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

LUDEK SCHREIER*, 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: - The paper analyses emergency stator feeding of a three-phase induction motor by injected currents after disconnection of the failed leg of feeding converter and subsequent reconfiguration of the converter. At reconfiguration, the winding fed by the damaged leg is disconnected and the stator winding neutral is connected with the mid point of bank of capacitors in dc link. It results in rise of the zero-sequence component of stator currents and the third space harmonic of current layer, magnetic flux density and yoke flux. The analysis was performed by the method of space vectors and symmetrical components, which guarantees reliable results in case higher space harmonics have to be considered. The analysis results in finding the way to reduce additional losses and parasitic torques that arise as a consequence of zero- and negative-sequence components in the currents.

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

1 Introduction

Induction motors are frequently used as drive units in driven systems with variable speed. The reason is their relatively low price and high reliability. Feeding converters, however, are rather liable to rise of failures. In case it is necessary to sustain the drive in operation till the driven equipment is shut down without damage, additional precautions are adopted after the failure of the converter. An example of a serious defect is failure of one of converter legs or breakdown of one of the stator phase windings. One of possible ways to maintain the drive in operation is inverter reconfiguration in such a way that the damaged leg is disconnected and the stator winding neutral is connected with the midpoint of the bank of dc-link capacitors (see [1] - [3]). The winding fed from the failed converter leg is kept open. The failed phase winding can be insulated in the same way. The situation after the converter reconfiguration is shown in the scheme in Fig. 1.

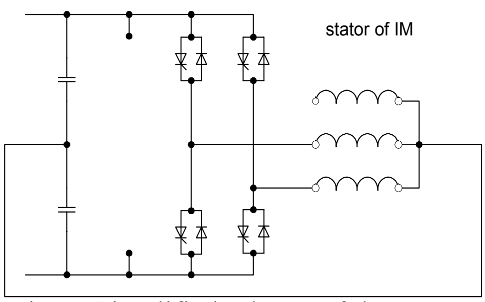

Fig. 1. Simplified scheme of the system

Connection of the stator neutral with the source of the feeding voltage induces the rise of the zero-sequence component of stator currents. This component may affect properties of the induction motor considerably. In the literature common assumption that zero-sequence component gives only rise to leakage flux is not applicable for the analysis of the induction motor with the cage rotor in this case. As it follows from the detailed analysis processed in the [4], along with the leakage flux, there arises the third space wave of the flux in the yoke and, consequently, the third space harmonic of the rotor current layer. It implies the rise of additional losses and parasitic torques.

The rise of the third flux harmonic, current layer and the torque generated by the third harmonic can be proved by simple experiments. These experiments are described e.g. in [5] and [6].

The present paper deals with the analysis of the situation in the machine at the rise of zero-sequence component of stator currents under the emergency operation with the feeding converter being controlled in such a way that the windings that were not disconnected are being flowed by so-called injected currents with the course defined by switching of individual active elements of the converter. Based on this analysis, it is possible to define the magnitude and mutual phase shift of these currents so that the magnitude of the additional losses and parasitic torques can be minimized.

2 Mathematical Analysis of System

Feeding of the induction motor in the emergency operation was analysed by the method of symmetrical components and space phasors [4]. This method enables consideration of the higher space harmonics in quite a simple way. Phase quantities (currents, possibly voltage) are expressed by means of the symmetrical components of the instantaneous values. The symmetrical components are proportional to the space phasors. According to [4], the magnitude of space phasor of an individual harmonic wave (e.g. current layer or yoke flux) is proportional to the amplitude of this wave and position of this phasor in the complex plane corresponds to the position of the maximum. For the three-phase stator current system it can be written

$$\mathbf{i}_{1S} = k\left(i_{SA} + \mathbf{a} i_{SB} + \mathbf{a}^2 i_{SC}\right) \quad (1)$$

$$\mathbf{i}_{2S} = k\left(i_{SA} + \mathbf{a}^2 i_{SB} + \mathbf{a} i_{SC}\right) \quad (2)$$

$$i_{3S} = k\left(i_{SA} + i_{SB} + i_{SC}\right) \quad (3)$$

The above constant k can be chosen arbitrarily. For this paper we chose 1/3. The symbols i_{SA}, i_{SB} and i_{SC} represent phase currents and the complex operator **a** is

$$\mathbf{a} = e^{j\frac{2\pi}{3}} \quad (4)$$

The components $\mathbf{i}_{1S}$ and $\mathbf{i}_{2S}$ are mutually complex conjugated quantities. These components of instantaneous values have to be strictly distinguished from the positive-, negative-, and zero- sequence components of time phasors of the unsymmetrical (unbalanced) three-phase system defined in [7]. The positive- and negative-sequence component, constitute symmetrical systems of time phasors having different magnitudes. In the case of symmetrical three-phase current system, for example, the negative- sequence component does not arise, while the component $\mathbf{i}_{2S}$ always develops according to the Eq. (2). The third component $\mathbf{i}_{3S}$ is an analogy to the zero-sequence component of time phasors, but according to its definition (3), it is a real quantity.

As it follows from the detailed analysis in [4], the first symmetrical component gives rise to the harmonics of the orders ν (the quantity ν is related to number of pole pairs p)

$$\nu = 1 + 3k' \quad (5)$$

and the second component to the harmonics of the range

$$\nu = 2 + 3k' \quad (6)$$

The waves of the orders

$$\nu = 3k' \quad (7)$$

belong to the third component. Quantity k' is a non-negative integer. From the Eq. (7) the link (connection) between the zero-sequence component and the third space harmonic is evident. Harmonic of the order ν = 1 is the basic wave of the group of space waves of orders given by Eqs. (5) and (6). Harmonic of the order ν = 3 is the basic wave of the group of harmonics belonging to the third symmetrical component. This is the reason why further in the text space harmonics of the individual quantities (current layers, magnetic flux density, yoke flux) of the order ν = 1 are denoted as the 1st harmonic instead of commonly used term basic harmonic in order not to be mistaken with basic harmonics of other groups of harmonics. In the case of cage rotor winding having generally m phases, the situation is more complicated. In this case m symmetrical components arise. Generally n-th symmetrical component of rotor currents $\mathbf{i}_{nR}$ (n is integer in the interval 1 to m) can be written in the following way

$$\mathbf{i}_{nR} = \frac{1}{m}\left(i_{RA} + \mathbf{a}_m i_{RB} + \mathbf{a}_m^{2n} i_{RC} + \ldots + \mathbf{a}_m^{(m-1)n} i_{RM}\right) \quad (8)$$

where i_{RA} to i_{RM} are phase currents (currents in bars) of the rotor and $\mathbf{a}_m$ is

$$\mathbf{a}_m = e^{j\frac{2\pi}{m}} \quad (9)$$

Particular groups of space harmonics of orders ν belong to symmetrical components according to the equations

$$\nu = 1 + mk', \ \nu = 2 + mk', \ \ldots\ldots\ldots, \ \nu = mk' \quad (10)$$

The importance of symmetrical components of a multi-phase system lies mainly in their relation with groups of higher space harmonics according to the Eqs. (10).

Influence of higher space harmonics on currents and torque of the machine falls substantially with their range. At the considered way of feeding, it is fully sufficient for most of currently produced induction machines to take just the first and third harmonics, which are the basic waves belonging to the first and third components of stator currents, into consideration. If the number of rotor phases $m > 6$, then the third harmonic is the basic wave of the group of harmonics of the orders $\nu = 3 + mk'$ and belongs to the third symmetrical component of rotor currents.

Mathematical description of induction motor with the cage rotor in emergency operation after reconfiguration of the feeding converter according to Fig.1 and fed by injected currents into the rotor can be quite easily derived from the system of differential equations holding true for feeding from the voltage source. When winding of the stator phase A is unplugged and $m > 6$, then, according to [6], these equations are

$$u_{SB} = 2\mathrm{Re}\left[\left(R_S \mathbf{i}_{1S} + L_{1S}\frac{d\mathbf{i}_{1S}}{dt} + L_{1h}\frac{d\mathbf{i}_{1RS}e^{j\rho}}{dt}\right)\mathbf{a}^{-1}\right] + \\ + R_S i_{3S} + L_{3S}\frac{di_{3S}}{dt} + \mathrm{Re}\left[L_{3h}\frac{d\mathbf{i}_{3RS}e^{j3\rho}}{dt}\right] \quad (11)$$

$$u_{SC}=2\mathrm{Re}\left[\left(R_S\mathbf{i}_{1S}+L_{1S}\frac{d\mathbf{i}_{1S}}{dt}+L_{1h}\frac{d\mathbf{i}_{1RS}e^{j\rho}}{dt}\right)\mathbf{a}^{-2}\right]+ +R_S i_{3S}+L_{3S}\frac{di_{3S}}{dt}+\mathrm{Re}\left[L_{3h}\frac{d\mathbf{i}_{3RS}e^{j3\rho}}{dt}\right] \quad (12)$$

$$0=R_{1R}\mathbf{i}_{1RS}+L_{1RS}\frac{d\mathbf{i}_{1R}}{dt}+L_{1h}\frac{d\mathbf{i}_{1S}e^{-j\rho}}{dt} \quad (13)$$

$$0=R_{3R}\mathbf{i}_{3RS}+L_{3R}\frac{d\mathbf{i}_{3RS}}{dt}+L_{3h}\frac{d\mathbf{i}_{3S}e^{-j3\rho}}{dt} \quad (14)$$

where u_{SB} and u_{SC} represent phase voltages of the feeding windings. Symbols R_S, R_{1R}, L_{1S}, L_{1R} and L_{1h} are resistance and inductance of stator and rotor and the main inductance for the first harmonic. Inductances L_{1S} a L_{1R} are defined by the sum of the main inductance and the stator and rotor leakage inductances $L_{\sigma S}$ and $L_{1\sigma R}$

$$L_{1S}=L_{\sigma S}+L_{1h} \quad (15)$$

$$L_{1R}=L_{1\sigma S}+L_{1h} \quad (16)$$

Resistance and rotor leakage inductance are rated to the effective number of conductors of one stator phase winding for the 1st space harmonic according to

$$R_{1R}=\frac{3}{m}\frac{\kappa_{1S}^2 N_S^2}{\kappa_{1R}^2 N_R^2}R_R \quad (17)$$

$$L_{1\sigma R}=\frac{3}{m}\frac{\kappa_{1S}^2 N_S^2}{\kappa_{1R}^2 N_R^2}L_{\sigma R} \quad (18)$$

where R_R, $L_{\sigma R}$, are resistance and leak inductance of the rotor, N_S and N_R are numbers of conductors of one stator and one rotor windings, m denotes number of rotor phases and κ_{1S} and κ_{1R} are winding factors of the 1st harmonic.

Under the simplified assumptions commonly used in the theory of electric machines inductance L_{1h} can be estimated, according to [4], from the relation

$$L_{1h}=\frac{3}{4}\kappa_{1S}^2 N_S^2\frac{\mu_0 Dl}{\pi\delta p^2} \quad (19)$$

where μ_0 represents permeability of vacuum, D is the stator bore, l is active length of the machine, and δ is width of air gap including the Carter's factor.
Similarly for the third space harmonic is

$$L_{3S}=L_{\sigma S}+L_{3h} \quad (20)$$

$$L_{3R}=L_{3\sigma S}+L_{3h} \quad (21)$$

$$R_{3R}=\frac{2\times 3}{m}\frac{\kappa_{3S}^2 N_S^2}{\kappa_{3R}^2 N_R^2}R_R \quad (22)$$

$$L_{3\sigma R}=\frac{2\times 3}{m}\frac{\kappa_{3S}^2 N_S^2}{\kappa_{3R}^2 N_R^2}L_{\sigma R} \quad (23)$$

where κ_{3S} and κ_{3R} are winding factors for the third harmonic and

$$L_{3h}=\frac{1}{6}\kappa_{3S}^2 N_S^2\frac{\mu_0 Dl}{\pi\delta p^2} \quad (24)$$

Symbol ρ represents stator and rotor mutual shift. The first and third symmetrical components of rotor currents $\mathbf{i}_{1R}$ and $\mathbf{i}_{3R}$ are rated to the effective number of conductors according to

$$\mathbf{i}_{1RS}=\frac{m}{3}\frac{\kappa_{1R}N_R}{\kappa_{1S}N_S}\mathbf{i}_{1R} \quad (25)$$

and

$$\mathbf{i}_{3RS}=\frac{m}{3}\frac{\kappa_{3R}N_R}{\kappa_{3S}N_S}\mathbf{i}_{3R} \quad (26)$$

Supposing the stator phase windings that were not disconnected are flowed by the injected currents, the induction motor in the emergency operation is only described by Eqs. (13) and (14).

For further processing these equations were introduced in the stator coordinate system and written in the form

$$\frac{d\mathbf{i}_{1R\lambda}}{dt}+\left(\frac{R_{1R}}{L_{1R}}-j\omega_m\right)\mathbf{i}_{1R\lambda}=\frac{L_{1h}}{L_{1R}}\left(j\omega_m\mathbf{i}_{1S}-\frac{d\mathbf{i}_{1S}}{dt}\right) \quad (27)$$

$$\frac{d\mathbf{i}_{3R\lambda}}{dt}+\left(\frac{R_{3R}}{L_{3R}}-3j\omega_m\right)\mathbf{i}_{3R\lambda}=\frac{L_{3h}}{L_{3R}}\left(3j\omega_m i_{3S}-\frac{di_{3S}}{dt}\right) \quad (28)$$

where ω_m is mechanical speed. Symbols $\mathbf{i}_{1R\lambda}$ and $\mathbf{i}_{3R\lambda}$ represent quantities $\mathbf{i}_{1RS}$ and $\mathbf{i}_{3RS}$ converted into stator coordinates

$$\mathbf{i}_{1R\lambda}=\mathbf{i}_{1RS}e^{j\rho} \quad (29)$$

$$\mathbf{i}_{3R\lambda}=\mathbf{i}_{3RS}e^{3j\rho} \quad (30)$$

and

$$\omega_m=\frac{d\rho}{dt} \quad (31)$$

In order to complete the equations, we have to add torque and motion equations. According to [4], torque in the air gap is generated by the 1st harmonic

$$T_1=6pL_{1h}\mathrm{Re}\left[j\mathbf{i}_{1S}^*\mathbf{i}_{1R\lambda}\right] \quad (32)$$

and torque of the 3rd harmonic is

$$T_3=9pL_{3h}\mathrm{Re}\left[j\mathbf{i}_{3S}^*\mathbf{i}_{3R\lambda}\right] \quad (33)$$

The resulting torque in the air gap is

$$T=T_1+T_3 \quad (34)$$

Motion equation can be written in the following way

$$\frac{d\omega_m}{dt}=\frac{p}{J}\left(T+T_l\right) \quad (35)$$

where J is moment of inertia of rotating masses and T_l represents load torque.

Equations (27), (28) and (32) to (35) represent mathematical model of the induction machine in emergency operation at considered way of feeding.

At contemporary drive systems in dependence on power of the motor, switching frequency is up to about 15 kHz. At these values of switching frequency, the output converter currents have almost sinusoidal waveforms. Distortion due to higher time harmonics does not have any significant influence on torque in the air gap and so it can be neglected mainly in steady-state operation. This is the reason why, at analysis of emergency operation of the driving system with one phase disconnected in steady state, higher time harmonics were neglected.

3 Steady-State Operation of System after Converter Reconfiguration

Injected stator currents after converter reconfiguration can be written as

$$i_{SA} = 0 \tag{36}$$

$$i_{SB} = I_S \cos(\omega t) \tag{37}$$

$$i_{SC} = I_S \cos(\omega t + \varphi) \tag{38}$$

where I_S, ω and φ are amplitude, angular frequency and phase shift of currents i_{SB} and i_{SC}.

The function cos of any angle α can be expressed as

$$\cos(\alpha) = \frac{e^{j\alpha} + e^{-j\alpha}}{2} \tag{39}$$

According to this equation, Eqs. (37) and (38) can be transformed to

$$i_{SB} = I_S \frac{e^{j\omega t} + e^{-j\omega t}}{2} \tag{40}$$

$$i_{SC} = I_S \frac{e^{j\omega t} e^{j\varphi} + e^{-j\omega t} e^{-j\varphi}}{2} \tag{41}$$

Substituting Eqs. (36), (40) and (41) into Eqs. (1) and (3) we have after the rearrangement

$$\mathbf{i}_{1S} = \frac{1}{6} I_S \Big[e^{j2\pi/3}\left(1 + e^{j2\pi/3} e^{j\varphi}\right) e^{j\omega t} + \\ + e^{j2\pi/3}\left(1 + e^{j2\pi/3} e^{-j\varphi}\right) e^{-j\omega t} \Big] \tag{42}$$

$$i_{3S} = \frac{1}{6} I_S \left[\left(1 + e^{j\varphi}\right) e^{j\omega t} + \left(1 + e^{-j\varphi}\right) e^{-j\omega t} \right] \tag{43}$$

The first $\mathbf{i}_{1S}$ and the third i_{3S} components of stator current can be written as

$$\mathbf{i}_{1S} = \mathbf{i}_{1SP} + \mathbf{i}_{1SN} \tag{44}$$

$$i_{3S} = \mathbf{i}_{3SP} + \mathbf{i}_{3SN} \tag{45}$$

where it was introduced

$$\mathbf{i}_{1SP} = \frac{1}{6} I_S \mathbf{K}_{1P} e^{j\omega t} \tag{46}$$

$$\mathbf{i}_{1SN} = \frac{1}{6} I_S \mathbf{K}_{1N} e^{-j\omega t} \tag{47}$$

$$\mathbf{i}_{3SP} = \frac{1}{6} I_S \mathbf{K}_{3P} e^{j\omega t} \tag{48}$$

$$\mathbf{i}_{3SN} = \frac{1}{6} I_S \mathbf{K}_{3N} e^{-j\omega t} \tag{49}$$

The constants $\mathbf{K}_{1P}$, $\mathbf{K}_{1N}$, $\mathbf{K}_{3P}$, and $\mathbf{K}_{3N}$ are defined by equations

$$\mathbf{K}_{1P} = e^{j2\pi/3}\left(1 + e^{j2\pi/3} e^{j\varphi}\right) \tag{50}$$

$$\mathbf{K}_{1N} = e^{j2\pi/3}\left(1 + e^{j2\pi/3} e^{-j\varphi}\right) \tag{51}$$

$$\mathbf{K}_{3P} = 1 + e^{j\varphi} \tag{52}$$

$$\mathbf{K}_{3N} = 1 + e^{-j\varphi} \tag{53}$$

The quantity $\mathbf{i}_{1SP}$, which is a part of the first symmetrical component, corresponds to the positive-sequence component of time phasors of stator currents given by Eqs. (36) to (38). According to Eq. (46) the component $\mathbf{i}_{1SP}$ rotates in the positive direction with angular frequency ω and as it gives rise to the first space harmonic of current layer in the space of the machine. The component generates the effective torque. The effective torque means such torque which drive in positive direction without any pulsating and braking components. The component $\mathbf{i}_{1SN}$ corresponds to the negative-sequence component of time phasors of stator currents and according to Eq. (47) it rotates in the opposite direction than $\mathbf{i}_{1SP}$ and so implicates increase of additional losses in stator winding and gives rise to braking torque.

Decomposition of the quantity $\mathbf{i}_{3S}$ into two complex conjugated quantities $\mathbf{i}_{3SP}$ and $\mathbf{i}_{3SN}$ is an analogy to the decomposition of pulsating field into two complex conjugated components rotating in the space in the opposite directions. So the zero-sequence component of stator currents can be compared to stator current of the main winding of a single-phase machine. As zero-sequence-component and consequently the quantities $\mathbf{i}_{3SP}$ and $\mathbf{i}_{3SN}$ give rise to third space harmonics, number of pole pairs of this suppositional single-phase machine is triple of number of poles of the investigated three-phase machine. From the above stated it follows that the components $\mathbf{i}_{3SP}$ and $\mathbf{i}_{3SN}$ also increase additional losses in the stator winding. According to Eqs. (46) to (49), individual components of stator current are proportional to the constants $\mathbf{K}_{1P}$, $\mathbf{K}_{1N}$, $\mathbf{K}_{3P}$, and $\mathbf{K}_{3N}$ in the magnitude. These constants depend on the phase shift φ of stator currents. Therefore, by a convenient choice of this angle, magnitude of these components can be suitably determined, to reduce additional losses and parasitic torques. Courses of rotor currents will be obtained by solving Eqs. (27) and (28), e.g. by means of the Laplace transformation. Substituting Eqs. (46) and (47) into Eq. (44) and Eqs. (48) and (49) into Eq. (45) we get

$$\mathbf{i}_{1S} = \frac{1}{6} I_S \mathbf{K}_{1P} e^{j\omega t} + \frac{1}{6} I_S \mathbf{K}_{1N} e^{-j\omega t} \tag{54}$$

$$\mathbf{i}_{3S} = \frac{1}{6} I_S \mathbf{K}_{3P} e^{j\omega t} + \frac{1}{6} I_S \mathbf{K}_{3N} e^{-j\omega t} \tag{55}$$

Differentiating the equations we have

$$\frac{d\mathbf{i}_{1S}}{dt} = j\frac{1}{6}\omega\ I_S \mathbf{K}_{1P} e^{j\omega t} - j\frac{1}{6} I_S \omega\ \mathbf{K}_{1N} e^{-j\omega t} \quad (56)$$

$$\frac{d\mathbf{i}_{3S}}{dt} = j\frac{1}{6}\omega\ I_S \mathbf{K}_{3P} e^{j\omega t} - j\frac{1}{6} I_S \omega \mathbf{K}_{3N} e^{-j\omega t} \quad (57)$$

After substitution Eqs. (54) to (57) into Eqs. (27) and (28) and rearrangements we can write

$$\frac{d\mathbf{i}_{1R\lambda}}{dt} + \left(\frac{R_{1R}}{L_{1R}} - j\omega_m\right)\mathbf{i}_{1R\lambda} = j\frac{I_S}{6}\frac{L_{1h}}{L_{1R}}\mathbf{K}_{1P}(\omega_m - \omega)e^{j\omega t} + + j\frac{I_S}{6}\frac{L_{1h}}{L_{1R}}\ \mathbf{K}_{1N}(\omega_m + \omega)e^{-j\omega t} \quad (58)$$

$$\frac{d\mathbf{i}_{3R\lambda}}{dt} + \left(\frac{R_{3R}}{L_{3R}} - 3j\omega_m\right)\mathbf{i}_{3R\lambda} = j\frac{I_S}{6}\frac{L_{3h}}{L_{3R}}\mathbf{K}_{3P}(3\omega_m - \omega)e^{j\omega t} + + j\frac{I_S}{6}\frac{L_{3h}}{L_{3R}}\ \mathbf{K}_{3N}(3\omega_m + \omega)e^{-j\omega t} \quad (59)$$

From the Eq. (58) it is apparent that the 1st component of currents $\mathbf{i}_{1R\lambda}$ can be similarly as the first component of stator currents $\mathbf{i}_{1S}$ decomposed into two components $\mathbf{i}_{1R\lambda P}$ and $\mathbf{i}_{1R\lambda N}$ rotating in the space in opposite directions. Accordingly, we can decompose $\mathbf{i}_{3R\lambda}$ into two components $\mathbf{i}_{3R\lambda P}$ and $\mathbf{i}_{3R\lambda N}$.

Laplace image of the equation for the component $\mathbf{i}_{1R\lambda P}$ can be derived from Eq. (58) and supposing zero initial currents in the rotor we have

$$\mathbf{I}_{1R\lambda P}(\mathbf{p})\mathbf{p} + \mathbf{A}\mathbf{I}_{1R\lambda P}(\mathbf{p}) = \mathbf{B}\frac{1}{\mathbf{p} - j\omega} \quad (60)$$

where $\mathbf{I}_{1R\lambda P}(\mathbf{p})$ is Laplace image of $\mathbf{i}_{1R\lambda P}$. The quantities **A** and **B** are

$$\mathbf{A} = \frac{R_{1R}}{L_{1R}} - j\omega_m \quad (61)$$

$$\mathbf{B} = j\frac{I_S}{6}\frac{L_{1h}}{L_{1R}} - \mathbf{K}_{1P}(\omega_m - \omega) \quad (62)$$

Equation (60) can be rearranged into form

$$\mathbf{I}_{1R\lambda P}(\mathbf{p}) = \frac{\mathbf{B}}{-\mathbf{A} - j\omega}\frac{1}{\mathbf{p} + \mathbf{A}} - \frac{\mathbf{B}}{-\mathbf{A} - j\omega}\frac{1}{\mathbf{p} - j\omega} \quad (63)$$

convenient for inverse transformation. After the transformation we obtain

$$\mathbf{i}_{1R\lambda P} = \frac{\mathbf{B}}{-\mathbf{A} - j\omega}e^{-\mathbf{A}t} - \frac{\mathbf{B}}{-\mathbf{A} - j\omega}e^{j\omega t} \quad (64)$$

The first part of the expression on the right hand side of Eq. (64) represents transient component of $\mathbf{i}_{1R\lambda P}$ and the following part of this expression is steady component of $\mathbf{i}_{1R\lambda P}$. As this work deals with analysis of emergency operation in the steady state, transient components will not be in focus in further text. After substitution of **A** and **B** in Eq. (64) and after rearrangements it is

$$\mathbf{i}_{1R\lambda P} = j\frac{L_{1h}(\omega_m - \omega)}{R_{1R} - jL_{1R}(\omega_m - \omega)}\mathbf{i}_{1SP} \quad (65)$$

In a similar way, relations

$$\mathbf{i}_{1R\lambda N} = j\frac{L_{1h}(\omega_m - \omega)}{R_{1R} - jL_{1R}(\omega_m + \omega)}\mathbf{i}_{1SN} \quad (66)$$

$$\mathbf{i}_{3R\lambda P} = j\frac{L_{3h}(3\omega_m - \omega)}{R_{3R} - jL_{3R}(3\omega_m - \omega)}\mathbf{i}_{3SP} \quad (67)$$

$$\mathbf{i}_{3R\lambda N} = j\frac{L_{3h}(3\omega_m - \omega)}{R_{3R} - jL_{3R}(3\omega_m + \omega)}\mathbf{i}_{3SN} \quad (68)$$

can be derived for $\mathbf{i}_{1R\lambda N}$, $\mathbf{i}_{3R\lambda P}$ and $\mathbf{i}_{3R\lambda N}$.

From the above equations it is apparent that in rotor winding, as a reaction to the third component (zero-sequence component) of stator currents, the third component of rotor currents arises taking an important part in increase of additional losses. Components of rotor currents are proportional to the corresponding components of stator currents in the magnitude. Hence, their magnitude, similarly as magnitude of stator current components, can be limited by a convenient choice of the angle φ.

According to Eq. (32), torque generated by the first symmetrical components of stator and rotor currents consists of the effective torque given by interaction of components $\mathbf{i}_{1SP}$ and $\mathbf{i}_{1R\lambda P}$

$$T_{1P} = 6pL_{1h}\mathrm{Re}\left[j\mathbf{i}^*_{1SP}\mathbf{i}_{1R\lambda P}\right] \quad (69)$$

and of an adverse component of asynchronous-type torque generated by quantities $\mathbf{i}_{1SN}$ and $\mathbf{i}_{1R\lambda N}$

$$T_{1N} = 6pL_{1h}\mathrm{Re}\left[j\mathbf{i}^*_{1SN}\mathbf{i}_{1R\lambda N}\right] \quad (70)$$

and of two pulsating components

$$T_{1PN} = 6pL_{1h}\mathrm{Re}\left[j\mathbf{i}^*_{1SP}\mathbf{i}_{1R\lambda N}\right] \quad (71)$$

and

$$T_{1NP} = 6pL_{1h}\mathrm{Re}\left[j\mathbf{i}^*_{1SN}\mathbf{i}_{1R\lambda P}\right] \quad (72)$$

The third components of stator and rotor currents generate parasitic torque given by Eq. (33). Analogically, it can be decomposed into

$$T_{3P} = 9pL_{3h}\mathrm{Re}\left[j\mathbf{i}^*_{3SP}\mathbf{i}_{3R\lambda P}\right] \quad (73)$$

$$T_{3N} = 9pL_{3h}\mathrm{Re}\left[j\mathbf{i}^*_{3SN}\mathbf{i}_{3R\lambda N}\right] \quad (74)$$

$$T_{3PN} = 9pL_{3h}\mathrm{Re}\left[j\mathbf{i}^*_{3SP}\mathbf{i}_{3R\lambda N}\right] \quad (75)$$

$$T_{3NP} = 9pL_{3h}\mathrm{Re}\left[j\mathbf{i}^*_{3SN}\mathbf{i}_{3R\lambda P}\right] \quad (76)$$

Individual components of the torque are given by product of components of stator and rotor currents. Hence, it is possible to control their magnitude and course by a suitable choice of the angle φ as well.

4 Conclusion

The paper shows rise of zero-sequence component of stator currents as a result of connecting stator-winding neutral with the midpoint of the bank of dc-link capacitors and disconnecting one stator phase caused by failure of feeding converter. From the performed analysis of this emergency feeding of an induction motor in two phase windings by injected currents follows rise of a component of currents in rotor winding that corresponds to zero-sequence component of stator currents. It is shown that these rotor current components together with the zero–sequence component of stator currents give rise to the third space harmonic of current layer and magnetic flux density along the air gap and to the third space harmonic of yoke flux. Further, as a result of unbalanced stator feeding, negative-sequence components in stator and rotor currents can also arise.

These components in motor currents imply increase in additional losses and rise of unfavourable parasitic torques. It is shown, that magnitude of individual current components and thus additional losses and parasitic torques can be reduced by a convenient choice of the phase shift of the first time harmonic of currents of two fed stator windings.

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