Electromagnetic processes during phase commutation in field regulated reluctance machine

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Abstract. The processes of currents switching in stator windings have been explained by the existence of the electromagnetic torque ripples in the electric drive with the field-regulated reluctance machine. The maximum value of ripples in the open loop control system for the six-phase machine can reach 20 percent from the developed electromagnetic torque. This method allows one to make calculation of ripple spike towards average torque developed by the electromotor for the different number of phases. Application of a trapezoidal form of current at six phases became the solution. In case of a less number of phases than six, a ripple spike considerably increases, which is inadmissible. On the other hand, increasing the number of phases tends to the increase of the semiconductor inverter external dimensions based on the inconspicuous decreasing of a ripple spike. The creation and usage of high-speed control loops of current (HCLC) have been recommended for a reduction of the electromagnetic torque’s ripple level, as well as the appliance of positive current feedback in switching phase currents. This decision allowed one to receive a mean value of the torque more than 10%, compared to system without change, to reduce greatly ripple spike of the electromagnetic torque. The possibility of the electric drive effective operation with FRRM in emergency operation has been shown.

1. Introduction

There is a change of stator currents that causes ripple of the electromagnetic torque in the field regulated reluctance machine (FRRM) at the turn of the rotor. The power-angle diagram of motor $T = f(\beta)$, recorded at the fixed value of current in stator windings, has two periods on a turn (figure 1, curve 2) [1, 2].

Upon rotation of the rotor, windings sequentially switch and pass from an excitation band to the armature zone. The curve of the electromagnetic torque during the function of rotor turn angle ($\beta$) goes on a family envelope of the power-angle diagram. Power-angle diagrams are displaced relatively each other at a size of a phase zone. This zone is equal to 30 degrees (for six phases) (figure 1, curve 2) [3]. The maximum value of ripples in the open-loop system scheme for the six-phase of the machine can reach 20% of the developed electromagnetic torque. In addition, in case of a supply FRRM from the semiconductor converter, because of the final response time of both the semiconductor converter and control system components, the original pattern of the ripples will be distorted (fig. 1) that can lead to further increasing of ripple spike amplitude. Therefore, in case of...
control system development, it is necessary to produce efforts to crack down on ripples. Questions about electromagnetic torque ripples in the semiconductor converter have been considered in the modern literature without an instruction on specific techniques for accounting this effect [4]. There are also no practical recommendations for reduction of this effect.

### 2. A design model of the electric drive

One of the most suitable methods for the analysis of processes in the electric drive with the FRRM is the method of winding functions [5]. This method allows one to make calculation of the ripple spike amplitude regarding the average torque developed by the electromotor for the different number of phases. This calculation is valuable also because such experimental research requires 5-8 different construction of electrical machines that complicates experimental conditions. For this reason, computing has been conducted for the first stage, which consists in a research of influence of the number of phases. In addition, the experimental research was conducted at the second stage, which consisted in a research of influence of the control system response time. The following was accepted as initial criteria for computing electromagnetic torque ripples:

- computing has been executed for two cases of the current waveform in a winding of each phase of the stator: trapezoidal and sinusoidal. In the first case, the current reverse operation time in each phase corresponded to the width of a phase zone of the stator. This case corresponded to a supply of phase windings from an individual current source (ICS). In the second case, the current waveform corresponded to a normal sine curve;
- a moment of commutation has been chosen for reaching the maximum average integral electromagnetic torque;
- the magnetic system was not saturated;
- value of a polar arc was accepted to be equal to half of the value of polar pitch of the machine;
- the number of stator slots is equal to 48.

Values of these ripples depending on the phases number of a winding are shown in figure 2. Ripples of the electromagnetic torque were made from 80% to 15% of the trapezoidal waveform current (fig.2, curve 1). For a sinusoidal current in phase windings, torque ripple made from 40% to 2% (fig 2, curve 2).

![Figure 1. Power-angle diagram of motor.](image1)

![Figure 2. Amplitude of moment pulsations as a function of the number of phases: 1 – trapezoidal waveform current; 2 – sinusoidal waveform current.](image2)
Application of a trapezoidal form of current at six phases became the solution. Torque ripple in this case made 20%. In case of the phases number fewer than six, a ripple spike considerably increases, which is inadmissible. On the other hand, an increase in the number of phases leads to the increase of equipment, with a slight decrease in the amplitude of ripples.

In the literature about FRRM, one of the main assumptions in researches [6] is that current in a phase switches instantaneously. Let us consider that in case of optimal adjustment of the electric drive and a finite number of phases \( m=6 \), the ripple spike amplitude depends on the switching time of a phase current in each of windings and on its value. This question was considered most noticeably in case of a supply of the stator windings rectangular current waveform as in this case the front of current change when switching the steepest. Let us consider further that the switching time was the time of current, rising from zero to the preset amplitude value, when switching phases taken separately. In figure 3, the type of the oscilloscope pattern of two-phase currents at the time of switching is shown. Here lag time \( t_1 \) shows the program lag time between switching caused by the response time and correctness of the phase currents generated block (PCGB); building-up time \( t_2 \) shows the response time of current in a phase determined by the rate of response of a control loop of current. For achievement of a minimum of electromagnetic torque ripples, it is necessary to achieve the minimum value of the designated time constants. This circumstance requires an increased rate of the response of the control system and current of the control loop. On the other hand, there is an opportunity to compensate torque "dip". It can be done if one will uprate artificially the value of phase current before switching. For this purpose, it is possible to enter the springy positive current feedback working depending on indications of the rotor position sensor [7].

![Figure 3. Phase currents at time of switching](image)

To check experimentally the suggestion and to estimate values of \( t_1 \) and \( t_2 \) in the real electric drive, the experimental oscilloscope was made for the sample of the phase current prototype of the electric drive with the FRRM. The experimental research was made for windings supplied from ICS "Maxi-Maestro".

3. Creation of control system
For reducing the electromagnetic torque ripple influence, it has been offered to use the springy positive compensating feedback on the current phase realized in the program way in the microcontroller control system. Similar feedback works functionally according to the following algorithm: the compensating couple is turned off when the rotating element reaches the provision of switching. In case of research of the compensating couple, the following parameters were chosen: the relevance of the reference current signal amplitude of a phase \( U_{CUR} \) towards the signal amplitude, and the coordinate of a rotor, in case of which there is a switching on of a compensation signal. During the experimental study, as the sensor in the situation is the absolute encoder with permission of 256 pulse signal; therefore, the compensating couple varied also at the moment of switching on a signal of correction and was used as \( P_K \), which was counted by the number of pulse signals till the moment in which there is a switching of currents of phases \( P_F \).
Dependence of the first harmonic amplitude of ripple on the amplitude of the compensation \(U_K\) signal is shown in figure 4. Curve 1 corresponds to \(P_K = 1\); pulse signal - to \(P_F\); curve 2 - \(P_K = 2\), pulse signal - to \(P_F\); curve 3 - \(P_K = 3\), pulse signal - to \(P_F\). From the figure, it is visible that three points are optimum: \(P_K = 1, U_K = 10\%\); \(P_K = 1, U_K = 15\%\); \(P_K = 2, U_K = 10\%\). From three of these options, let us take the first of them at the beginning. In this case, action time \(U_K\) and its amplitude are the smallest; therefore, the effective value of stator current will be also smaller. To monitor the influence of the current delay time in phase \(t_4\) on the ripple of the electromagnetic torque, let us change experimentally the response rate of a control loop of current (CLC). Thus, by changing the time of current delay, let us fix, at the same time, the mean value of the torque on a FRRM shaft by means of the load machine. Since optimal adjustment of a control loop was accepted by one of the initial experiments conditions, let us change the delay time from 1 msec to 50 msec. (figure 5) [8].

**Figure 4.** Dependence of the amplitude of the first harmonic on the amplitude of the correction signal

**Figure 5.** Dependence of the torque amplitude pulsation on the shaft on the current time lag

Dependence of the first harmonica amplitude of ripple \(A\) on delay time \(t_4\) has been considered. Three options of operation of the electric drive were compared: in the first option, the compensating couple was absent (figure 5, curve 1). In the second case, the compensating couple influenced only in the disconnected current period (negative-going edge) (figure 5, curve 2). In the third case, the compensating couple influenced both the negative-going edge and the building-up edge (figure 5, curve 3).

In case of switching time lasting up to 5 microseconds, the ripple spike of the torque was shown slightly, but by the time of switching, was equal to 50 microseconds. The value of ripples reaches a notable value and can lead to low-quality operation of the electric drive. It completely confirms a hypothesis of increasing in the ripple of the torque by the imperfect operation of a CLC [9].

Let us consider that the switching time of current depends on the response rate of a CLC [10]. One should accept that the maximum value of delay time \(t_4 = 5\text{ms}\) in case of the ripples spike is smallest. It corresponds to the cutoff frequency of CLC necessary for elimination of a negative impact of the electromagnetic torque ripple of an order of 200 rad/s. This argument speaks also in favor of the functional diagram with ICS, which has the maximum rate of response of CLC among other versions of main circuits.

Concerning the compensating couples, it is possible to conclude that compensation on two fronts (negative-going edge, building-up edge) allows one to receive the mean value of the torque by 10% bigger than in the system without compensation in case of high values \(t_4\). Therefore, application of the compensating feedback is most effective for control systems, in which there is no opportunity to implement a high-speed control loop of speed. In this case, one can achieve the greatest efficiency of the compensating feedback, and noticeably reduce the ripple spike of the electromagnetic torque. The field research includes only the static modes, the ripple spike can increase in the transient response [11]. Therefore, use of the compensating couple is expedient for systems with a high-speed control loop. However, application of high-speed compensating couples will demand appliance of reliable devices of analog digital conversion, which exact indices can be considerably improved by application of elements constructed on the principles of the sweeping conversion of a signal.
4. Values of the torque ripple in emergency operation modes
The possibility of effective operation in emergency modes is the essential advantage of any electric
drive. The increased reliability and functionality of multiphase electric drives in comparison with a
three-phase one was shown in the modern publications, and opportunities for increasing the reliability
of operation of the alternating-current drive were specified [12].

Let us consider influence of failures on the electric drive characteristics with FRRM. One should
understand switch-off of a phase windings part as "failures". In case of switch of each winding off the
source, the electric drive will save working capacity. At the same time, loading will be redistributed
between remaining phases. The authors will not consider short circuits because in this case the fuse
disconnects a phase winding.

Let us consider step by step the switch-off of one, two, three, and four phase windings by the
example of the six-phase electric machine with a value of a polar arc equal to 0.5, powered from the
ICS. Let us take the trapezoidal form of current. In case of simulation, the authors supported such time
rating in case of which the value of effective phase current in working phases will be rated ($I = I_N =
const$).

Let us consider the quality rating of the operation:
- mean value of the electromagnetic torque during commutation $T$ in the relative units;
- the relative value of the electromagnetic torque ripple $A_M/T$.

In case of switch-off of one phase, the electromagnetic torque mean value decreases to 60%. The
relative value of this torque ripple increases 1.5 times.

In case of switch-off of two-phase windings, the operation mode of the disconnected phases is
equidistant from each other and optimum. In this case, the mean value of the electromagnetic torque of
quite normal time rating decreases twice. The relative value of this torque ripple increases 1.5 times.
The most unfavorable is the time rating when the disconnected phases are located by a row with each
other. In this case, the mean value of the electromagnetic torque of rather normal time rating decreases
three times. The relative value of this torque ripple increases 2.5 times.

In case of three-phase windings switch-off, the time rating when the disconnected phases are
equidistant from each other is optimum. In this case, the mean value of the normal time rating
electromagnetic torque decreases 4 times. The relative value of ripple of this torque increases 1.6
times. The most unfavorable time rating is the one when the disconnected phases are located by a row
with each other. In this case, the mean value of the electromagnetic torque of rather normal time rating
decreases 7 times. The relative value of this torque ripple increases 6 times.

In case of switch-off of four phase windings, the time rating when the disconnected phases are
equidistant from each other is optimum. In this case, the mean value of the electromagnetic torque of
rather normal time rating decreases 9 times. The relative value of this torque ripple increases 3.5
times. The most unfavorable time rating is the one when the disconnected phases are located by a row
with each other. In this case, the mean value of the rather normal time rating electromagnetic torque
decreases 27 times. The relative value of this torque ripple increases 12.5 times.

The increase of the level of the ripple of the electromagnetic torque increases the level of surface
heating of the rotor [8].

5. Conclusion
For suppression of ripple, the methods consisting in the change of the electrical machine construction
and a method affecting the change of structure of the control system, the electric drive has been
offered.

During computing, it has been defined that taking into account the cost of the electric drive, mass-
dimensional and energetic indices are the number of phases equal to six. In emergency operation
modes, in the process of increasing the number of turned off phase windings, the mean value of the
electromagnetic torque decreases monotonically and reaches 10% of the rated value in case of failure
of four out of six windings.
Summing up the result of the experimental research of the electromagnetic torque ripple, the authors can formulate the main results of the conducted research. As the results of the research, it is possible to recommend creation and use of high-speed CLC (cutoff frequency \( \geq 200 \text{rad/s} \)) as means of the electromagnetic torque suppression of ripple. Secondly, application of springy positive current feedback when wiring phase currents, an alternative current can be provided in case of impossibility of high-speed CLC creation. In addition, these two methods can be shared.

Electric drives with FRM can be recommended for objects with heavy duty operating conditions and for those technological mechanisms in which it is required to solve problems of energy saving [6].

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