Modelling of Induction Motor for Simulation of Internal Faults

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Abstract—**Accurate and flexible computer model of an induction motor is a very important tool for diagnostic and fault protection algorithms investigation. This paper considers modelling of an internal faults in stator windings of an induction motor. General approach to inter-turn faults modelling in such machines is discussed and implementation of the model in ATP-EMTP program in a form of Type-94 element is presented. 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.**

Keywords-component; modelling of induction motor; transient simulation; internal turn to turn fault

I. 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. Diagnosing 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 (so called mechanical 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. Motor's parameters that occur in the mentioned case are hard to identify, which is the reason that 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 mechanical tensions, consequently leading to the loss of power in one of the phases. Turn 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, (in the situation when stator is powered by a source with PWM) 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], [2], [3], [4], [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.

This article presents a mathematical model by which the transient behaviour of an induction motor with a winding fault can be successfully analyzed. The squirrel cage motor was chosen for further investigation. The model was prepared in the ATP – EMTP simulation program [6]. Included simulation results show its fundamental properties. It can be seen that it is a tool handy to use, enabling an easy way to obtain the simulation results by any given conditions. In the following stages the turn-to-turn fault model is presented and described in detail. 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.

II. Mathematical Model Of Induction Motor - Basic Considerations

Electrical equivalent of asynchronous machine is shown in Fig. 1. Companion circuits of induction motor can be described by system of equation (1), where three phase of stator and rotor are presented in vector form [12].

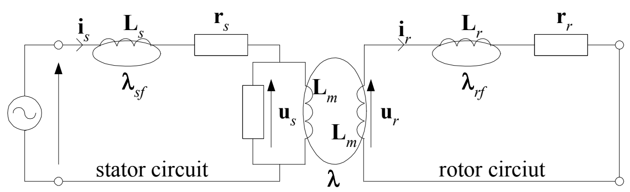

Figure. 1.Electrical equivalent of asynchronous machine

Vectors $\mathbf{u}^s_{abc}$, $\mathbf{i}^s_{abc}$ and $\boldsymbol{\lambda}^s_{abc}$ represent stator voltages, currents and flux. $\mathbf{i}^r_{abc}$ and $\boldsymbol{\lambda}^r_{abc}$ 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 diagonal matrix.

$$\begin{aligned}
\frac{d\boldsymbol{\lambda}^s_{abc}}{dt} &= \mathbf{u}^s_{abc} - \mathbf{r}_s\,\mathbf{i}^s_{abc} \\
\frac{d\boldsymbol{\lambda}^r_{abc}}{dt} &= -\mathbf{r}_r\,\mathbf{i}^r_{abc} \\
\boldsymbol{\lambda}^s_{abc} &= \mathbf{L}_s\mathbf{i}^s_{abc} + \mathbf{L}_m(\theta)\mathbf{i}^r_{abc} \\
\boldsymbol{\lambda}^r_{abc} &= \mathbf{L}^T_m(\theta)\mathbf{i}^s_{abc} + \mathbf{L}_r\mathbf{i}^r_{abc}
\end{aligned} \tag{1}$$

Elements of matrix $\mathbf{L}_s$, $\mathbf{L}_r$, and $\mathbf{L}_m$ are described by equations (2). l_{ls} and l_{lr} are self – inductance for stator and rotor, and l_m is mutual inductance

$$\begin{aligned}
\mathbf{L}_s &= l_{ls}\mathbf{I} + \mathbf{L}_m(0) \\
\mathbf{L}_r &= l_{lr}\mathbf{I} + \mathbf{L}_m(0)
\end{aligned} \tag{2}$$

where

$$\mathbf{L}_m(\theta) = l_m \begin{bmatrix} \cos(\theta) & \cos\left(\theta - \frac{2}{3}\pi\right) & \cos\left(\theta + \frac{2}{3}\pi\right) \\ \cos\left(\theta + \frac{2}{3}\pi\right) & \cos(\theta) & \cos\left(\theta - \frac{2}{3}\pi\right) \\ \cos\left(\theta - \frac{2}{3}\pi\right) & \cos\left(\theta + \frac{2}{3}\pi\right) & \cos(\theta) \end{bmatrix}$$

Mechanical part of induction motor can be described by (3) and (4), where ω_r is angular rotor velocity, J – moment of inertia, T_m - mechanical torque, T_{em} electromagnetic torque, z_p number of pole pairs.

$$J\frac{d\omega_r(t)}{dt} = T_{em} - T_m \tag{3}$$

$$T_{em} = z_p\left(\mathbf{i}^s_{abc}\right)^T \frac{\partial \mathbf{L}_m(\theta)}{\partial\theta}\mathbf{i}^{\mathbf{r}}_{abc} \tag{4}$$

Model described by the above equations is exceptionally difficult for direct application. Transformation from *abc* to *dq*0 system is carrying out by using of transformation matrix (5).

$$\mathbf{T}_{dq0} = \frac{2}{3}\begin{bmatrix} \cos(\theta) & \cos\left(\theta - \frac{2}{3}\pi\right) & \cos\left(\theta + \frac{2}{3}\pi\right) \\ \sin(\theta) & \sin\left(\theta - \frac{2}{3}\pi\right) & \sin\left(\theta + \frac{2}{3}\pi\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \tag{5}$$

Relations (1) can be transformed with the matrix $\mathbf{T}_{dq0}$, to $dq0$ coordinates as in (6) and (7), where $\mathbf{u}^s_{dq} = [u^s_d\ u^s_q]^T$, $\mathbf{i}^s_{dq} = [i^s_d\ i^s_q]^T$ and $\mathbf{i}^r_{dq} = [i^r_d\ i^r_q]^T$ are adequately voltages and currents matrix of stator and currents matrix of rotor [7].

$$\begin{aligned}
\frac{d\boldsymbol{\lambda}^s_{dq}}{dt} &= \mathbf{u}^s_{dq} - \mathbf{r}_s\,\mathbf{i}^s_{dq} \\
\frac{d\boldsymbol{\lambda}^r_{dq}}{dt} &= -\mathbf{r}_r\,\mathbf{i}^r_{dq} + z_p\omega_r\mathbf{K}\boldsymbol{\lambda}^r_{dq}
\end{aligned} \tag{6}$$

where flux are given by:

$$\begin{aligned}
\boldsymbol{\lambda}^s_{dq} &= \mathbf{L}_s\mathbf{i}^s_{dq} + \mathbf{L}_m\mathbf{i}^r_{dq} \\
\boldsymbol{\lambda}^r_{dq} &= \mathbf{L}_m\mathbf{i}^s_{dq} + \mathbf{L}_r\mathbf{i}^r_{dq}
\end{aligned} \tag{7}$$

$\mathbf{r}_s$, $\mathbf{r}_r$, $\mathbf{L}_s$, $\mathbf{L}_r$ and $\mathbf{L}_m$ and are diagonal matrix at the size of (2 x 2), and $\mathbf{K} = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$.

III. 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. 2. Turns sum µus and µsh is overall numbers of turns stator in phase A ($\mu_{us} + \mu_{sh} = N_s$). Phase B and C have the same number of turns equal N_s.

If the number of turns in all three stator phases are the same, we can apply basic model (with specific modification) to describe a mathematical model of induction motor with turn-to-turn fault.

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]:

$$\begin{aligned}
\frac{d\boldsymbol{\lambda}^s_{abc}}{dt} &= \mathbf{u}^s_{abc} - \mathbf{r}_s\left(\mathbf{i}^s_{abc} - \boldsymbol{\mu}_{abc}i_f\right) \\
\frac{d\boldsymbol{\lambda}^r_{abc}}{dt} &= -\mathbf{r}_r\,\mathbf{i}^r_{abc} \\
\boldsymbol{\lambda}^s_{abc} &= \mathbf{L}_s\left(\mathbf{i}^s_{abc} - \boldsymbol{\mu}_{abc}i_f\right) + \mathbf{L}_m(\theta)\mathbf{i}^r_{abc} \\
\boldsymbol{\lambda}^r_{abc} &= \mathbf{L}^T_m(\theta)\left(\mathbf{i}^s_{abc} - \boldsymbol{\mu}_{abc}i_f\right) + \mathbf{L}_r\mathbf{i}^r_{abc}
\end{aligned} \tag{8}$$

where $\boldsymbol{\mu}_{abc} = [\mu_{sh}\ 0\ 0]^T$ is a vector representing position of turn-to-turn fault in the stator circuit.

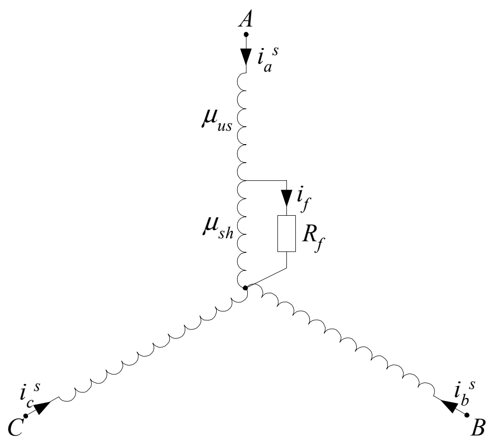

Figure. 2. Three phase stator winding with turn to turn fault in phase A

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

$$\frac{d\lambda_a^{sh}}{dt} = R_f i_f - \mu_{sh} r_s (i_a^s - i_f) \tag{9}$$

where i_f – short-circuit current.

Transforming (5) into *dq0* coordinates, with taking into consideration of (9), one can obtain:

$$\begin{aligned} \frac{d\boldsymbol{\lambda}_{dq}^s}{dt} &= \mathbf{u}_{dq}^s - \mathbf{r}_s \left(\mathbf{i}_{dq}^s - \mathbf{T_{dq}} \boldsymbol{\mu}_{\mathbf{dq}} i_f \right) \\ \frac{d\boldsymbol{\lambda}_{dq}^r}{dt} &= -\mathbf{r}_r \mathbf{i}_{dq}^r + z_p \omega_r \mathbf{K} \boldsymbol{\lambda}_{dq}^r \\ \frac{d\lambda_q^{sh}}{dt} &= R_f i_f - \mu_{sh} r_s (i_{qs}^s - i_f) \end{aligned} \tag{10}$$

where flux are given by:

$$\begin{aligned} \boldsymbol{\lambda}_{dq}^s &= \mathbf{L}_s \left(\mathbf{i}_{dq}^s - \mathbf{T}_{dq} \boldsymbol{\mu}_{dq} i_f \right) + \mathbf{L}_m \mathbf{i}_{dq}^r \\ \boldsymbol{\lambda}_{dq}^r &= \mathbf{L}_m \left(\mathbf{i}_{dq}^s - \mathbf{T}_{dq} \boldsymbol{\mu}_{dq} i_f \right) + \mathbf{L}_r \mathbf{i}_{dq}^r \\ \lambda_q^{sh} &= \mu_{sh} l_{ls} \left(i_q^s - i_f \right) + \mu_{sh} L_m \left(i_q^s + i_q^r - \frac{2}{3} \mu_{sh} i_f \right) \end{aligned} \tag{11}$$

where $\boldsymbol{\mu}_{dq} = [\mu_{sh}\ 0]^T$. Detailed model of the considered circuits is shown in Fig. 3.

Mechanical part of induction motor in *dq* system is described by (3) and (12),

$$T_{em} = \frac{3}{2} z_p \left(\lambda_d^s i_q^s - \lambda_q^s i_d^s \right) - z_p \mu_{sh} \lambda_d^s i_f \tag{12}$$

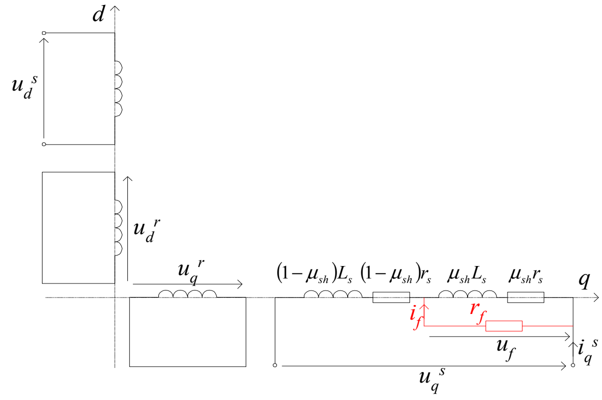

Figure. 3. Motor model with turn to turn stator short circuit

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.

IV. EMTP Simulation Model

The considered model is implemented in ATP-EMTP program as the Type-94 iterative element (Figure 4). In the simulation course the model processes of the input voltages and generates of the output currents according to the following general iterative relation [6]:

$$\mathbf{I}^m(k) = \mathbf{G}^{m-1}(k)\mathbf{U}^m(k) + \mathbf{I}_{hist} \tag{13}$$

where: $\mathbf{G}^{m-1}(k) = \left. \frac{\partial \mathbf{I}(t)}{\partial \mathbf{U}(t)} \right|_{t=t_k}^{m-1}$ is the Jacobian matrix, $\mathbf{I}_{hist}$ represents the history current (depending on the applied integration method), $\mathbf{U}(k)$ – vector of input voltages, $\mathbf{I}(k)$ – vector of output currents, k – simulation step number, m – iteration number.

In the analyzed model current and voltage vectors have the structure: $\mathbf{U} = \left[u_a^s \quad u_b^s \quad u_c^s \quad \omega_r \right]^T$ $\mathbf{I} = \left[i_a^s \quad i_b^s \quad i_c^s \quad T_{em} \right]^T$. The last positions are related to the model of the mechanical part. In the transformation matrix (5) also the system frequency need to be known. Consequently, the considered model is of 4th order and the conductance matrix **G** has 4×4 size [8]. The relation (13) is applied for iterative solution of the whole model in the consecutive time steps. That is equivalent to the known Newton iteration routine of ATP, used for finding a solution point for nonlinear components of the circuit. However, real reaction of the internal induction motor model to given voltage is calculated according to the above derived models: for pre-fault and after-fault condition respectively.

In the general case when the model is nonlinear the matrix **G** (transfer conductance) should be upgraded in each iterative step. In a linear model – as in the considered case – this matrix rests unchanged and need to be recalculated only at the beginning and during fault inception due to the topology and algorithm changing.

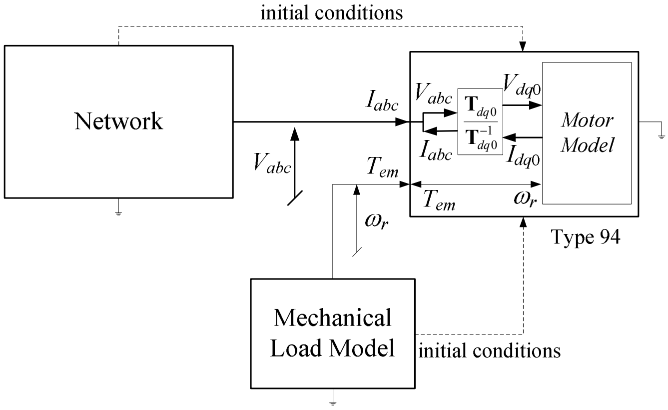

Figure 4. Structure of the EMTP Type 94 induction motor model

The Type-94 procedure is written in MODELS code and, therefore, the model starts at t = 0 and initial steady-state conditions could not be automatically calculated. However, the element has additional mechanism for inserting the steady-state initial conditions (voltages and currents – Figure 4) to the internal procedure. This enables start of the simulation from different initial states.

V. SIMULATION RESULTS

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

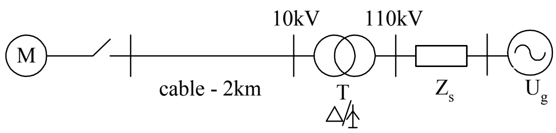

Figure. 5. Structure of simulation model

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.

Figure 6 presents typical waveforms related to start-up of the motor. Motor starts under no-load condition and next, at t = 2.8s additional load with nominal value was added. These waveforms was compared with the results obtained from tests with standard EMTP model. Both results are very close each other.

In the second part of simulations the inter-turn fault was considered. Some results can be track at Figs. 7 – 9. The fault included 5% of stator phase A winding was introduced at t = 3.5s. It can be seen that the fault current takes great magnitude and the negative sequence current also appears. It is well known that appearance of the negative sequence current at the supplied current is a good detector to reveal an internal fault.

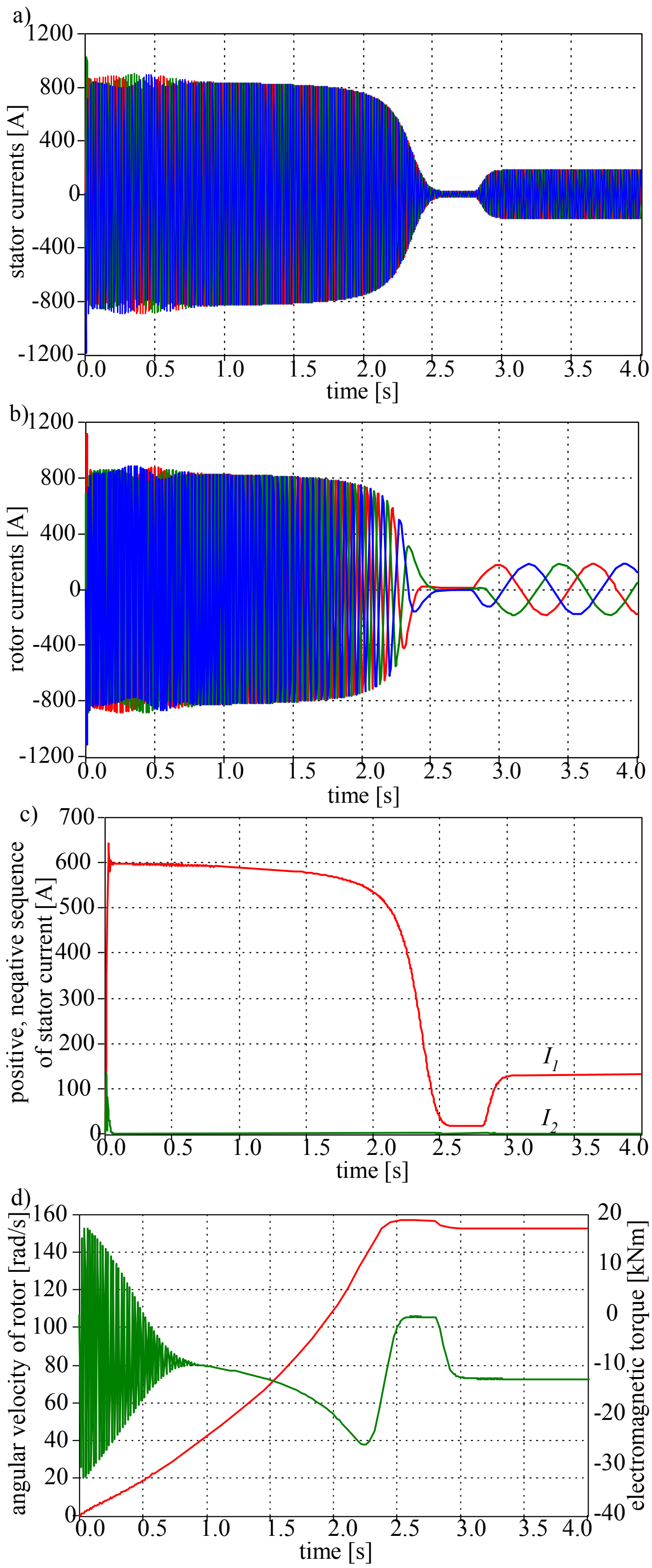

Figure 6. Simulation of induction motor (without a fault) – a - stator currents, b – rotor currents, c – positive and negative sequence of stator currents, d - angular rotor velocity an electromagnetic torque.

It isn't hard to see, that introducing an additional resistor into the short circuit scheme causes the reducing of fault current and also the negative sequence of stator current.

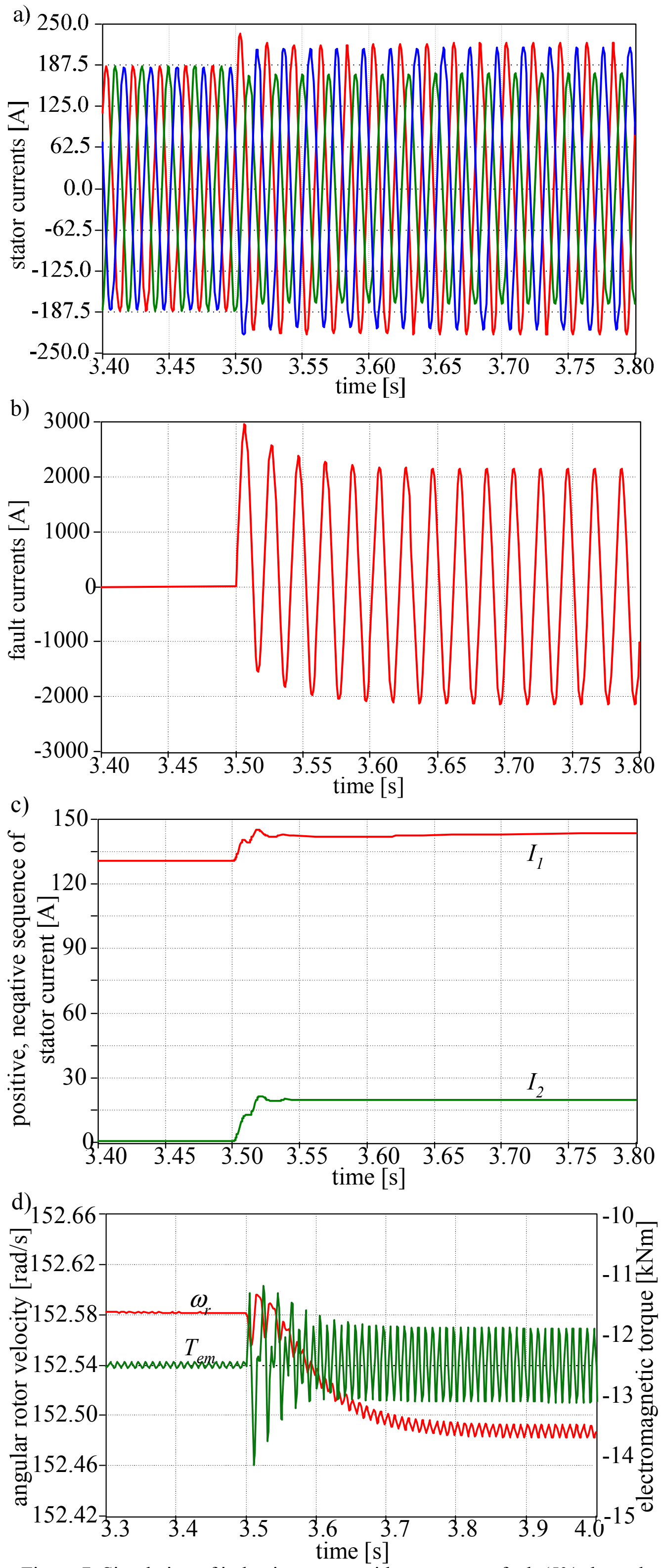

Figure 7. Simulation of induction motor with turn to turn fault (5% shorted turns and $r_f = 0$) – a - stator currents, b – fault current, c – positive and negative sequence of stator currents, d - angular rotor velocity an electromagnetic torque.

The protection has to be designed in such a way so that it doesn't work during the start - up when the starting current is several times bigger from rated current. However, it has to work when in the process of start - up short current occurs. In order to identify such a state, it is very handy to use information carried in themselves by symmetrical components.

In can be seen as well that turn-t-turn faults have big influence on mechanical values, especially on angular speed of rotor and the mechanical torque, which with doubled network frequency changes both the value of itself and direction Simulation results for this cases is shown in Fig. 7d. and Fig. 9e.

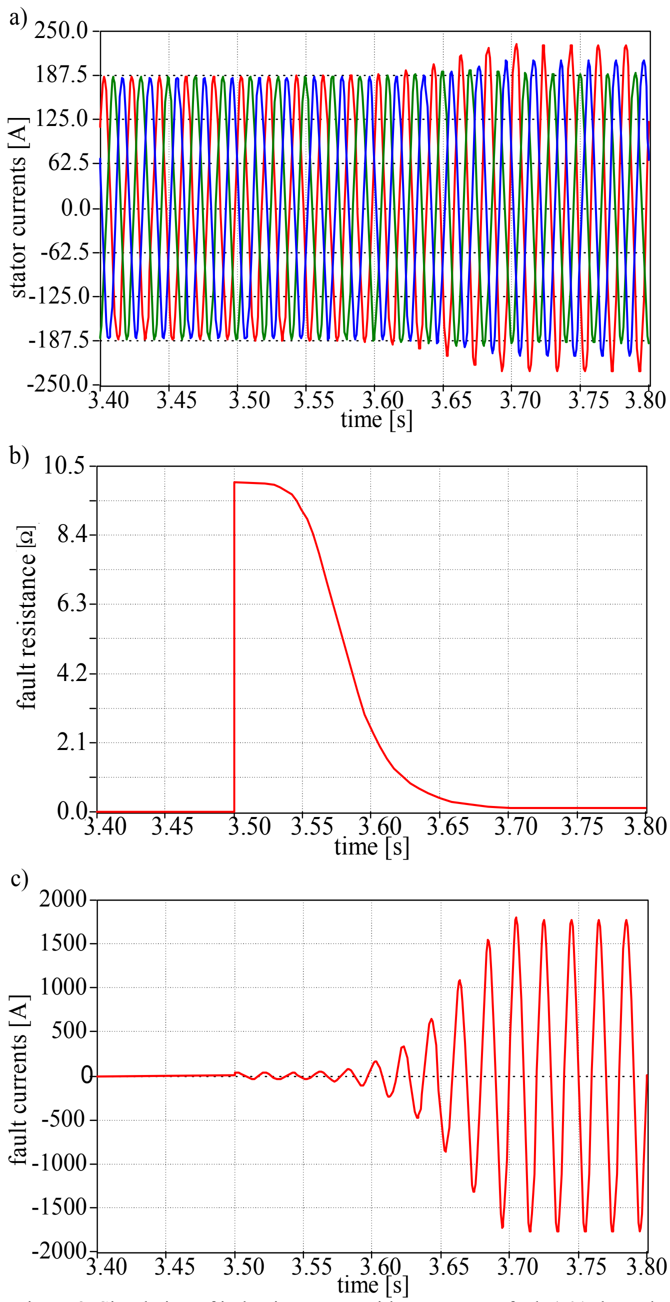

Figure 8. Simulation of induction motor with turn to turn fault (5% shorted turns and r_f - nonlinear) – a - stator currents, b- fault resistance, c – fault current.

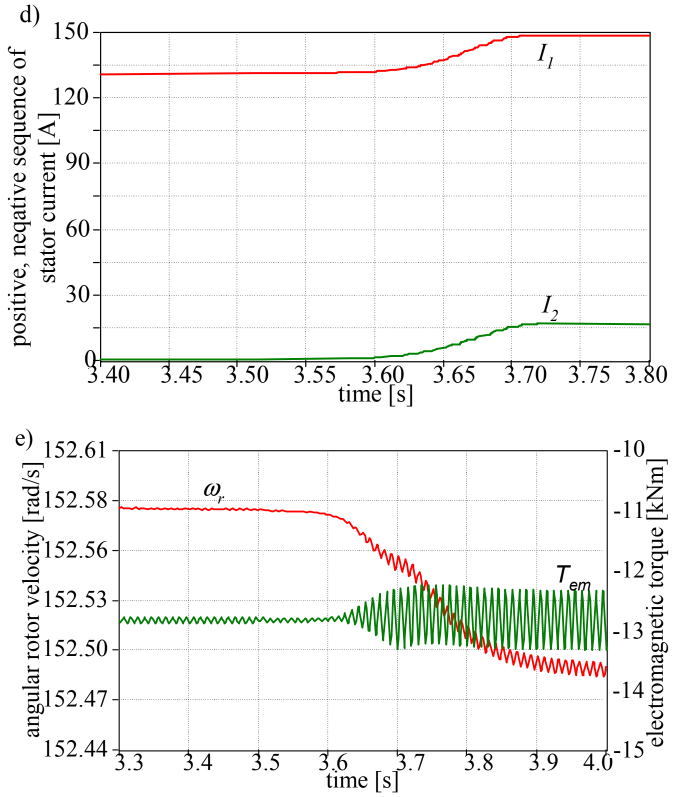

Figure 9. Simulation of induction motor with turn to turn fault (5% shorted turns and r_f - nonlinear) – d – positive and negative sequence of stator currents, e – angular rotor velocity an electromagnetic torque.

Positive and negative sequence stator current are proportional to percent number of shorted turns. The current at the motor terminals increases along with growing number of shorted turns. Relation between positive and negative sequence currents vs. shorted turns is presented in Fig. 10.

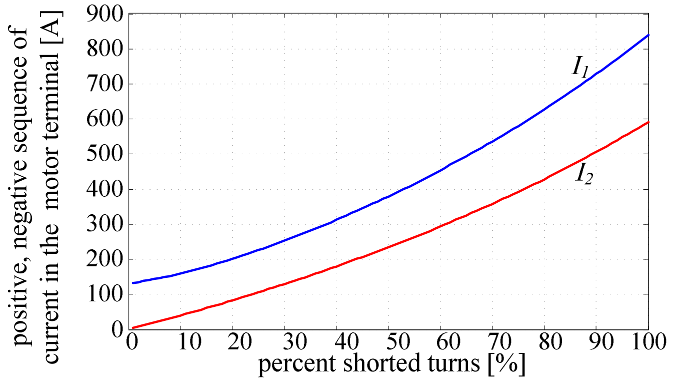

Figure 10. Positive and negative sequence current vs. shorted turns ($r_f = 0$)

VI. CONCLUSIONS

The problems related to modelling of induction motors, and particularly turn-to-turn faults in stator windings are presented in the paper. The model was prepared by using of the ATP – EMTP program. 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 wider analysis of the internal structure of motor and part of the network, which enable to conduct a series of research and simulations from the range of phase to phase faults and ground faults in induction motors, that on the basic of an analysis of the accompanying power system protection.

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