Monitoring and control of the protection system of electric drives with the method of pulse-width modulation

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Abstract. This article deals with increasing the stability of power supply by improving the protection and control of electric drives using the pulse-width modulation (PWM) method. The method consists in the formation of periodic series of pulses of a certain duty cycle, creating separately positive and negative half-waves of the current sinusoid in the motor windings. The PWM method of base vectors (vector modulation) consists in switching between several pre-selected states of the inverter, each of which corresponds to a certain spatial position of the resulting voltage vector applied to the engine. In the PWM method, each phase zone is divided into 3 subzones with its own duty cycle. This method is suitable for both three-stage inverter and six-stage inverter. It can be seen in the work that the quality of the resulting current depends not only on the number of subzones for the formation of base vectors, but also on the number of voltage pulses per subzone. The more pulses fall on the formation subzone, the cleaner the resulting current curve is.

1 Introduction

In recent years, there has been a tendency in the power supply system to increase the number of phase breaks in the supply network, due to the high wear of power lines. This further contributes to a decrease in the operational reliability of electric motors and a deterioration in the stability of the power supply. Such problems are revealed in case of poor-quality power supply to consumers, as well as the lack of devices that allow the electric drive to remain operational with asymmetry of the supply voltage, reduce the operational reliability of electric motors and lead to significant technological damage. The reliability of electric motors and the deterioration of the stability of the power supply can be solved by monitoring and controlling the electric motor protection system. In this regard, the task of developing control and management of a protection system using magneto-modulation sensors with pulse-width modulation is relevant. Pulse-width modulation (PWM) is a method of generating three-phase sinusoidal current in the windings of three-phase asynchronous electric motors when used as a DC voltage source. The method consists in the formation of periodic series of pulses of a certain duty cycle, creating separately positive and negative half-waves of the current sinusoid in the engine windings. The conversion of direct current into alternating three-phase

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is carried out using a transistor inverter. The method of pulse-width modulation of base vectors (vector modulation) consists in switching between several, pre-selected states of the inverter, each of which corresponds to a certain spatial position of the resulting voltage vector applied to the motor (Figure 1). Having six base vectors that are shifted in space by 60 electrical degrees (Figure 2), it is possible to reproduce any required switching output voltage vector on the PWM period between the two base vectors of the current sector U_X and U_{X+60}. Figure 3 shows the generation of a three-phase voltage using PWM. All three phases of the voltage generated by the inverter are presented, and the phase currents that occur in the motor windings when connected according to the Y scheme. The linear currents of the electric motor connected according to the Δ scheme will also look.

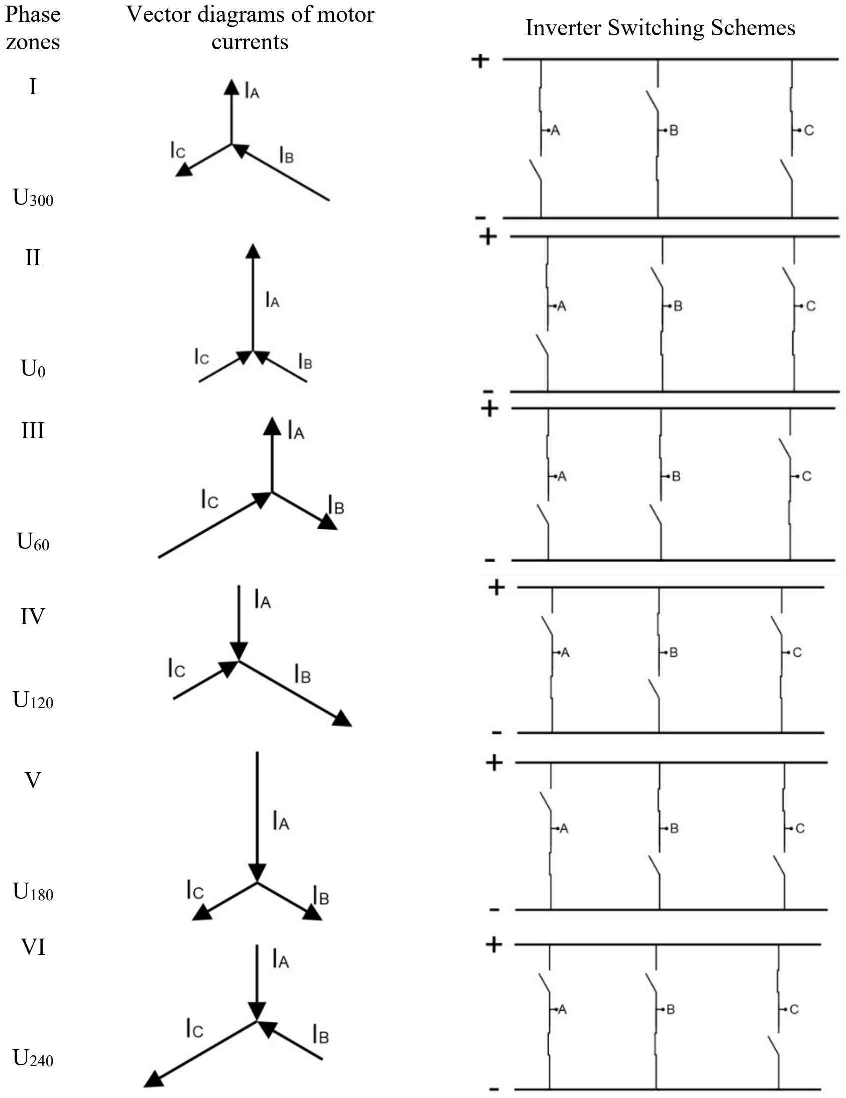


Fig. 1. Switching circuits of the inverter keys when forming the basic vectors of voltages and currents in the windings of an asynchronous electric engine connected according to the star (Y) scheme and the classic six-zone PWM.

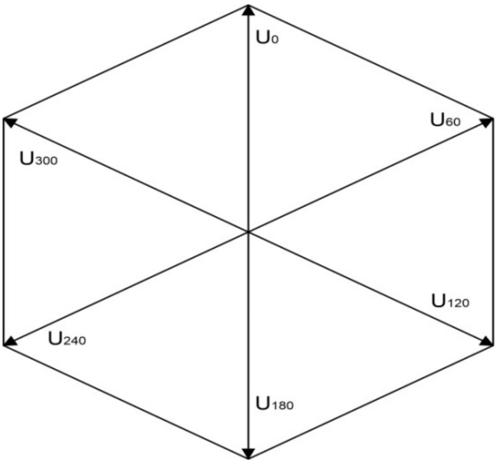
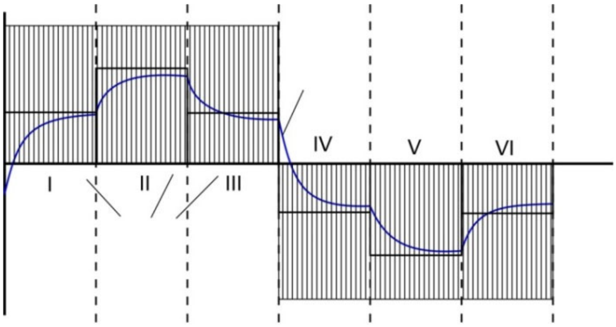


Fig. 2. Base vector modulation.

2 Materials and methods

Figure 4 shows simplified equivalent circuits for the engine windings when connected according to the Y and Δ scheme, explaining the origin of the current curves shown in Figure 3 and Figure 6. Based on the equivalent circuits shown in Figure 4, it is possible to determine the linear saturation currents in phase zones (zones of formation of base vectors), for example, for phase A of the inverter. Linear saturation currents in the first phase zone of phase Φ of the inverter for circuits Y and Δ, respectively, are determined from the expressions

$$I_A = 0.5\frac{U_{inv}}{Z/2} \quad \text{and} \quad I_A = 0.5\frac{U_{inv}}{Z+Z/2} \tag{1}$$



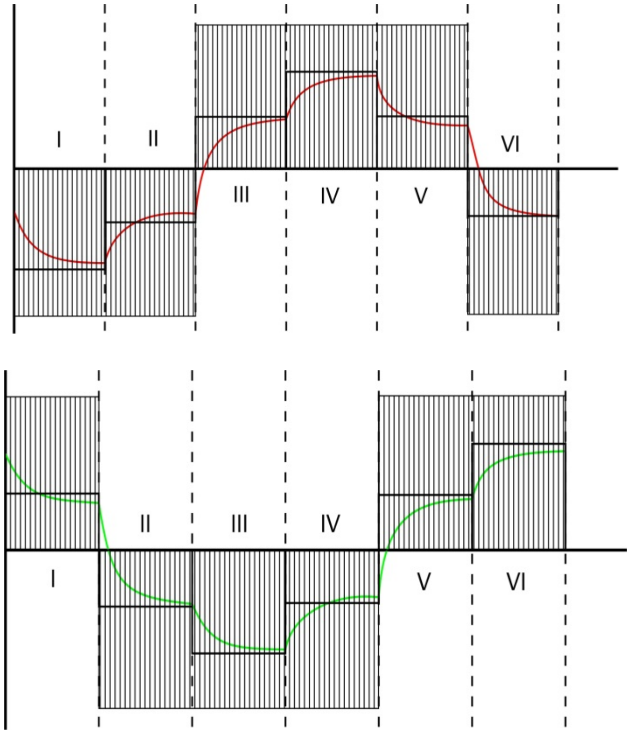


Fig. 3. The voltage shape at the inverter terminals and the shape of the linear currents flowing in the electric motor when the windings are connected according to the Y and Δ scheme.

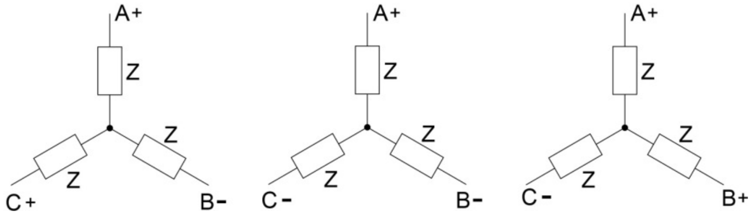


Fig. 4. Equivalent circuits of the motor windings when connected according to the Y scheme.

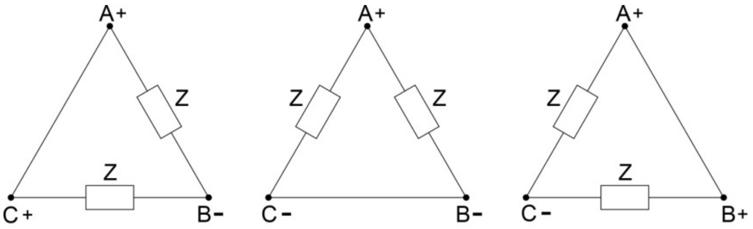


Fig. 5. Equivalent circuits of the motor windings when connected according to the scheme Δ.

Linear saturation currents in the second phase zone of phase A of the inverter for circuits Y and Δ, respectively

$$I_A = \frac{U_{inv}}{Z/2} \text{ and } I_A = \frac{U_{inv}}{Z+Z/2} \tag{2}$$

Linear saturation currents in the third phase zone of phase A of the inverter for circuits Y and Δ, respectively, are determined from the expression

$$I_A = 0.5\frac{U_{inv}}{Z/2} \text{ и } I_A = 0.5\frac{U_{inv}}{Z+Z/2} \tag{3}$$

Where I_A – line saturation current for inverter phase A;

U_{inv} – voltage on tire inverter;

Z_a – engine winding impedance.

Although the engines are only connected in Y. Figure 6 shows the currents flowing in the motor windings when it is connected according to the Δ scheme. Phase currents and voltages will have some forced dips in the base vector formation zones responsible for the current curve decay.In the AB phase - zones III and VI, in the BC phase - zones II and V, and in the CA phase - zones I and IV. It is these failures that will lead to some loss of engine power. Based on the equivalent circuits presented in Figure 3, it is possible to determine the phase saturation currents in the engine for any winding at any time.

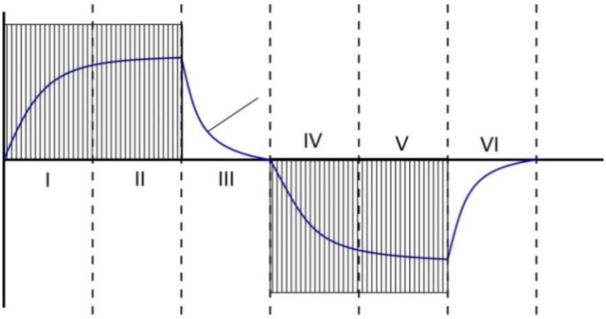
$$I_{ph} = \frac{U_{inv}}{z} \tag{4}$$

Where I_{ph} – phase current in the engine winding.

Let's analyze the PWM - base vector modulation using the example of PWM sinusoidal current in one phase of the motor Y.

3 Results

In Figure 7, 6 zones are clearly expressed, in each zone the duty cycle of the pulses is the same, as a result, a non-sinusoidal resulting current is obtained. Such a picture of the resulting current curve will be in almost all modes and is determined: firstly, by a three-phase system, secondly, by a three-arm voltage inverter shown in Figure 9, and thirdly, by the same pulse duty cycle in all zones.



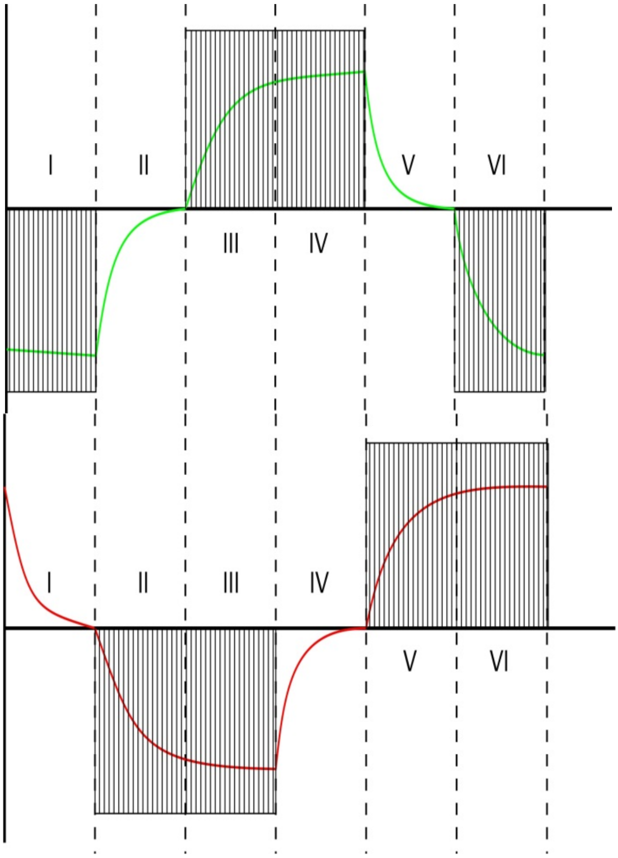


Fig. 6. The shape of the phase voltages and currents generated by PWM for the engine winding connection scheme Δ.

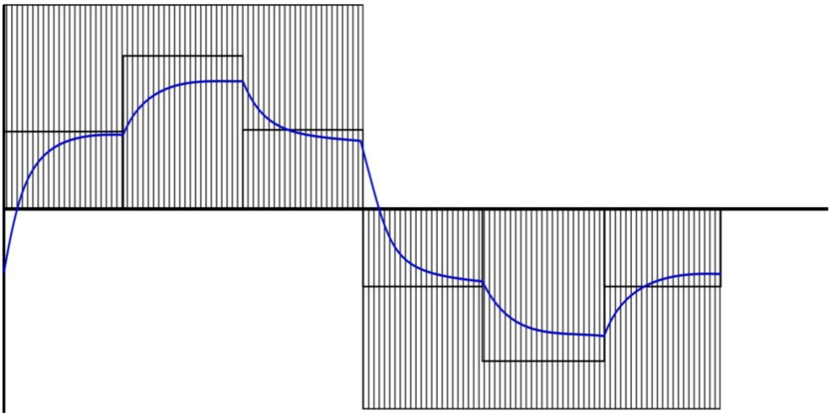


Fig. 7. PWM sinusoidal current in one phase of the engine for a three-arm inverter with the same duty cycle in the zones.

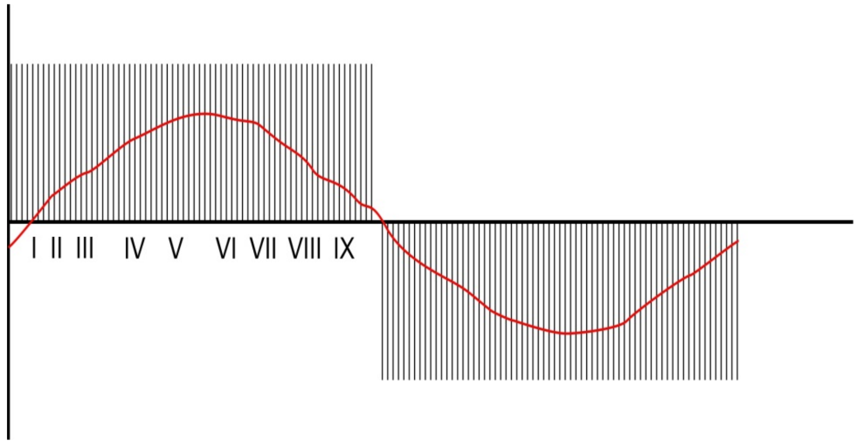
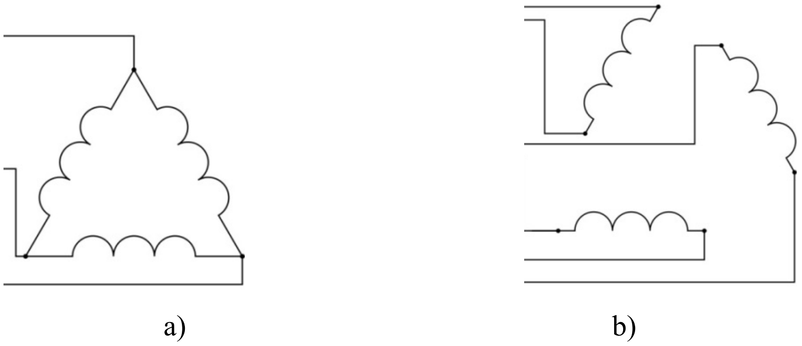


Fig. 8. PWM sinusoidal current in one phase of the motor for a three- stage or six- stage inverter with different duty cycles in the zones.

With classical six-zone switching (Figure 1), a non-sinusoidal curve of the resulting current is obtained, theoretically such a curve is undesirable for the engine, since parasitic components of the higher harmonics of the current, can lead to strong heating of the motor and degrade the moment. Therefore, we consider another method of pulse-width modulation of base vectors. In this method, each phase zone is divided into 3 subzones with its own duty cycle (Figure 8). This method is suitable for both a three- stage inverter (Figure 9) and a six-stage inverter (Figure 9). The use of a six- stage inverter is justified when simulating a engine connection scheme in a triangle (Δ), for the formation of sinusoidal currents in it with minimal harmonic components of higher orders. With 18 subzone PWM, the first three subzones are needed to increase the current, the second three subzones - in which the current has a maximum value and three subzones - for the current to drop to zero. In total, 9 subzones for the formation of a positive half-wave and 9 subzones for the formation of a negative half-wave. The number of subzones per half-wave must necessarily be a multiple of 3, in order to be able to accurately ensure a phase shift of 120^0. Three subzones for current rise and three subzones for current fall are necessary in order for the resulting current to be as close as possible to a sinusoidal one and not to have jumps and zones of imaginary current saturation. Zones of imaginary current saturation arise as a result of the fact that the current in the pulse changes according to the exponential law. If the duty cycle in the step is constant, and the number of steps is small, then the resulting current increases to a certain value until the increase in current per pulse is compensated by the decrease. This compensation will continue until the other stage turns on, with a current surge first, and then a balancing occurs, which also goes into saturation.

Of course, the number of subzones can be more than 18. This will complicate the inverter control system, but a smaller number of subzones is not recommended due to the fact that the resulting currents will have high values of parasitic higher order harmonics.

A system with a six-stage inverter allows you to form a current sine wave with lower values of parasitic harmonic components, compared to a three-stage inverter, but has a higher cost. This is due to the fact that the number of inverting keys doubles, and they organize the bulk of the cost. In addition, the key management system also becomes more complex. Therefore, a system with a six-arm inverter is practically not used.



a) b)

Fig. 9. Voltage inverter circuits: a) three stage voltage inverter; b) six stage voltage inverter.

The quality of the resulting current depends not only on the number of base vector formation subzones, but also on the number of voltage pulses per subzone. The more pulses fall on the formation subzone, the cleaner the resulting current curve is. When designing, such a concept as the PWM carrier frequency is used, or sometimes it is called the PWM duty cycle.

The carrier frequency of the PWM modulation is determined by the formula:

$$F_{PWM} = \frac{n_{sinx}}{z_{PWM}}; \tag{5}$$

Where n_{sinx} – frequency of clock pulses of the PWM signal generation unit.

z_{PWM} - the number of clock pulses for the formation of one PWM period. the number of pulses in the zone (subzone) required to form a sinusoidal current of the required frequency can be determined by the formula

$$Z = \frac{n_{sinx}}{f \cdot Y \cdot z_{PWM}}; \tag{6}$$

Where Z – number of pulses per zone (subzone);

f – output current frequency;

Y – number of zones (subzones).

In order for the PWM carrier frequency not to create parasitic harmonic components, it is necessary that its value reaches several tens of kHz. Moreover, the higher the PWM modulation frequency, the less harmonic components in the modulated current.

Consider the main provisions of the PWM theory related to transients occurring in the motor windings. When a voltage pulse is applied to the motor winding, transient processes will occur at the initial and final moments, described by the formulas:

$$i\,(t) = \frac{E}{R} - \frac{E}{R} e^{\frac{-R}{L} \cdot t}; \tag{7}$$

$$i\,(t) = \frac{E}{R} e^{\frac{-R}{L} \cdot t}; \tag{8}$$

Where E – E.M.F power supply;

R – active resistance of the motor winding;

L – engine winding inductance;

t – time.

It is these transients that underlie PWM, let's consider them in more detail. Suppose at the initial time the current in the motor windings is 0 (Figure 10). When the first pulse is applied to the engine winding, a transient process occurs, described by expression (7). In accordance with this, the current in the motor winding will increase to the conditional value i, then the voltage supply to the winding stops, and the current in the motor winding will begin to change according to expression (8) to the value i_I. Next, the next voltage pulse is applied to the motor winding, a little more than the first pulse, and the current in the motor winding will begin to increase to the value $i_{II} > i_I$. After that, the pulse stops again and for a pause that is slightly less than the first pause, the current in the winding drops to the value $i_{II} > i_I$. So the process continues again and again until the current in the motor winding reaches the required maximum value. After that, the reverse process of formation occurs, the pulses begin to shorten, and the pauses increase, this happens until the current in the motor winding becomes different from zero. Further, the process is repeated only the voltage pulses supplied to the winding have a negative sign. It should be noted that with PWM of a sinusoidal current, the resulting current curves in each zone (subzone) also change according to exponential laws (7) and (8), but taking into account the duty cycle of the pulses in the zone of formation of base vectors and the individual characteristics of the motor. By changing the duty cycle of the pulses, it is possible to change the amplitude of the resulting curve of the generated current.

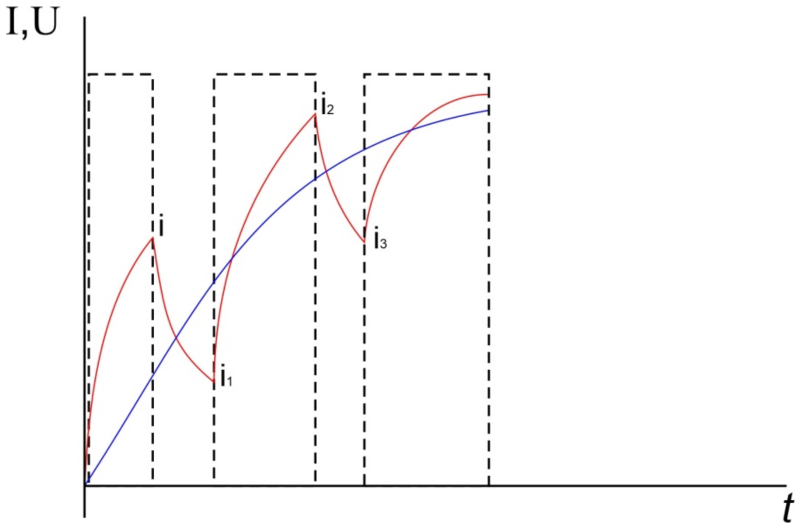


Fig. 10. Transients in the engine winding with PWM.

4 Conclusion

With sinusoidal current PWM with different duty cycles in the base vector formation zones (18 subzone PWM), by selecting the pulse duty cycle individually for each subzone, you can not only change the amplitude of the resulting curve of the generated current, but also bring its shape as close as possible to a sinusoidal one. In conclusion, it should be noted that in order to achieve the set task, to need develop and research a protection and control device for electric motors, which allows them to maintain their performance in the event of an unbalance in the supply voltage. The best way is to convert alternating sinusoidal currents into alternating sinusoidal currents with an intermediate DC link, operating on the principal pulse width modulation. It is necessary to develop a functional diagram of the device and develop algorithms for the implementation of these functions.

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