Two Phase Emergency Feeding of Induction Motors by Injected Currents-Discussion

LUDEK SCHREIER*, JIRI BENDL*, JIRI KLIMA**
*Institute of Electrical Engineering ASCR
*Dolejskova 5, 182 02 Prague 8
**Department of Electrical Engineering and Automation, Technical Faculty, CZU
**Kamycka 129, 165 021 Prague 6
CZECH REPUPLIC

Abstract: - Continuing the paper "Two Phase Emergency Feeding of Induction Motors by Injected Currents-Analysis", attention is focused on a possibility to reduce additional losses and parasitic torques arising as a result of the considered way of stator feeding in the emergency drive operation. It is shown that these undesirable phenomena can be reduced by a convenient choice of phase shift of stator currents.

Key words: - Induction motor, Emergency operation of electrical drives, Additional losses, Parasitic torques

1 Introduction

This paper is the sequel of the paper "Two-Phase Emergency Feeding of Induction Motors by Injected Currents-Analysis" also presented at this conference, where operation of the induction motor after converter reconfiguration due to one converter leg failure was analyzed. Relations for stator and rotor currents and torque in the air gap including parasitic torques arising as a consequence of the considered way of feeding were derived. Cross-references to the preceding paper will be made by referring to numbers of equations and equation numbering will continue here. Quantity denotations and definitions will also be taken over.

According to the preceding analysis, the positive-, negative-, and zero-sequence components of both stator and rotor currents arise at the considered way of feeding. Effective torque, however, is only generated by the positive-sequence component. The negative- and zero-sequence components increase losses in the stator and rotor windings and give rise to parasitic torques. The positive- and negative-squence components are represented by the quantities $\mathbf{i}_{1SP}$ and $\mathbf{i}_{1SN}$, the zero-sequence component corresponds to the quantities $\mathbf{i}_{3SP}$ and $\mathbf{i}_{3SN}$. According to the Eq. (47), magnitude of the quantity $\mathbf{i}_{3SN}$ is in proportion with the constant $\mathbf{K}_{1N}$ defined by Eq. (51). Similarly, according to Eqs. (48) and (49), magnitudes of the quantities $\mathbf{i}_{3SP}$ and $\mathbf{i}_{3SN}$ are proportional to $\mathbf{K}_{3P}$ and $\mathbf{K}_{3N}$ given by Eqs. (52) and (53). From Eq. (51) to (53) follows that such values of the angle φ can be determined that either negative- or zero-sequence components equal zero and so unfavorable influence of either of them can be eliminated. As it will be shown further in the text, complete elimination of one of these components, however, does not have to lead to the optimum solution of the problem mainly from the viewpoint of losses in the windings.

2 Elimination of Zero-Sequence Component

According to Eq. (51), magnitude of $\mathbf{K}_{1N}$ is proportional to the expression in the brackets in the right hand side of this equation. If this expression is

$$\left(1+e^{j2\pi/3}e^{-j\varphi}\right)=0 \tag{77}$$

than $\mathbf{i}_{1SN} = 0$ as well.

Equation (77) holds true for φ = -60°. For this value of φ, it follows from Eqs. (46) and (50)

$$\mathbf{i}_{1SP}=\frac{I_S}{2\sqrt{3}}e^{j5\pi/6}e^{j\omega t} \tag{78}$$

As it is well known, torque of the induction motor in steady state at balanced feeding is proportional to the square of amplitude of stator currents (or their components). According to Eq. (78), magnitude of $\mathbf{i}_{1SP}$ equals $I_S/2\sqrt{3}$, in this case. In steady state before the failure, magnitude of the first symmetrical component $\mathbf{i}_{1S}$ is $I_S/2$ (holds true for $k=1/3$). Therefore, the value of effective torque after converter reconfiguration decreases three times.

Phase shift 60° is proposed for emergency operation in [1]. Let us suppose that the machine before the failure operated with the nominal current and amplitude I_{Sn} and with the nominal torque T_n. If, with regard to the driven device, it is necessary that the machine have to operate with this torque also after the failure, the amplitude of stator currents must increase to $\sqrt{3}\ I_{Sn}$.

Substituting $\sqrt{3} I_{Sn}$ for I_S in Eq. (78) we obtain

$$\mathbf{i}_{1SP} = \frac{I_{Sn}}{2} e^{j5\pi/6} e^{j\omega t} \tag{79}$$

This equation confirms that the effective torque equals to the nominal torque because magnitude of the first symmetrical component $\mathbf{i}_{1S}$ before the failure equals to magnitude of the quantity $\mathbf{i}_{1SP}$ after the failure elimination. For φ = -60° and $I_S = \sqrt{3} I_{Sn}$, the quantities $\mathbf{i}_{3R\lambda P}$ and $\mathbf{i}_{3R\lambda N}$ can be derived from Eqs. (48), (49), (52), and (53) as

$$\mathbf{i}_{3SP} = \frac{I_{Sn}}{2} e^{-j\pi/6} e^{j\omega t} \tag{80}$$

$$\mathbf{i}_{3SN} = \frac{I_{Sn}}{2} e^{j\pi/6} e^{-j\omega t} \tag{81}$$

Magnitude of the zero-sequence component i_{3S} is given by the sum of magnitudes of these quantities. As it follows from Eqs. (80) and (81), the magnitude of i_{3S} equals to amplitude of the nominal current in this case. Losses P_{Sn} in stator winding before the failure can be estimated as

$$P_{Sn} = 3R_S \left(\frac{I_{Sn}}{\sqrt{2}} \right)^2 \tag{82}$$

Losses P_{Sf} after converter reconfiguration may be estimated as

$$P_{Sf} = 2R_S \left(\frac{\sqrt{3}}{\sqrt{2}} I_{Sn} \right)^2 \tag{83}$$

Ratio $P_{Sf} / P_{Sn} = 2$, therefore the machine will operate with double losses in comparison to the operation before the failure. Similar increase of losses can be supposed in the rotor. This 100% increase of the losses is considerable. With such losses, the motor can only work for a short time. Situation in the induction motor in steady state for the phase shift 60° of stator currents will be shown in the following figures. The machine with main parameters in per unit system: $R_S = R_{1R} = 0.02$, $L_{1S} = L_{1R} = 9.55\times10^{-3}$, and $L_{1h} = 9.23\times10^{-3}$ was taken into account. Further the stator winding with nine slots per pole pair and with step shortened by one slot pitch was considered. In this case, the winding factor $\kappa_{1S} \cong 0.945$ and $\kappa_{3S} \cong 0.577$. The winding factors of cage windings may be considered equal to one for simplification. Parameters for the third harmonic can be determined from Eqs. (17) to (19) and from Eqs. (22) to (24). Further, operation with the nominal torque $T_n = 1$ was considered at the nominal slip $s_n = 0\ 02$. The currents of stator windings *B* and *C* are in Fig. 1. At the RMS value of nominal current equal to 1, amplitude of these currents have to be $\sqrt{2}\sqrt{3} \doteq 2.45$.

Figure 2 shows the real $i_{1S\alpha}$ and imaginary $i_{1S\beta}$ parts of the first component of stator currents and their third component. As after the elimination of the components $\mathbf{i}_{1SN}$, $\mathbf{i}_{1S} = \mathbf{i}_{1SP}$, amplitudes of $i_{1S\alpha}$ and $i_{1S\beta}$ before and after the failure equal each other in this case. The real $i_{1R\alpha}$ and imaginary $i_{1R\beta}$ parts of the first component of rotor currents $\mathbf{i}_{1R\lambda}$ and the real $i_{3R\alpha}$ and imaginary $i_{3R\beta}$ parts of the third component of rotor currents $\mathbf{i}_{3R\lambda}$ are in the Fig. 3.

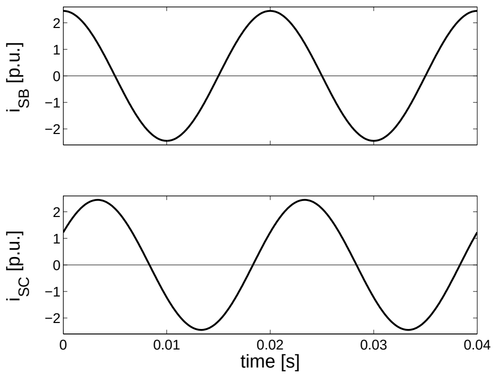

Fig. 1. Stator currents, φ = 60°

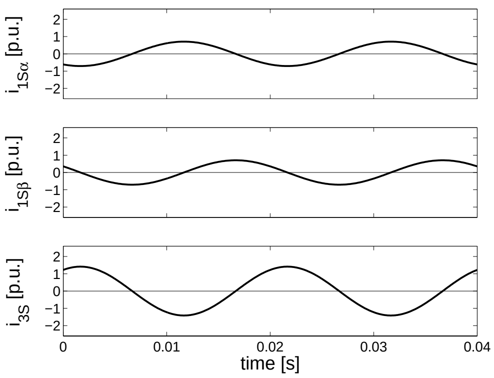

Fig. 2. Components of stator currents, φ = 60°

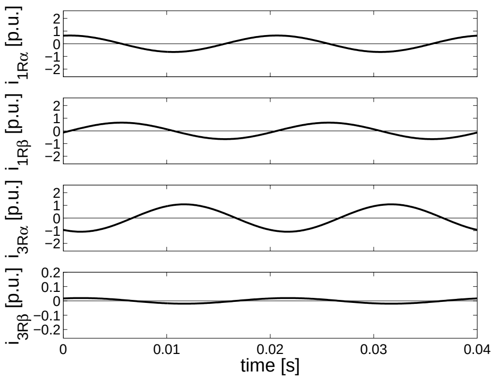

Fig. 3. Components of rotor currents, φ = 60°

Influence of current components on magnetic circuit of the machine can be deduced from magnetization current or from flux in the yoke. According to [2], the first $\mathbf{\Phi}_1$ and third $\mathbf{\Phi}_3$ waves of flux can be derived as

$$\mathbf{\Phi}_1 = \frac{2}{N_S \kappa_{1S}} L_{1h} \left(\mathbf{i}_{1S} + \mathbf{i}_{1R\lambda} \right) \tag{84}$$

$$\mathbf{\Phi}_3 = \frac{1}{N_S \kappa_{3S}} L_{3h}\left(i_{3S} + \mathbf{i}_{3R\lambda}\right) \tag{85}$$

Magnitudes $|\mathbf{\Phi}_1|$ and $|\mathbf{\Phi}_3|$ of the first and third waves of the flux rated to the nominal magnitude of the first flux wave are in Fig. 4. Figure 5 shows flux distribution along the air gap for one pole pair as a function of the polar coordinate α. The curve $\Phi_1(\alpha)$ represents the first harmonic, the curve $\Phi_3(\alpha)$ the third wave and the quantity $\Phi_r(\alpha)$ is the resulting flux in the yoke given by the sum of $\Phi_1(\alpha)$ and $\Phi_3(\alpha)$. The graphs in this figure were calculated for $t = 0$. Figure 6 shows courses analogical to those in Fig. 5 for the time t, when the curve $|\mathbf{\Phi}_3|$ in Fig. 4 reaches the maximum. Magnitude of the third wave of flux is about 10% of magnitude of the first wave.

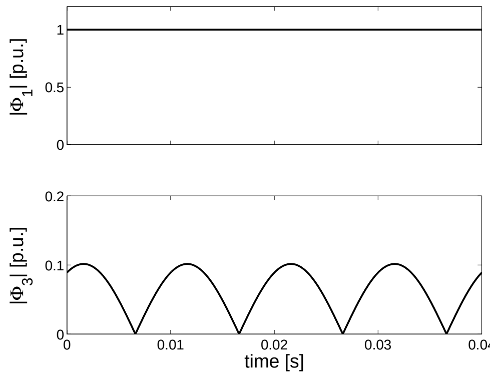

Fig. 4. Magnitudes of flux components, φ = 60˚

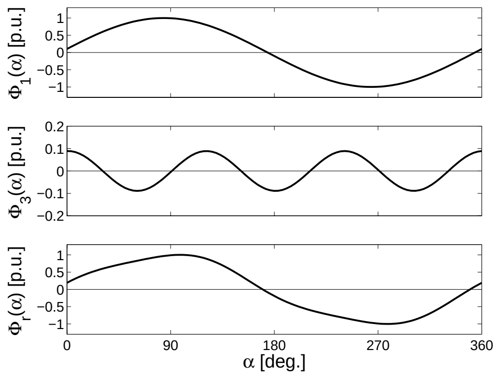

Fig. 5. Distribution of flux along air gap for $t = 0$, φ = 60˚

It may be supposed that flux distortion by influence of the zero-sequence component of stator currents would not change properties of the magnetic circuit and values of inductances L_{1h} and L_{3h} substantially. The components of parasitic torques generated by the third harmonic calculated from Eqs. (73) to (76) are in Fig. 7. Whole torque generated by the first harmonic, whole torque generated by the third harmonic, and resulting torque in the air gap calculated according to Eqs. (32) to (34) are in Fig. 8. Decrease of average value of the resulting torque due to the zero-sequence component of stator currents is only about 1% of the nominal torque. Amplitude of the pulsating component of the torque is also about 1% of the nominal torque. Hence, the influence of the zero-sequence component on the resulting torque of the machine can be neglected.

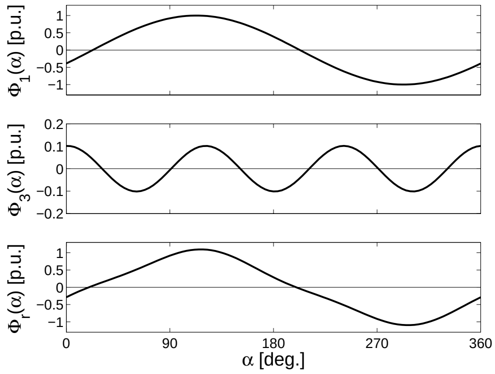

Fig. 6. Distribution of flux along air gap for maximum $|\mathbf{\Phi}_3|$, φ = 60˚

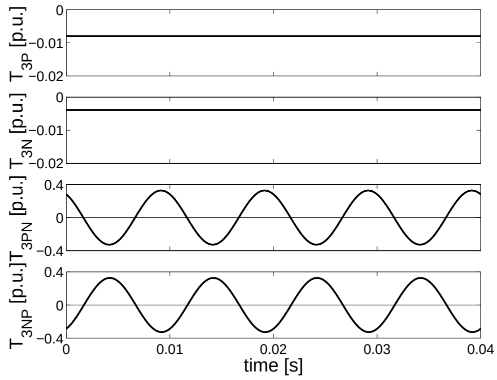

Fig. 7. Torque components T_{3P}, T_{3N}, T_{3PN}, and T_{3NP}, φ = 60˚

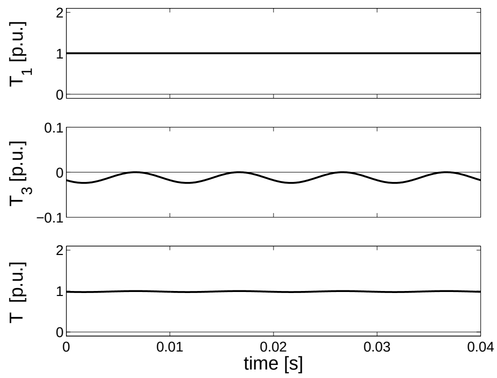

Fig. 8. Torque components T_1, T_3, and resulting torque, φ = 60˚

3 Elimination of Negative-Sequence Component

As it follows directly from Eqs. (52) and (53), the zero-sequence component does not arise for φ = 180˚. The components $\mathbf{i}_{1SP}$ and $\mathbf{i}_{1SN}$ are

$$\mathbf{i}_{1SP} = \frac{I_S}{2\sqrt{3}} e^{j5\pi/6} e^{j\omega t} \tag{86}$$

$$\mathbf{i}_{1SN} = \frac{I_S}{2\sqrt{3}} e^{-j5\pi/6} e^{-j\omega t} \qquad (87)$$

Both the quantities are mutually complex conjugated. Equations (86) and (78) are identical, therefore the identical quantities $\mathbf{i}_{1SP}$ rise in both cases. From the viewpoint of increase of amplitude of stator currents, the same conclusions hold true as in the previous case. Also in this case, the losses increase by 100%. The stator currents and their components are in Figs. 9 and 10. The third component does not arise. As winding of the phase *A* is not flowed by the current and the zero-sequence component is eliminated, the current component $i_{1S\alpha}$ cannot arise. Therefore, the operation of the three-phase induction motor is analogous to the operation of a single-phase machine with opened auxiliary winding in this case.

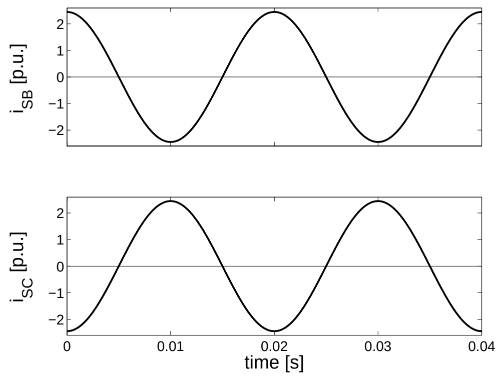

Fig. 9. Stator currents, φ = 180˚

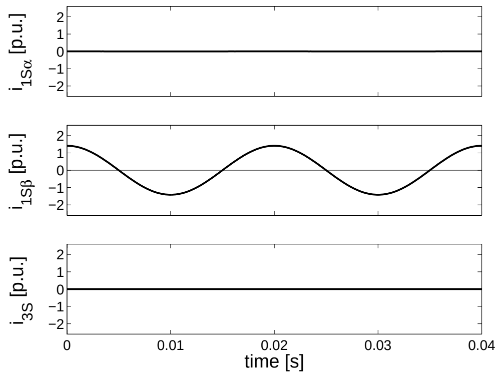

Fig. 10. Components of stator currents, φ = 180˚

Figure 11 shows the course $|\mathbf{\Phi}_1|$ of the first wave of flux in the yoke. The third wave does not arise. Fluctuation in the magnitude $\mathbf{\Phi}_1$ is about 10% of the nominal value and is comparable with flux distortion by the third harmonics. So it may be supposed that similarly as the third flux harmonics, it will not influence the magnetic circuit substantially. Flux distribution along the air gap is sinusoidal and it is not shown. The individual torque components generated by the first harmonics according to Eqs. (69) to (72) are in Fig. 12. Here, the torque given by the sum of these components is also the resulting torque in the air gap shown in the Fig. 13. Decrease of the resulting torque average value due to the braking torque generated by $\mathbf{i}_{1SN}$ is again only about 1% of the nominal torque and can be neglected. Nevertheless, pulsating torques with amplitudes about 100% of nominal torque arise, which can influence the driven device unfavorably. These pulsations can be reduced to some extend by a convenient choice of the angle φ so that the components $\mathbf{i}_{1SP}$ and $\mathbf{i}_{1SN}$ can increase and decrease respectively.

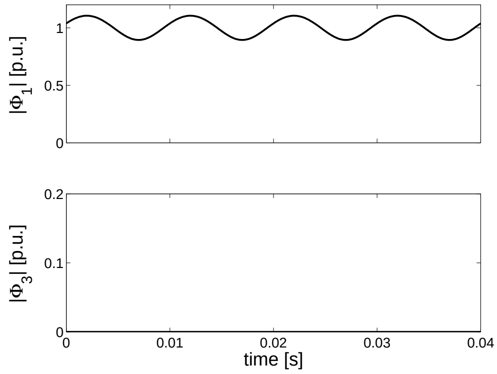

Fig. 11. Magnitudes of flux components, φ = 180˚

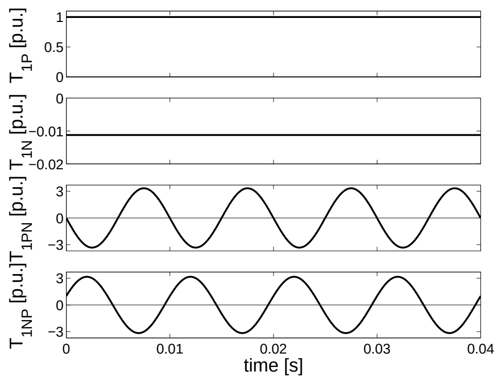

Fig. 12. Torque components T_{1P}, T_{1N}, T_{1PN}, and T_{1NP}, φ = 180˚

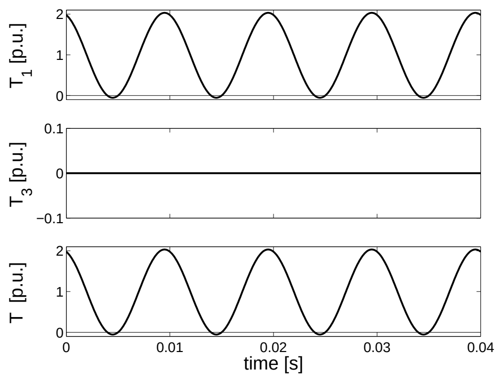

Fig. 13. Torque components T_1, T_3, and resulting torque, φ = 180˚

4 Optimization of Positive-Sequence Component

In order that magnitude of the component $\mathbf{i}_{1SP}$ can reach the maximum, it must hold true according to Eqs. (46) and (50)

$$\left(1+e^{j2\pi/3}e^{+j\varphi}\right)=2 \tag{88}$$

This equation is valid for φ = -120°. Then

$$\mathbf{i}_{1SP}=\frac{I_S}{3}e^{j2\pi/3}e^{j\omega t} \tag{89}$$

$$\mathbf{i}_{1SN}=\frac{I_S}{6}e^{-j\pi/3}e^{-j\omega t} \tag{90}$$

$$\mathbf{i}_{3SP}=\frac{I_{Sn}}{6}e^{-j\pi/3}e^{j\omega t} \tag{91}$$

$$\mathbf{i}_{3SN}=\frac{I_{Sn}}{6}e^{j\pi/3}e^{-j\omega t} \tag{92}$$

So that the machine can generate the nominal torque also after converter reconfiguration, amplitudes of stator currents has to be increased to the value $I_S=(3/2)I_{Sn}$. Losses in stator winding are

$$P_{Sf}=2R_S\left(\frac{3}{2\sqrt{2}}I_{Sn}\right)^2 \tag{93}$$

In this case there is $P_{Sf}/P_{Sn}=3/2$. The losses only rise by 50% here and their increase is a half in comparison to both the preceding cases. It is evident that further decrease of losses by other choice of φ is impossible. Stator currents are in Fig. 14 and their components in Fig. 15.

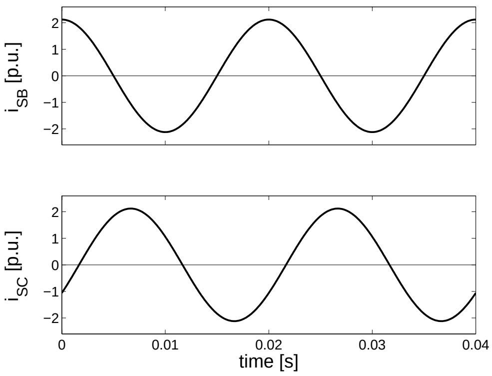

Fig. 14. Stator currents, φ = 120°

Loci of the quantities $\mathbf{i}_{1S}$ and $\mathbf{i}_{3S}$ are in Fig. 16. Locus of $\mathbf{i}_{1S}$ is ellipse due to the negative-sequence component. Flux distortion by negative- and zero-sequence components will be smaller than in the preceding cases because magnitudes of these components decreased. Figure 17 shows the components of the torque generated by the first harmonic. The components of torque from the third wave are in Fig. 18. The whole torques from the first and third harmonics and the resulting torque in air gap are in Fig. 19. The torque of the third harmonic can be neglected. The pulsating torque decreased by a half in comparison to the preceding case. Therefore its possible unfavorable influence on the driven device is reduced.

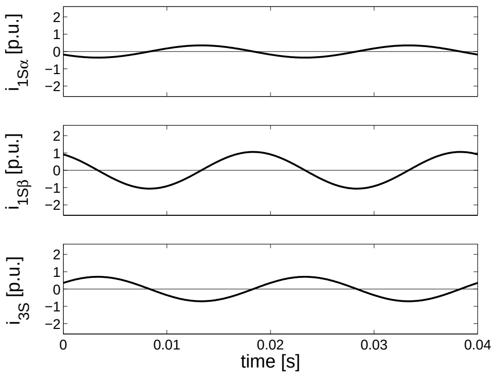

Fig. 15. Components of stator currents, φ = 120°

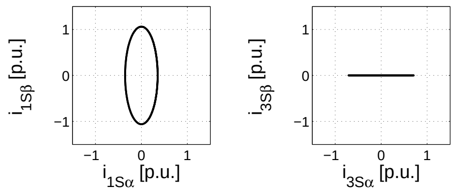

Fig. 16. Loci of the first and the third stator current components, φ = 120°

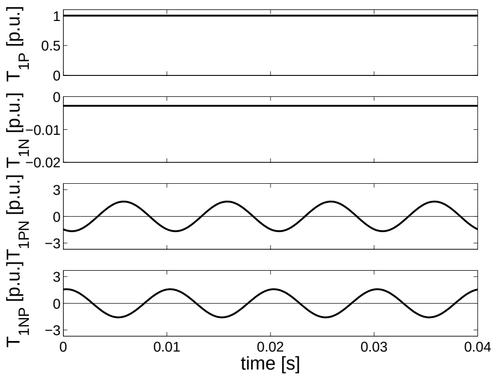

Fig. 17. Torque components T_{1P}, T_{1N}, T_{1PN}, and T_{1NP}, φ = 120°

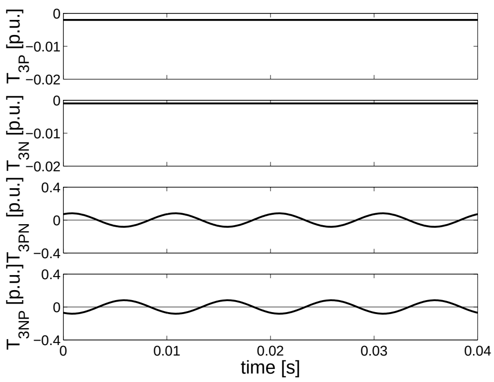

Fig. 18. Torque components T_{3P}, T_{3N}, T_{3PN}, and T_{3NP}, φ = 120°

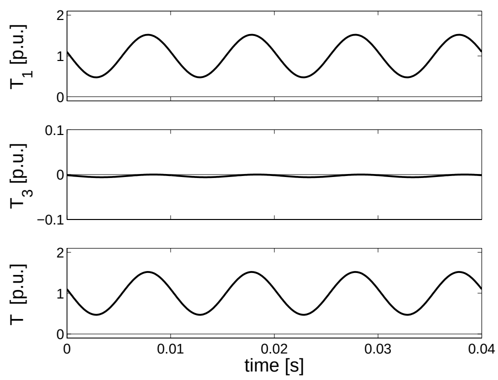

Fig. 19. Torque components T_1, T_3, and resulting torque, $\varphi = 120^\circ$

5 Conclusion

It was shown that at the considered way of emergency feeding of induction machine, unfavorable influence of the negative- and zero-sequence components in stator and rotor currents can by reduced substantially by a convenient choice of phase shift of stator currents. This choice can eliminate either one or the other component totally. The negative component is eliminated by phase shift 60˚. In this case decrease of average value of the resulting torque and its pulsation due to the zero-sequence component are almost negligible. However, extensive additional losses in stator and rotor windings arise. At operation of the machine with nominal torque, losses in stator winding increase by 100 % and similar loss increase can be expected in the rotor. At the choice of phase shift 180˚, zero-sequence component is eliminated. By influence of negative component, pulsating torques arise. Amplitude of these pulsations is equal roughly to average value of the resulting torque. Additional losses remain the same as in the previous case. From the viewpoint of additional losses, choice of phase shift 120˚ seems to be optimal one. In this case losses only increase by 50% and torque pulsations decrease to a half in comparison to pulsations at phase shift 180˚. Further loss decrease by another choice of phase shift is not possible.

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[2] J. Štěpina. *Symmetrical Components in Rotating Electrical Machines Theory*, Academia, Prague, 1969, (in Czech).

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