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ON THE ERRORS WHEN USING THE SIMPLIFIED ORTHOGONAL MODEL OF THE INDUCTION MACHINE IN TERMS OF FLUXES

BY

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Abstract. In order to use the simplified orthogonal model of the induction machine in terms of fluxes, equality between a stator and a rotor voltage is needed. Based on the relationship between the two voltages and on how the difference between the stator and rotor resistances induces the difference between these voltages, the paper analyses the simulation errors in different circumstances and evaluates these errors. Finally, a value equal to the rotor resistance is suggested as the optimum value for the R_m resistance for minimal errors.

Key words: induction machine; two-phase model; equivalent circuit; PSpice.

1. Introduction

When the orthogonal model is used to describe the behavior of an induction machine, the PSpice implementation can be based on a typical equivalent circuit and the solution of the mechanical eqs. can be obtained using generic integrators (Cociu & Cociu, 1997). The voltage eqs. written in terms of currents and those in terms of fluxes give similar but not identical topologies of the equivalent circuit. The model using only fluxes has an additional controlled voltage source and an additional node as in Fig. 1 *a*. Simulation is a bit slower

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and the output data file a bit larger (Cociu & Cociu, 2012). This situation is specific only for the PSpice implementation.

A simplified equivalent electrical schematic is proposed by Cociu & Cociu, (2013). In this case, even if the model in terms of fluxes is used, the topology of the equivalent circuit, shown in Fig. 1 *b*, turns out identical to the classical case when the model in terms of currents is used. Now the same number of nodes and controlled sources is involved. The output files have the same size and the speed simulation increases.

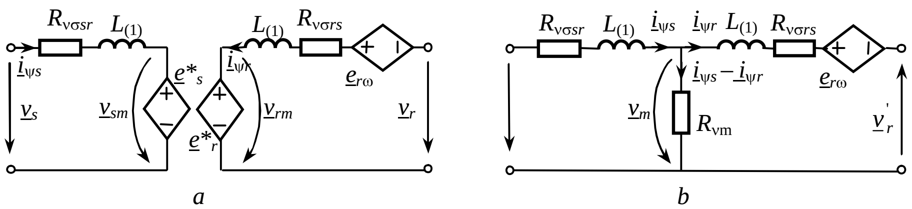

Fig. 1 – Equivalent circuit of the two-phase model of induction machine using fluxes: *a* – original equivalent circuit; *b* – simplified equivalent circuit.

In order to simplify the equivalent circuit, we assumed the equality of the two voltages:

$$\underline{v}_{sm} = v_{sm}\left(\underline{\psi}_s - \underline{\psi}_r^{'}\right), \ \ \underline{v}_{rm} = v_{rm}\left(\underline{\psi}_r^{'} - \underline{\psi}_s\right), \tag{1}$$

where, using the notation $\Delta_L = L_s L_r / L_m^2$, we have:

$$v_{sm} = \frac{R_s L_m}{\Delta_L}, \ \ v_{rm} = \frac{R_r^{'} L_m}{\Delta_L}. \tag{2}$$

But considering the equality $\underline{v}_{rm} \cong \underline{v}_{sm} \cong \underline{v}_m$, even when $R_s \neq R_r^{'}$, is similar to accepting errors in final results. The analytic analysis presented by Cociu & Cociu, (2013) emphasizes two different situations: the induction machine operates in normal load, for small slip values that are around the synchronism speed, and overload operation or start-up operation, when the slip has greater values. Another important result was the fact that the difference of the two voltages is responsible for simulation errors and this difference scales with the relative difference between the stator and rotor resistance, ε_R.

This paper aims to evaluate, using simulation results, the errors introduced by using the simplified equivalent circuit and to analyse the possibilities of controlling the size of these errors in different circumstances. The numerical simulations use the same orthogonal model of an induction machine as Cociu & Cociu, (2013), rated as follows:

$P_n = 5$ kW;	$R_s = 1\ \Omega$;	$L_{\sigma s} = 8$ mH;	$J = 30$ g.m^2;
$U_{1\text{ln}} = 380$ V;	$R_r^{'} = 1\ \Omega$;	$L_{\sigma r}^{'} = 8$ mH;	$F_\alpha = 30$ N.m.s/rad;
$f_1 = 50$ Hz;	Y connection;	$L_m = 120$ mH;	$p = 1$.

2. Choosing the Best Expression for R_m

The basis of the equivalent circuit simplification is considering the equality of the two voltages (1) which implies the equality of the two parameters (2).

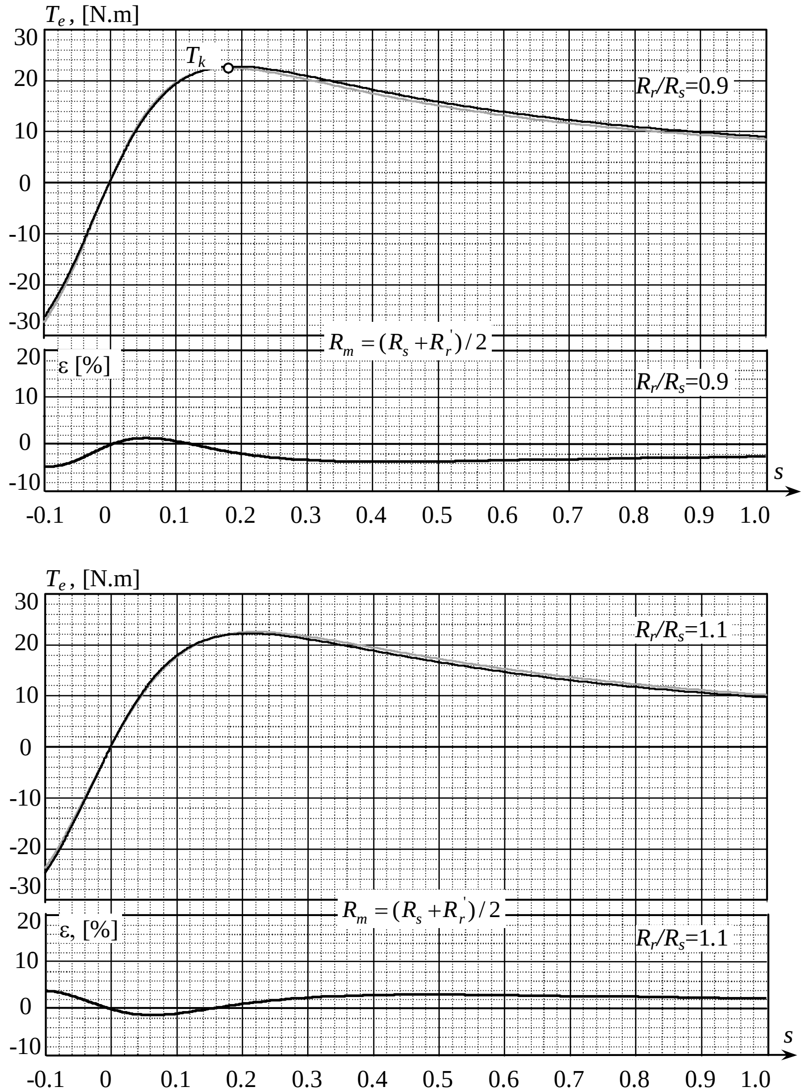

Fig. 2 – Torque and error *versus* slip for close R_s and $R_r^{'}$ values.

In the simplified equivalent circuit these two parameters, in the general case with different values, are replaced by a new parameter:

$$v_{sm} \approx v_{rm} \approx v_m = \frac{R_m L_m}{\Delta_L}, \tag{3}$$

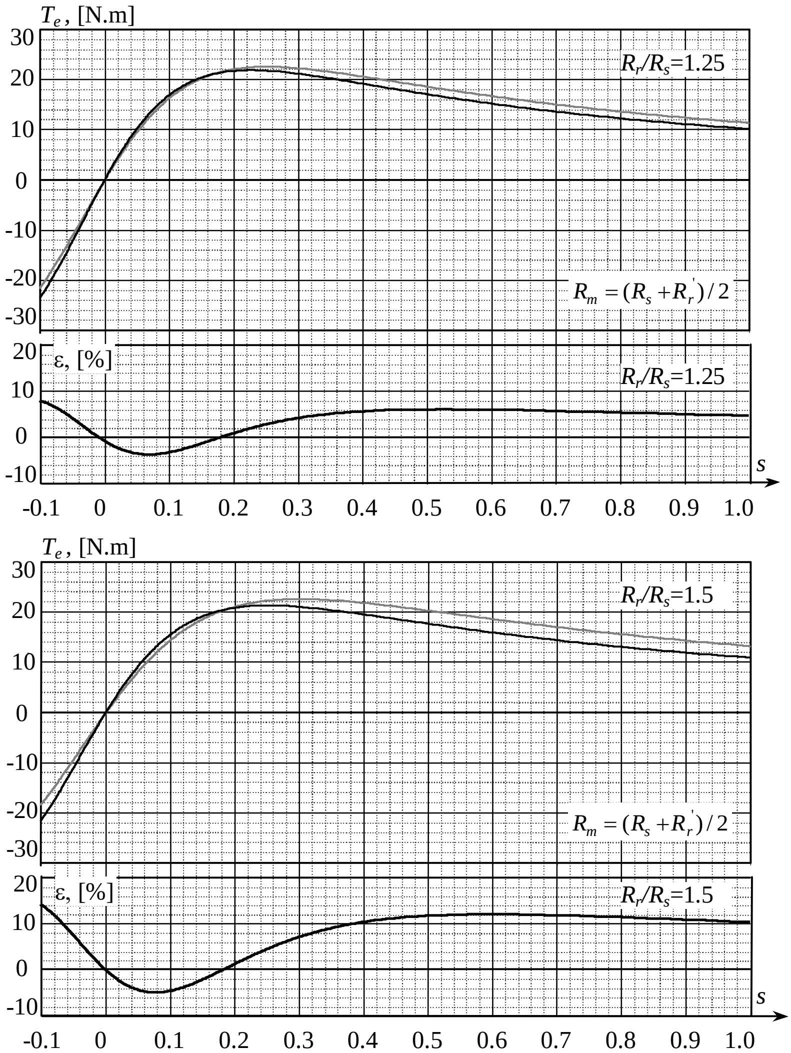

Fig. 3 – Torque and error *versus* slip for values of R_s and $R_r^{'}$ that are more different from each other.

It is natural, based on relations (2) and (3), to consider R_m as having a value between R_s and $R_r^{'}$. The average value seems to be a good choice. That is why the analysis begins with

$$R_m = \frac{1}{2}(R_s + R_r^{'}) . \tag{4}$$

At first, the mechanical characteristic, $T_e = f(s)$, was considered. This characteristic is representative for the general induction machine behavior. The dark line is used for the results obtained using the simplified model and the light line is the standard, when the complete model is used. The relative error was considered normalized to the maximum electromagnetic torque value, T_k.

Figs. 2 and 3 show the simulation results based on relation (4). A large range for the ratio $R_r^{'}/R_s$, from 0.9…1.5, was considered. As expected, the differences between the two curves are little for $R_r^{'}/R_s = 0.9...1.1$ and greater for $R_r^{'}/R_s$ =1.25…1.5.

Depending on slip, *s*, the difference between the torque characteristics and the error is positive or negative. At the synchronism speed, $s = 0$, there is no error. Passing from $R_r^{'}/R_s < 1$ to $R_r^{'}/R_s > 1$, the sign of the error changes. Of course, for $R_r^{'}/R_s = 1$, the error is zero. As Fig. 1 shows, the errors are acceptable for close values for R_s and $R_r^{'}$. That is why, in the following, only the case $R_r^{'}/R_s = 1.25...1.5$ was analysed.

Starting from the fact that the errors become large enough to be taken into account if the difference of the two resistances is greater, another formula for R_m was examined namely

$$R_m = R_s\,. \tag{5}$$

Fig. 4 shows the simulation results based on relation (5). The difference between the results given by the simplified model and those yielded by the standard model is greater than when using (4). In this case, even when the induction machine operates in normal load the results are not acceptable.

For example, in the range s = –0.1…0.1 the error is ε = –8%…17% for $R_r^{'}/R_s = 1.25$ and ε = –14%…28% for $R_r^{'}/R_s = 1.5$, as shown in Fig. 5. Considering $R_m = R_s$ proves to be a bad choice. The explanation lies in the fact that the torque characteristic is influenced in a small extent by the stator resistance, but strongly influenced by the rotor resistance. Considering $R_m = R_s$ means minimizing the importance of the rotor resistance effect on the torque characteristic.

These considerations lead to another expression for R_m:

$$R_m = R_r^{'}\,. \tag{6}$$

As expected, in this case the torque characteristic obtained using the simplified model is closer to the standard model characteristic.

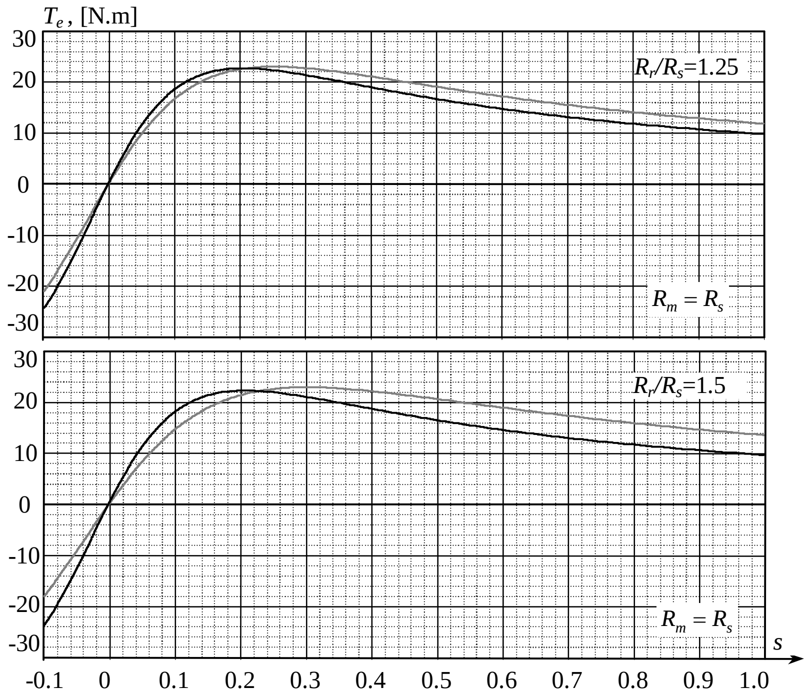

Fig. 4 – Torque *versus* slip for $R_m = R_s$.

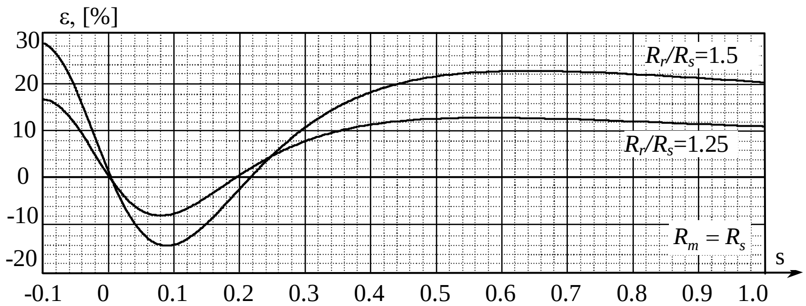

Fig. 5 – Simulation error *versus* slip for $R_m = R_s$.

Fig. 6 emphasizes a different influence of the approximation on the torque characteristic. Only the maximum value of the torque is slightly modified, but the critical slip seems to be unchanged. The errors shown in Fig. 7 are smaller and always have positive values. The maximum error is 10% at $s = s_k$. In the range $s = -0.1...0.1$ the maximum error is 5% for $R_r^{'} / R_s = 1.5$.

A comparison of the approximations given by relations (4),…,(6) reveals that the best expression for R_m is $R_m = R_r^{'}$. This expression leads to the smallest errors, same shape of torque characteristic and can be used not only in normal load operation but also in start-up and generator operation. The use of approximation $R_m = R_s$ is unacceptable in any cases.

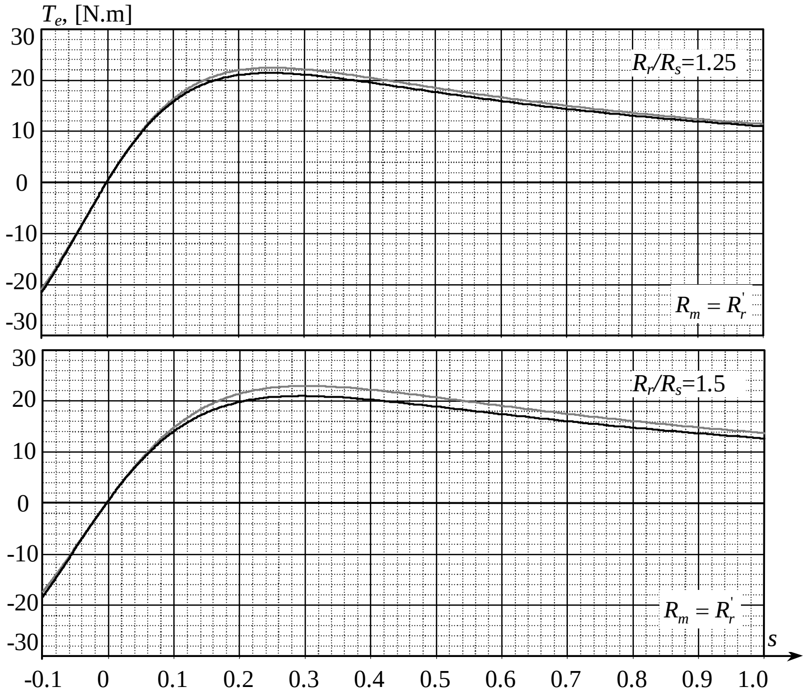

Fig. 6 – Torque *versus* slip for $R_m = R_r^{'}$.

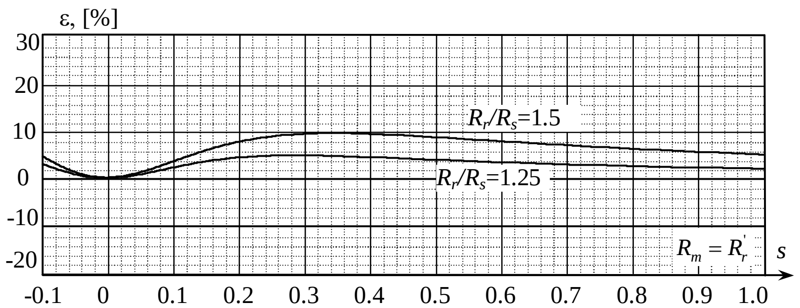

Fig. 7 – Simulation errors *versus* slip for $R_m = R_r^{'}$.

3. Start-up and Transient Considerations

The next step in error evaluation is to verify the most complex dynamic operation, namely the start-up. Two very important mechanical quantities have been taken into account: the angular rotor speed and the electromagnetic torque. As shown in Figs. 3, 4 and 6, no matter the formula used for R_m, the static torque has smaller values than the standard ones.

The dynamic electromagnetic torque is also expected to be smaller than the standard one. Fig. 8 points out that the dynamic torque has slightly smaller values for $R_m = R_r^{'}$ and smaller values for $R_m = (R_s + R_r^{'})/2$.

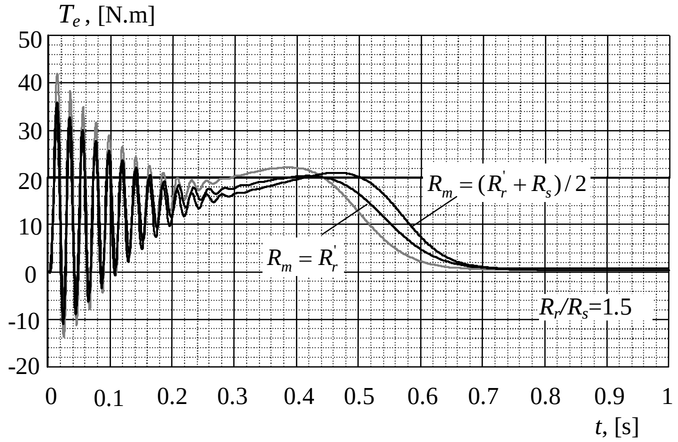

Fig. 8 – The dynamic electromagnetic torque in start-up.

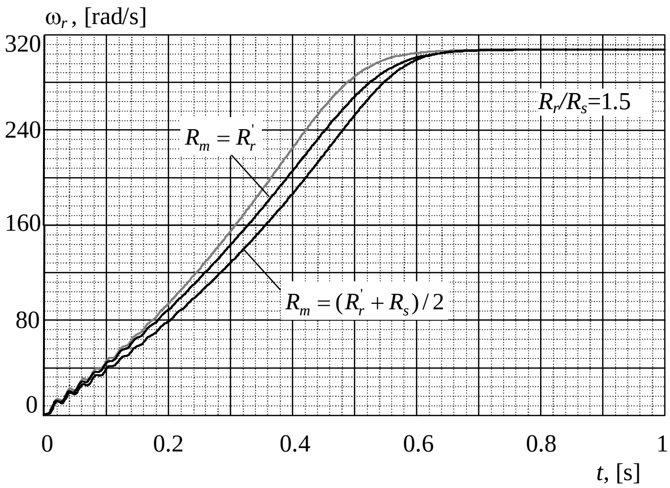

Fig. 9 – The angular speed variation in start-up

Consequently, Fig. 9 presents the speed variation in start-up operation. Also in this case, the use of approximation $R_m = R_r^{'}$ gives a result that is closer to the standard. But significant differences when using the simplified model can be pointed out, especially in the middle of the range.

Fig. 10 presents a typical transient of the induction machine. The motor working in no load is loaded at t = 1 s with T_r = 15 N.m and continues to operate in full load afterwards. In this case, the two approximations give similar errors. According to the static torque characteristic, the assumption $R_m = R_r^{'}$ gives a smaller value for the final speed, while the other formula gives greater value.

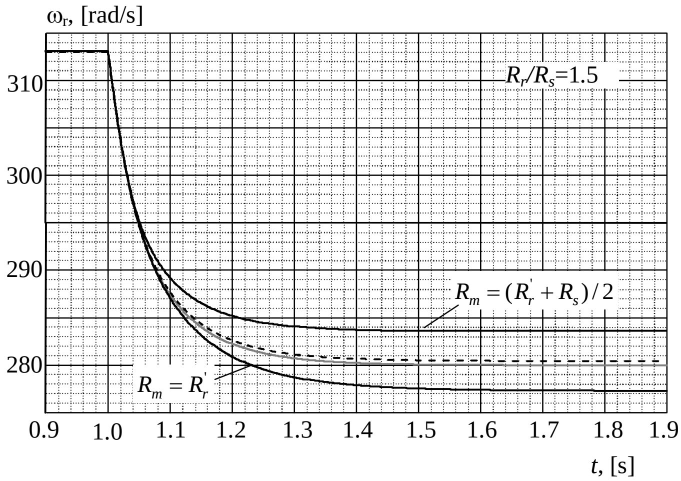

Fig. 10 – The transient for a step load.

In either case not only the final value is affected, but also the time constant of the transient. Considering $R_m = R_r^{'}$ seems to bring better results. The best transient can be obtained using a new expression: $R_m = 0.75R_r^{'} + 0.25R_s$. The simulation results are presented with a dashed line. Because in other cases the formula fails, its use is not recommended.

4. Conclusions

The simplified model of the two-phase model in terms of fluxes can be used in the PSpice implementation to analyse the behavior of the induction machine. Considering the equality $\underline{v}_{rm} \cong \underline{v}_{sm} \cong \underline{v}_m$, even when $R_s \neq R_r^{'}$, is similar to accepting errors in final results. The simplified model brings advantages in induction machine simulation, but can not be applied without introducing errors.

The analysis presented in a previous paper, (2013), emphasizes two different situations: when the induction machine operates in normal load and in overload operation or start-up operation.

The present analysis based on the PSpice simulation brings a highly useful practical result. In all cases when using the simplified model to analyse the behavior of the induction machine, using the assumption $R_m = R_r^{'}$ has more advantages than $R_m = (R_s + R_r^{'})/2$. The errors are less and the expression can be employed in all situations: no load, full load, start-up and generator operation.

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ASPECTE CRITICE PRIVIND MODELUL SIMPLIFICAT UTILIZÂND FLUXURI TOTALE AL MAŞINII DE INDUCȚIE

(Rezumat)

Utilizarea modelului ortogonal al maşinii asincrone, exprimat în fluxuri totale, implică considerarea egalității a două tensiuni, una statorică şi alta rotorică. Pornind de la relația dintre cele două tensiuni şi de la modul în care diferența dintre valorile rezistențelor statorice şi rotorice determină diferența dintre cele două tensiuni, se analizează erorile de simulare introduse de modelul simplificat în diferite situații de funcționare şi se evaluează mărimea acestor erori. Se propune ca valoare optimă pentru rezistența R_m valoarea rezistenței rotorice, situație în care erorile sunt minime în orice condiții de funcționare.