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SIMULATION ANALYSIS OF INDUCTION MOTOR TURN-TO-TURN FAULTS IN STATOR WINDINGS

Accurate and flexible computer model of an induction motor is a very important tool for diagnosis and fault protection algorithms investigation. This paper presents a new method for internal inter-turn faults in an induction motor stator windings. General approach to inter-turn faults representation in such machines is discussed. The simulation model is implemented in ATP-EMTP programme by using of Type-94 element. The aim of the provided simulation is to investigate new algorithms for induction motor internal fault protection under different conditions. Included examples demonstrate basic characteristics of the proposed model and its application for internal fault analysis in the complex system included motor, load and a supplying network.

1. INTRODUCTION

Damage of stator insulation is the most frequent failure in electrical motor. Protection of the induction motor against different internal faults would limit the fault duration and prevent motor from substantial damage, what is particularly important for higher motor ratings. Diagnosis of faults in electrical motors is a very important function, which enables to protect the motor against the results of disruptions. In order to design an algorithm, which will effectively eliminate this kind of disruptions; it is necessary to make a proper model of the motor.

Traditional models of electrical machines are based on electrical circuit equations and equations of motion (circuit model). Mathematical model of induction motor described in this way is composed of differential and algebraic equations. Generally, it is an arrangement of high order set of equations containing nonlinear functions. The model is extremely hard to use directly [10].

Loss of power in one of the phases is often caused by mechanical tension and vibrations. Vibrations can lead to loosening of the screws on the machine's terminal or

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mechanical tensions, consequently leading to the loss of power in one of the phases. Turns to turn faults are caused by different factors affecting stator directly. For example, mechanical tensions during assembly or while machine is working, and also by partial discharges caused by high voltage among the turns, can cause damage to the insulation, and in consequence the flow of short circuit current. Various solutions are available in literature for detection of internal faults [1]-[5], [9], [10]. Efficient motor protection should detect all possible faults and isolate the motor in order to minimize the damage size. Common method for investigation of the process involved is based on application of suitable computer models.

Widely used computer models have a close connection with mathematical models. Obtained results based on these models of computer simulation are more and more reliable and because of that, play an important part in designing and testing of the devices themselves, and also relating to them automatics systems.

The squirrel cage motor was chosen for further investigation. The model was prepared in the ATP – EMTP simulation program [6]. Included examples demonstrate basic characteristics of the proposed model and the detection results obtained using the proposed protection algorithm.

2. SIMULATION OF TURN TO TURN FAULTS IN STATOR WINDINGS

Let us consider turn-to-turn fault on phase A. Winding in this phase is divided on two parts – un – faulted turns winding section μ_{us} and shorted turns winding μ_{sh}, as in Fig. 1. Phase B and C have the same number of turns as the phase A.

If the number of turns in all three stator phases is the same, we can apply basic model to describe a mathematical model of induction motor with turn-to-turn fault [12].

The model of a faulty motor can be derived from standard relations (1). Flux equations of induction motor with turn-to-turn fault in *abc* system take the following form [11]:

$$
\begin{aligned}
\frac{d\boldsymbol{\phi}_{sABC}}{dt} &= \mathbf{u}_{sABC} - \mathbf{r}_s \left(\mathbf{i}_{sABC} - \boldsymbol{\mu}_{ABC} i_f\right) \\
\frac{d\boldsymbol{\phi}_{rABC}}{dt} &= -\mathbf{r}_r \, \mathbf{i}_{rABC} \\
\boldsymbol{\phi}_{sABC} &= \mathbf{L}_s \left(\mathbf{i}_{sABC} - \boldsymbol{\mu}_{ABC} i_f\right) + \mathbf{L}_m(\theta)\mathbf{i}_{rABC} \\
\boldsymbol{\phi}_{rABC} &= \mathbf{L}_m^T(\theta)\left(\mathbf{i}_{sABC} - \boldsymbol{\mu}_{ABC} i_f\right) + \mathbf{L}_r \mathbf{i}_{rABC}
\end{aligned}
\tag{1}
$$

where vectors $\mathbf{u}_{sABC}$, $\mathbf{i}_{sABC}$ and $\boldsymbol{\lambda}_{sABC}$ represent stator voltages, currents and flux. $\mathbf{i}_{rABC}$ and $\boldsymbol{\lambda}_{rABC}$ are currents and flux of rotor. As a symmetrical machine is considered, it is assumed: $\mathbf{r}_s = r_s\mathbf{I}$ and $\mathbf{r}_r = r_r\mathbf{I}$, where $\mathbf{I}$ is identity matrix. $\boldsymbol{\mu}_{ABC} = [\mu_{sh}\ 0\ 0]^{\mathrm{T}}$ is a vector representing position of turn-to-turn fault in the stator circuit.

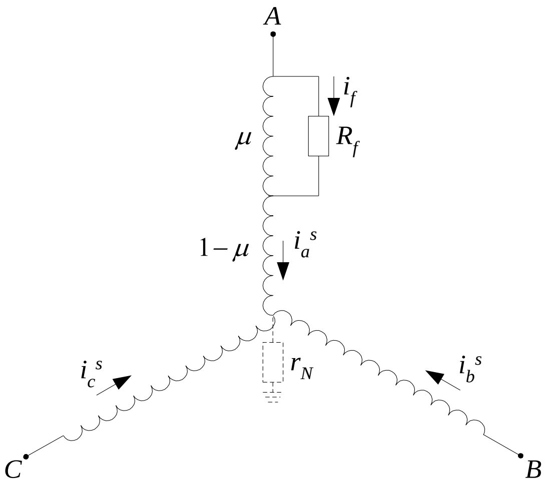

Fig. 1. Three phase stator winding with turn to turn fault in phase A

The flux in circuited part of winding *A* can be calculated according to the following equation:

$$\frac{d\phi_{sha}}{dt} = R_f i_f - \mu_{sh} r_s (i_{sA} - i_f) \tag{2}$$

where i_f – short-circuit current (Fig. 1).

Transforming above equations into $\alpha\beta 0$ coordinates, with taking into consideration of (2), one can obtain:

$$\begin{aligned}
\frac{d\boldsymbol{\phi}_{s\alpha\beta 0}}{dt} &= \mathbf{u}_{s\alpha\beta 0} - \mathbf{r}_s \left(\mathbf{i}_{s\alpha\beta 0} - \mathbf{T}_{\alpha\beta 0} \boldsymbol{\mu}_{\alpha\beta 0} i_f \right) \\
\frac{d\boldsymbol{\phi}_{r\alpha\beta 0}}{dt} &= -\mathbf{r}_r \mathbf{i}_{r\alpha\beta 0} + z_p \omega_r \mathbf{K} \boldsymbol{\phi}_{r\alpha\beta 0} \\
\frac{d\phi_{sh\alpha}}{dt} &= R_f i_f - \mu_{sh} r_s (i_{s\alpha} - i_f)
\end{aligned} \tag{3}$$

where fluxes are given by:

$$\begin{aligned}
\boldsymbol{\phi}_{s\alpha\beta0} &= \mathbf{L}_s\left(\mathbf{i}_{s\alpha\beta0} - \mathbf{T}_{\alpha\beta0}\boldsymbol{\mu}_{\alpha\beta0} i_f\right) + \mathbf{L}_m \mathbf{i}_{r\alpha\beta0} \\
\boldsymbol{\phi}_{r\alpha\beta0} &= \mathbf{L}_m\left(\mathbf{i}_{s\alpha\beta0} - \mathbf{T}_{\alpha\beta0}\boldsymbol{\mu}_{\alpha\beta0} i_f\right) + \mathbf{L}_r \mathbf{i}_{r\alpha\beta0} \\
\phi_{sh\alpha} &= \mu_{sh} l_{ls}\left(i_{s\alpha} - i_f\right) + \mu_{sh} L_m\left(i_{s\alpha} + i_{r\alpha} - \frac{2}{3}\mu_{sh} i_f\right)
\end{aligned} \tag{4}$$

and: $\boldsymbol{\mu}_{\alpha\beta 0} = [\mu_{sh}\ 0\ 0]^{\mathrm{T}}$, $\mathbf{u}_{s\alpha\beta} = [u_{s\alpha}\ u_{s\beta}\ u_{s0}]^{\mathrm{T}}$, $\mathbf{i}_{s\alpha\beta} = [i_{s\alpha}\ i_{s\beta}\ i_{s0}]^{\mathrm{T}}$, $\boldsymbol{\phi}_{s\alpha\beta} = [\phi_{s\alpha}\ \phi_{s\beta}\ \phi_{s0}]^{\mathrm{T}}$, and $\mathbf{i}_{r\alpha\beta} = [i_{r\alpha}\ i_{r\beta}\ i_{r0}]^{\mathrm{T}}$, $\boldsymbol{\phi}_{r\alpha\beta} = [\phi_{r\alpha}\ \phi_{r\beta}\ \phi_{r0}]^{\mathrm{T}}$ are adequately voltages, currents, flux matrix of stator and currents, flux matrix of rotor [7]; $\mathbf{r}_s$, $\mathbf{r}_r$, $\mathbf{L}_s$, $\mathbf{L}_r$, $\mathbf{L}_m$ are diagonal matrix at the size of (2 x 2); $\mathbf{K} = \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$.

Mechanical part of induction motor in $\alpha\beta 0$ system is described by:

$$J\frac{d\omega_r(t)}{dt} = T_{em} - T_m \tag{5}$$

$$T_{em} = \frac{3}{2} z_p\left(\phi_{s\alpha} i_{s\beta} - \phi_{s\beta} i_{s\alpha}\right) - z_p \mu_{sh} \phi_{s\alpha} i_f \tag{6}$$

Intensity level of turn to turn faults in this model can be adjusted through the change of number of shorted turns and resistance (r_f), limiting short current.

3. TURN – TO – TURN FAULTS PROTECTION ALGORITHM

3.1. ISOLATED STAR POINT OF STATOR WINDINGS

Proposed protection algorithm is based on the information contained in the symmetrical components – especially negative sequence component of current and difference angle of space vectors (α and β) voltages and currents of stator. Negative sequence components of current gives information that the modeled system state is not allowed. However, this component occurs when the fault is both external and internal. Therefore, it additionally uses information that comes from impedance angle, which is calculated from the spatial vectors voltages and current of stator.

Transforming the phase currents and voltages to a stationary system of coordinates $\alpha\beta$ is realized by:

$$
\begin{aligned}
i_{s\alpha} &= \frac{2}{3} i_{sA} - \frac{1}{3}\left(i_{sB} + i_{sC}\right) \\
i_{s\beta} &= \frac{1}{\sqrt{3}}\left(i_{sB} - i_{sC}\right)
\end{aligned}
\tag{7}
$$

$$
\begin{aligned}
u_{s\alpha} &= \frac{2}{3} u_{sA} - \frac{1}{3}\left(u_{sB} + u_{sC}\right) \\
u_{s\beta} &= \frac{1}{\sqrt{3}}\left(u_{sB} - u_{sC}\right)
\end{aligned}
\tag{8}
$$

where: i_{sA}, i_{sB}, i_{sC} – currents of stator in phase A, B, C; u_{sA}, u_{sB}, u_{sC} – phase voltages; $i_{s\alpha}$, $i_{s\beta}$ – stator current space vector components and $u_{s\alpha}$, $u_{s\beta}$ – supplying voltage space vector components.

The impedance angle is obtained from:

$$
\underline{Z} = \frac{\underline{U}}{\underline{I}} \Rightarrow |Z| e^{j\varphi_z} = \frac{|u_{\alpha\beta}| e^{j\varphi_u}}{|i_{\alpha\beta}| e^{j\varphi_i}} = \frac{|u_{\alpha\beta}|}{|i_{\alpha\beta}|} e^{j(\varphi_u - \varphi_i)}
\tag{9}
$$

$$
\varphi_z = \varphi_u - \varphi_i
\tag{10}
$$

where: $\varphi_u = \arg(u_\alpha, u_\beta)$, $\varphi_i = \arg(i_\alpha, i_\beta)$, $\underline{U} = u_\alpha + ju_\beta$, $\underline{I} = i_\alpha + ji_\beta$.

During symmetrical steady-state the impedance angle φ_z is close to 0, otherwise this angle carries the following information:

$$
\varphi_z \Rightarrow \begin{cases} > \varphi_0 \text{ then internal fault} \\ < -\varphi_0 \text{ then external fault} \end{cases}
\tag{11}
$$

where: φ_0 - a threshold value.

3.2. EARTHED STAR POINT OF STATOR

In this case it is proposed to apply the zero-sequence of motor voltage and current at the motor terminal. The fault in this power network is identified by the appearance of zero sequence components of stator voltage u_0. But the voltage u_0 occurs when the fault is both external and internal. Therefore, additionally uses information that comes from current angles of symmetrical components (negative and zero).

Zero sequence component of stator voltage and angles of symmetrical components are calculated by:

$$
u_0 = \frac{1}{3}\left(u_{sA} + u_{sB} + u_{sC}\right) - u_N
\tag{12}
$$

$$\begin{aligned} \varphi_{I_2} &= \arg\left(\mathrm{Im}(I_2), \mathrm{Re}(I_2)\right) \\ \varphi_{I_0} &= \arg\left(\mathrm{Im}(I_0), \mathrm{Re}(I_0)\right) \end{aligned} \tag{13}$$

Proper combination of pairs of angles, allows to identify the type of faults. If $\varphi_{I_2} \in \left(-\frac{\pi}{2}, 0\right)$ and $\varphi_{I_0} < \frac{\pi}{2}$ then fault is internal. In the other cases, the damages (faults, voltage unbalance, open phase) are external.

4. SIMULATION RESULTS

The squirrel cage induction motor was used in the simulation tests. That was the motor of 2 MW power with supply voltage 10 kV and electrical parameters: stator resistance r_s = 0.3607 Ω, stator inductance x_{ls} = 0.011482 Ω, rotor resistance, r_r = 1.1685 Ω, rotor inductance x_{lr} = 0.011482 Ω, mutual inductance x_m = 0.494 Ω. Structure of simulation model is presented in Fig. 5.

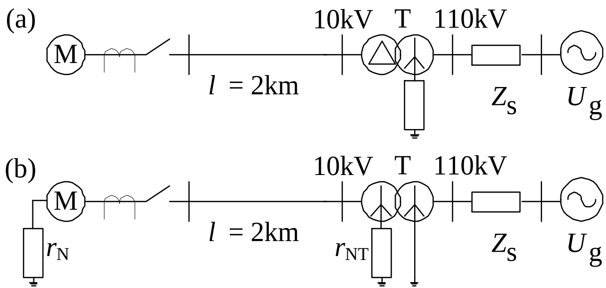

Fig. 2. Structure of simulation model (a) isolated star point of stator, (b) earthed star point of stator

The aim of simulation was to verify the given assumptions and to check the obtained results with a similar data available from the literature. It is considered to further use of this model for investigation of protection algorithms. Selected waveforms obtained during simulations are presented below.

In the first part of simulations the inter-turn fault was considered, in the system with isolated of the star point of stator. Simulation parameters r_f = 0.1 Ω, $T_m = T_N$. Some results can be track at Figs. 3–6. The fault included 1%, 5% and 50% of stator phase A winding was introduced at t = 0.04 s. Fig. 3. shows very interesting case because number of shorted turns is equal 1% and voltage (Fig. 3(a)) and current waveshapes (Fig. 3(b)) do not carry information, that fault in the motor has occurred. It is well known that appearance of the negative sequence current at the supplied current is a good detector of an turn - to - turn fault. However, this information is not sufficient, because the external faults would be detected. Therefore the algorithm additionally uses information that comes from φ_z. This case presents a challenge for designer of protective algorithm, because despite this fault is very difficult to detect.

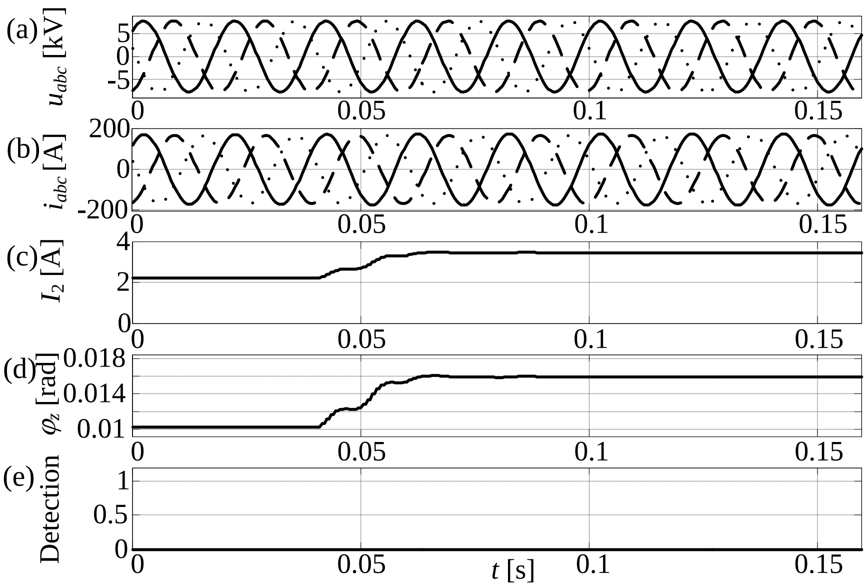

Fig. 3. Turn to turn fault in the stator, isolated star point of stator, μ = 1%, (a) voltages of stator, (b) currents of stator, (c) negative sequence component of current, (d) impedance angle, (e) detection efficiency

Figs. 4-5 present other fault situations. It can be seen, that with an increase in the number of shorted turns, criteria signals I_2 and φ_z can effectively eliminate these faults.

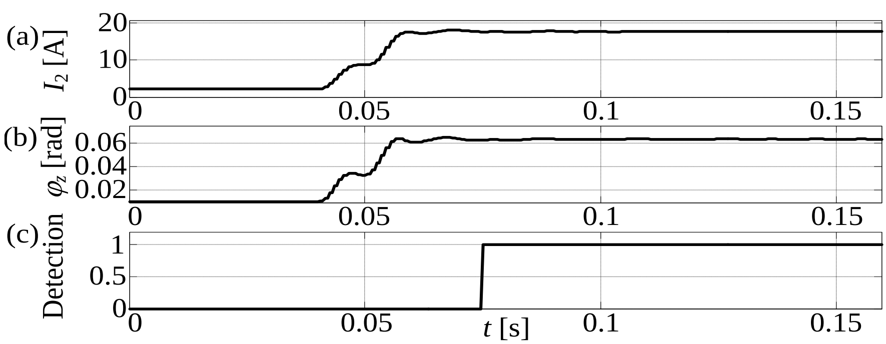

Fig. 4. Turn to turn fault in the stator, isolated star point of stator, μ = 5%, (a) negative sequence component of current, (b) impedance angle, (c) detection efficiency

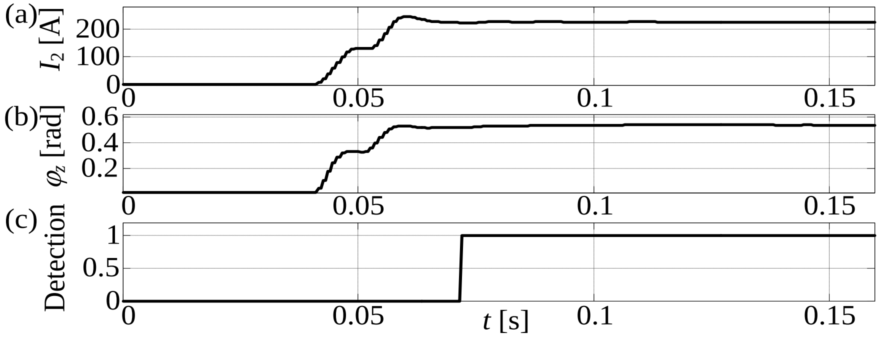

Fig. 5. Turn to turn fault in the stator, isolated star point of stator, μ = 50%, (a) negative sequence component of current, (b) impedance angle, (c) detection efficiency

Fig. 6 shows external fault. At the time of fault, angle φ_z is less than zero, but after inception of disturbance its value is fixed (Fig. 6(b)) over 1.5 period. This situation prevents proper working of the protection. Therefore, the detection time delay introduced - 30 ms.

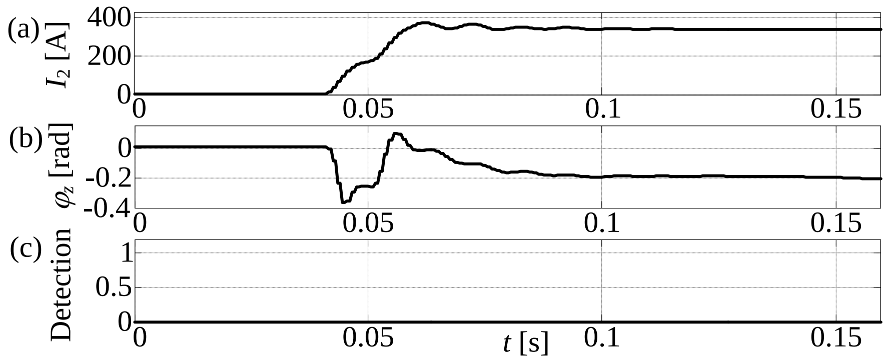

Fig. 6. External fault, isolated star point of stator, $r_f = 1\ \Omega$, (a) negative sequence component of current, (b) impedance angle, (c) detection efficiency

In the second part of simulations the inter–turn fault was considered, in the system with earthed of the star point of stator. Simulation parameters $r_f = 0.1\ \Omega$, $r_N = 10\ \Omega$, $T_m = 0.5T_N$. Some results can be track at Figs. 7 – 10. The fault included 1%, 5% and 50% of stator phase A winding was introduced at t = 0.04 s. Criteria signals used in the algorithm U_0, φ_{I2}, φ_{I0}, give information that effectively detects internal faults (Fig. 7(c), 8(c), 9(c)) simultaneously block external faults (Fig. 10(c)). Time delay (20 ms) was introduced – (as above) because of the transient state in the waveform angle φ_{I2} occurred (Fig. 10(b)).

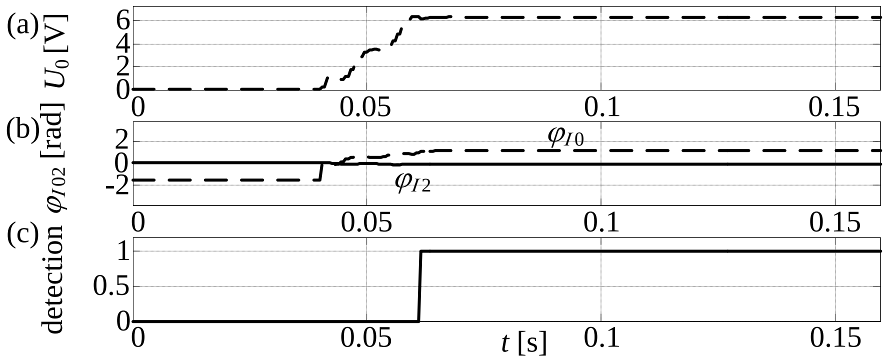

Fig. 7. Turn to turn fault in the stator, earthed star point of stator, r_f = 0.1 Ω, μ = 1%, (a) negative sequence component of current, (b) impedance angle, (c) detection efficiency

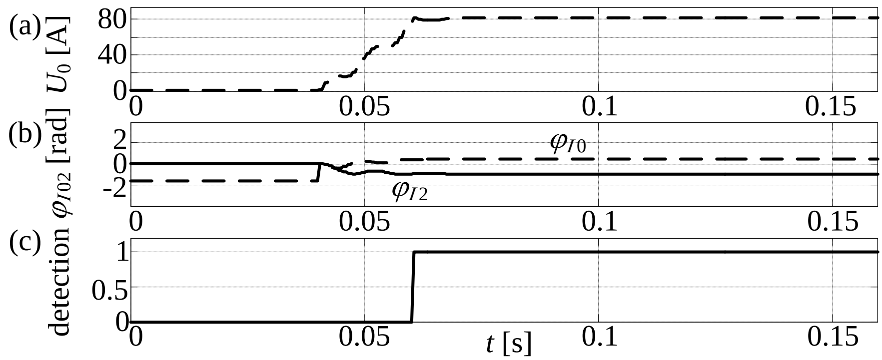

Fig. 8. Turn to turn fault in the stator, earthed star point of stator, r_f = 0.1 Ω, μ = 5%,(a) negative sequence component of current, (b) impedance angle, (c) detection efficiency

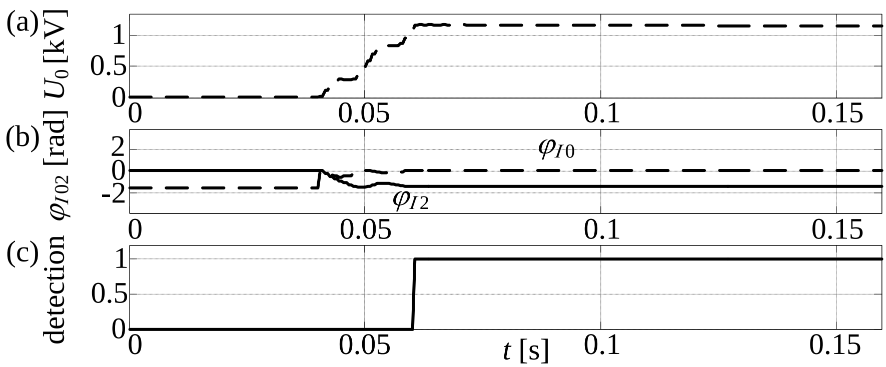

Fig. 9. Turn to turn fault in the stator, earthed star point of stator, r_f = 0,1Ω, μ = 50%, (a) negative sequence component of current, (b) impedance angle, (c) detection efficiency

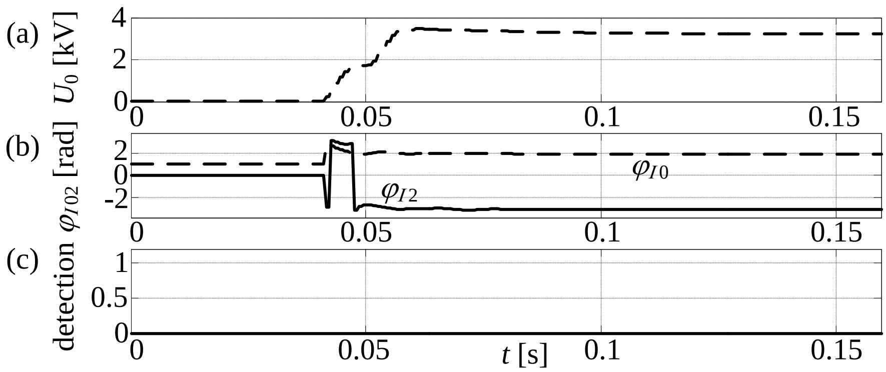

Fig. 10. External fault, earthed star point of stator, r_f = 1Ω, (a) negative sequence component of current, (b) impedance angle, (c) detection efficiency

5. CONCLUSIONS

The problems related to modelling of turn - to - turn faults in induction motors, and their detection are presented in the paper. The fault model was prepared by using of the ATP – EMTP program. Protection algorithm was tested also by using of the ATP – EMTP. Included simulation results show its fundamental properties during transients. It can be concluded that the proposed method gives a handy to use tool which enables to analyse the fault induced transients in induction machines. The future works will focus on improvement the effectiveness of the protection algorithm by choosing new criteria signal or new decision making method.

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ANALIZA SYMULACYJNA ZWARĆ ZWOJOWYCH W UZWOJENIU STOJANA SILNIKA INDUKCYJNEGO

W artykule przedstawiono propozycje dwóch algorytmów detekcji zwarć wewnętrznych zwojowych w silnikach indukcyjnych średniego napięcia. Analizę przeprowadzono z użyciem cyfrowego modelu zawierającego model silnika, umożliwiający symulowanie zwarć wewnętrznych. Przedstawiono także wpływ charakteru uziemienia punktu gwiazdowego stojana na skuteczność detekcji tego rodzaju zakłóceń. Zamieszczono przykłady symulacji zwarć wewnętrznych zwojowych zawierających różną liczbę zwojów objętych zwarciem w sytuacji, kiedy punkt gwiazdowy jest izolowany lub uziemiony. Model symulacyjny jak i proces testowania algorytmów zabezpieczeniowych zostały wykonane w programie ATP/EMTP.