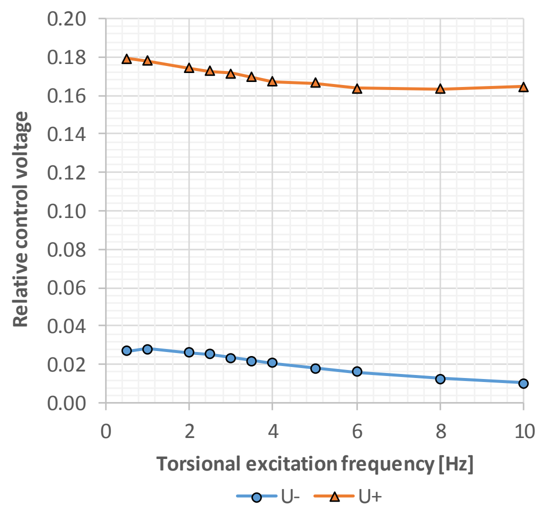

Fig. 12. Amplitudes of voltage harmonics needed to suppress the torsional vibration and lower current harmonic of the 6 MW motor (Case 3).

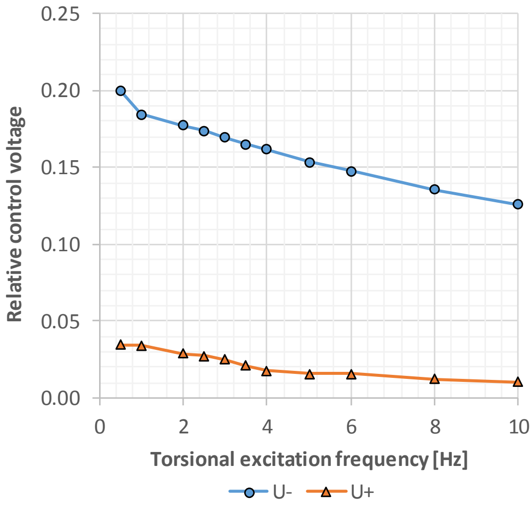

Fig. 13. Amplitudes of voltage harmonics needed to suppress the torsional vibration and upper current harmonic of the 6 MW motor (Case 4).

Both of the vibration harmonics are alone valid for vibration control but, as mentioned, the control voltage has to be relatively large (Figs. 12 … 13).

Comparison of the results in Figs. 12 and 13 shows that using the lower vibration harmonic $f_s - f_v$ as the control variable (Case 4) requires a larger voltage at low excitation frequencies than the other case. The situation changes at the larger excitation frequencies. This is simply related to the fact that at the smaller harmonic frequency $f_s - f_v$ a smaller voltage is enough to drive a certain current and produce a certain harmonic torque than at the higher frequency $f_s + f_v$.

When the two vibration harmonics $f_s \pm f_v$ are used simultaneously as control variables, the minimum losses are found and the relative control voltages remain smaller (Fig. 14) than in the other two vibration suppression Cases 3 and 4 (Figs. 12 and 13).

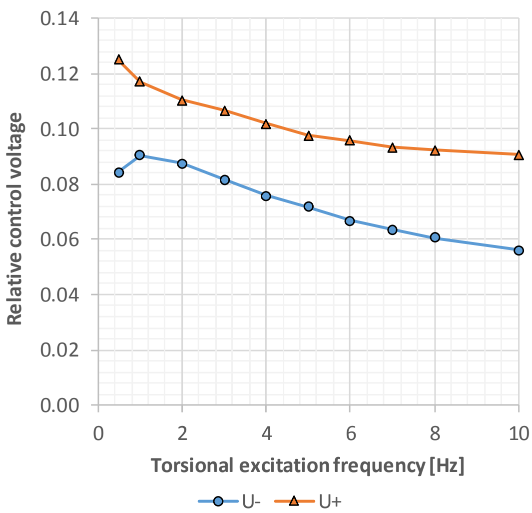

Fig. 14. Amplitudes of voltage harmonics that suppress the torsional vibration and lead to the minimum electromagnetic loss of the 6 MW motor (Case 5).

IV. Discussion

The losses and currents in Figs. 1, 3, 8 and 10 clearly indicate that something has to be done if a large torsional excitation occurs close to the natural frequency of the rigid-body mode. The losses are so high that the machines would not stand them thermally. Furthermore, the harmonics of line currents grow so large that the requirements on current distortion set by standards are not fulfilled [15]. Tables II and III show loss segregation for the two motors without and with a torsional excitation at the rigid-body resonance frequency, 17.5 Hz for the smaller motor and 2.75 Hz for the larger one. The amplitude of excitation is half of the rated torque.

TABLE II
Losses in different parts of the 37 kW motor [W]

	No torsional excitation	Excitation at resonance
Resistive loss in stator winding	1141	2180
Core loss in stator	560	595
Resistive loss in rotor cage	755	1848
Core loss in rotor	145	161
Total electromagnetic loss	2602	4784

TABLE III
Losses in different parts of the 6 MW motor [kW]

	No torsional excitation	Excitation at resonance
Resistive loss in stator winding	51.6	186.4
Core loss in stator	24.0	24.0
Resistive loss in field winding	33.1	41.9
Resistive loss in damper cage	1.7	68.4
Core loss in rotor	7.2	8.9
Total electromagnetic loss	117.5	329.7

A loss reduction method that seems to suit for all excitation frequencies is to use both the current harmonics $f_s \pm f_v$ for suppressing the amplitude of torsional vibration to zero. If an optimal combination of the two harmonics is used, the total electromagnetic loss can be kept within 10% of the case without torsional excitation. This result was obtained for a large excitation having an amplitude of half the rated torque. The 10% increase in losses may force to a slight reduction of the rated power of the machine.

Another potential solution could be to use the voltage supply to force the first-order vibration harmonics of current at frequencies $f_s \pm f_v$ to zero. From loss point of view, this would be an almost perfect solution in the frequency range around the natural frequency of the rigid-body mode. However, this method reduces the natural electromagnetic vibration damping of the machine and the vibration amplitudes may grow very large at low excitation frequencies. This method can be recommended for a restricted frequency range, only.

It is also worth noting that the proposed control Cases 2 - 5 give better results from the loss point of view than just using a sinusoidal voltage and letting the machine vibrate at a frequency close to the rigid-body resonance (Case 1).

What comes to the power supply, the generation of the excitation signal can be easily implemented in the control algorithms of a standard frequency converter. The harmonics can be added, e.g. in the voltage reference that is supplied to the pulse-width modulator that generates the control signals of the power semiconductors. The switching frequency is needed to be one order over the highest generated frequency component. The standard frequency converters use a switching frequency of 2 … 16 kHz, which is sufficient for the cases discussed in this paper. However, the effect of harmonic content on the amplitude of the output voltage must be considered and a sufficient margin to the maximum available voltage of the converter must be left. The harmonic components increase the peak and rms values of the current (Figs. 3 and 10). This has to be taken into account when selecting the current rating of the frequency converter.

It is significant that the rotor oscillations can be reduced by suppressing the current harmonics $f_s \pm f_v$. There is no need for additional torsional vibration sensors or actuators. In the past, the active vibration control of torsional drivetrains has been a separate topic with its own goals. In this paper, the alternative strategies of vibration control are considered simultaneously with electrical effects. The obtained results show that an optimal solution can be found to combine these separate goals.

This study was done using time-discretized finite-element analysis. The aim was to get reliable estimates of the additional losses of the electrical machines associated with the torsional vibration. This particularly concerns the core losses. If we were only interested in the vibration harmonics of voltage, current and speed, about similar results would have been obtained much faster from circuit models of the electrical machines, such as space-vector or two-axis models. Some care should have been taken in the choice of the model parameters, as the vibration amplitudes are so large in some cases that the magnetic non-linearity of the machine makes also the vibration non-linear.

The method of loss analysis was validated for the 37 kW motor in [3]. No further validation is given in the present paper. The largest difference between the measured and computed total electromagnetic losses of the machine was 9%. This occurred well below the rigid-body resonance at a torsional excitation frequency of 4 Hz.

V. Conclusions

Time-discretized finite element analysis was used to study how to reduce the relatively large additional losses of electrical machines in torsional vibration at low frequencies. The most general way of loss reduction was obtained by using the vibration harmonics of the current to suppress the torsional vibration and simultaneously search for the minimum electromagnetic loss. If the vibration occurred very close to the rigid-body natural frequency, it was worth to force both the vibration harmonics of current to zero and thus obtain the smallest loss. This control strategy reduces both the torsional oscillations and the additional losses, which are traditionally considered as two separate goals.

The control of vibration harmonics can be implemented in the control algorithms of a standard frequency converter. The switching frequency should be high enough compared to the maximum frequency content and the maximum available voltage of the converter has to be considered when adding the harmonic content to the output voltage. The current rating of the frequency converter must be high enough to supply the peak values of the currents increased by the vibration.

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VII. Biographies

Antero Arkkio was born in Vehkalahti, Finland in 1955. He received his M.Sc. (Tech.) and D.Sc. (Tech.) degrees from Helsinki University of Technology in 1980 and 1988. Currently he is a Professor of Electrical Engineering at Aalto University. His research interests deal with modeling, design, and measurement of electrical machines.

Eemeli Mölsä received the B.Eng. degree in electrical engineering from Metropolia University of Applied Sciences, Helsinki, Finland in 2012 and M.Sc.(Tech.) degree in electrical engineering from Aalto University, Espoo, Finland in 2015. He is currently working toward the D.Sc.(Tech.) degree at Aalto University. His main research interest is the control of electrical drives.

Timo P. Holopainen received his M.Sc. (Tech.) and D.Sc. (Tech.) degrees from Helsinki University of Technology in 1987 and 2004. He has worked for ABB Motors and Generators since 2004. Currently he is a Senior Principal Engineer and his research interests deal with rotordynamics and vibration control of large electric machines. He is a member of the IFToMM Technical Committee for Rotordynamics.