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The Analysis of Induction Motor Rundown Regime Concomitant Electromechanical Processes in Two Phase Coordinate System α,β

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Abstract **– Concomitant rundown regime electromechanical processes demonstrate success of the following induction motor operation regimes linked to different kinds of switching: self start at repeated closing and changeover, wye-delta start-up, reverse etc. This article presents an induction motor mathematical model in two phase coordinate system α,β, which allows to compare characteristics obtained on a model and characteristics received in experimental way without additional transformations. Such characteristics as rotation frequency, residual voltage, electromagnetic torque, stator and rotor currencies and flux linkages were obtained using this model. That gave opportunity to analyze induction motor rundown regime concomitant processes.**

Keywords **– analysis, induction motor, mathematical model, reclosing, rundown regime, transient processes.**

I. INTRODUCTION

Induction motors are dominant consumers of power supply systems today. These motors are rather cheap and do not need large service expenses [1]. Thereto induction motors (IM) utilize about 60% of energy produced in the European Union [2]. Therefore processes in IM investigation remain topical even today. Switching regime is one of the most extensively used in practice IM operation regimes. Switching regime is accompanied by two processes: stator winding switching off and repeated closing. Most interesting for us is stator winding switching off process, respectively induction motor rundown regime investigation. The matter is that this regime specifies success of machine repeated closing at regimes like self start, where to assure important consumers power supply continuity use automatic load transfer automation or repeated closing automation or reverse, wye-delta start-up etc.

The sources overview in this matter showed that there were many issues dedicated to IM switching regimes investigations, but last years there is given particular attention to electromagnetic transient processes [3-7]. The reason of that is fast-response switching automation development succeeding acting time respectable decrease last years [8]. At IM repeated closing in short time there proceeds processes analogical with synchronous machine with certain excitation determined by residual motor flux and residual voltage on terminals switching on [9]. At switching on moment appears inrush current initiating raised impacting windings electrodynamical forces and raised torque. At such conditions it is impossible to ignore residual voltage after IM switching off and this argument led to more deep investigations of this regime. In papers [5-7] there is presented transient processes analysis for IM rapid switching. There are investigated IM repeated switching variants depending on residual voltage and network vectors location for different IM operation load level. But in this papers there is not provided accurate mathematical model describing transient processes at rundown regime and at repeated closing for inrush currents and torques determination. In paper [5] special attention dedicated to inrush currents and torques determination at IM repeated closing. In paper [7] there is presented investigation of IM group repeated closing after repeated closing automation and automatic load transfer acting and its impact on network.

In this article there is provided mathematical model in two phase coordinate system α,β, for IM rundown regime accompanied processes investigation, which allows to get characteristics of rotation frequency, residual voltage, electromagnetic torque, stator and rotor currents flux linkages. Thus we get clear understanding of rundown regime accompanied processes.

II. RUNDOWN REGIME SINGULARITY

To model IM rundown regime we need to understand processes proceeding after IM stator windings switched off power supply.

We know that in accordance with commutation first rule “in circuit with active-inductive load the current impossible to change by step”. Electromagnetic energy accumulated in IM couldn’t be dispersed instantaneously. Electromagnetic energy is concentrated in the main magnetic circuit – excitation circuit and in stator and rotor dispersion magnetic fluxes. Remaining part of electromagnetic energy at opening moment remains constant and supported by squirrel cage rotor windings.

Rundown regime become at IM stator winding switching off power supply. Power interruption might appear by purpose or by any network emergency [10, 11].

Switching IM off power supply stator winding current value suddenly drops to zero. Because of interconnected with stator winding magnetic flow change there inducts voltage the larger the faster acts interruption.

Electromagnetic energy accumulated in IM stay constant and it is supported by rotor winding. This circumstance is important because it allows coordinate final electromagnetic conditions before switching off and initial electromagnetic conditions of rundown regime.

III. ASSUMPTIONS

Making IM rundown regime analysis we assume following [12]:

- ✓ The motor keeps a constant speed when switching off or reclosing is taking place;
- ✓ Saturation is only considered in the calculation of the motor parameters. They remain unchanged for a given transient calculation. This gives a linear nature to the analysis of the transient circuits ;
- ✓ The neutrals of the motor and the power-factor correction capacitors are not grounded; consequently, the current of coordinate zero can be neglected. It is worth mentioning that the current and flux of coordinate zero, even if they exist, do not produce torque;
- ✓ Multiple re-ignition and voltage escalation caused by switch-gears are not considered.

IV. INDUCTION MOTOR MATHEMATICAL MODEL

IM mathematical model in two phase coordinate system α, β looks following:

$$\left.\begin{aligned} \frac{d\psi_{s\alpha}}{d\tau} &= U_m \cdot \cos(\tau) - R_s \cdot i_{s\alpha};\\ \frac{d\psi_{s\beta}}{d\tau} &= -U_m \cdot \sin(\tau) - R_s \cdot i_{s\beta};\\ \frac{d\psi_{r\alpha}}{d\tau} &= -R_r \cdot i_{r\alpha} + \omega_r \psi_{r\beta};\\ \frac{d\psi_{r\beta}}{d\tau} &= -R_r \cdot i_{r\beta} + \omega_r \psi_{r\alpha}; \end{aligned}\right\}, \tag{1}$$

$$\frac{d\omega_r}{d\tau} = (M_{em} - M_l)/T_M, \tag{2}$$

where current values have gotten from flux linkages expressions:

$$\left.\begin{aligned} i_{s\alpha} &= (XR \cdot \psi_{s\alpha} - XAD \cdot \psi_{r\alpha})/del;\\ i_{s\beta} &= (XR \cdot \psi_{s\beta} - XAD \cdot \psi_{r\beta})/del;\\ i_{r\alpha} &= (XS \cdot \psi_{r\alpha} - XAD \cdot \psi_{s\alpha})/del;\\ i_{r\beta} &= (XS \cdot \psi_{r\beta} - XAD \cdot \psi_{s\beta})/del, \end{aligned}\right\}, \tag{3}$$

where $del = XS \cdot XR - XAD \cdot XAD$,

$$M_{em} = XAD(i_{s\alpha} \cdot i_{r\beta} - i_{s\beta} \cdot i_{r\alpha}), \tag{4}$$

$$M_l = SM \cdot \omega_r^2 + SMK. \tag{5}$$

To model rundown regime at IM switching off moment we point start-up steady parameters $\psi_{r\alpha 0}; \psi_{r\beta 0}; \omega_{r0}; i_{r\alpha 0}; i_{r\beta 0}$.

Interrupting motor power supply we assume that stator circuit broken instantly, stator currents are equal to zero [13].

Forced stator current nullification (7) actuates rotor currents $i_{r\alpha}; i_{r\beta}$ change from rotor flux linkage vector invariability at switching moment condition.

$$i_{s\alpha 1} = 0;\ i_{s\beta 1} = 0, \tag{6}$$

Thus, IM rundown process behavior is determined by following differential equations system:

$$\left.\begin{aligned} \frac{d\psi_{r\alpha 1}}{d\tau} &= -RR \cdot i_{r\alpha 1} + \omega_{r1} \psi_{r\beta 1}\\ \frac{d\psi_{r\beta 1}}{d\tau} &= -RR \cdot i_{r\beta 1} + \omega_{r1} \psi_{r\alpha 1} \end{aligned}\right\}, \tag{7}$$

$$\frac{d\omega_{r1}}{d\tau} = (M_{em} - M_l)/T_M. \tag{8}$$

Provided model usage gives opportunity to get rotation frequency, current, flux linkages, electromagnetic torque, residual voltage characteristics at rundown regime for further estimation of safe repeated closing if fast-response automation applied.

V. RUNDOWN REGIME CHARACTERISTICS ANALYSIS

On the base of IM mathematical model presented in previous chapter it was modeled IM with following parameters (in relative units) [14]: $X_1 = 0.099$, $X_2 = 0.14$, $X_{ad} = 5.7$, $R_1 = 0.012$, $R_2 = 0.027$ rundown regime.

After switching off motor continue to rotate by inertia. Motional energy spends for all kind of motion resistance overcome. Therefore motor rotation frequency after complete motional energy spending time interval will become zero (Fig.1).

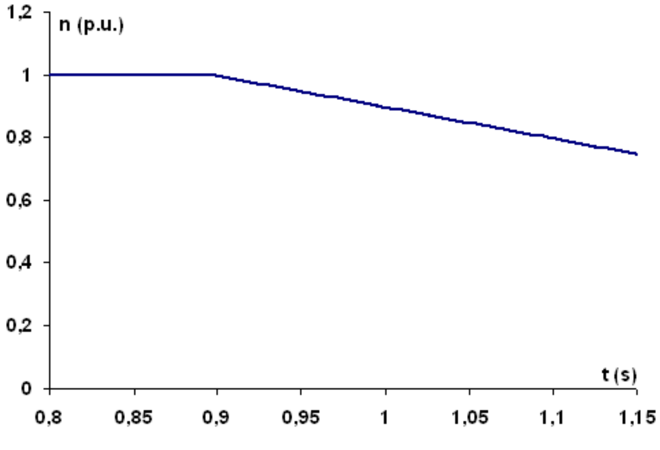

Fig. 1. Rotation frequency curve at IM rundown regime

IM rotation frequency curve at rundown regime gives opportunity to determine exact IM rundown time or residual rotation frequency value at fixed time point after power supply switching off. Exact rotation frequency definition is needed for driven mechanism behavior determination in such regimes as self start, reverse, repeated closing.

Thus, there is opportunity to get rotation frequency curves for any IM with different load factors and load torques without graphic and analytic methods usage.

For mechanism exact stoppage it is important to know not only rotation frequency residual value but residual voltage on stator terminal value as well. Free rundown motor inducted electromotive force (EMF) value has decisive influence on switching on current at power supply renewal (Fig.2). Residual voltage may damp in several periods for small capacity motors but might continue more that 5 seconds in large capacity machines [15].

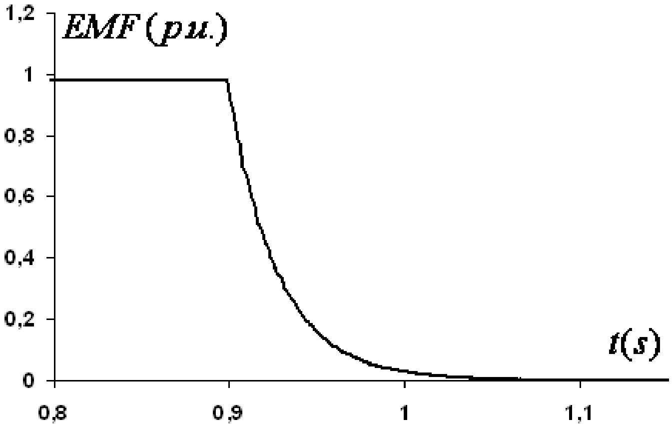

Fig. 2. Residual voltage curve at IM rundown regime

Residual voltage curve at rundown regime gives opportunity to define stator winding residual voltage damping time for any IM independent on its parameters and load type. Thus, there is opportunity to define the time interval needed for residual voltage on stator winding would be limited by $0.33U_N$ on the model, which assure following IM operation regimes safety [16].

On figures 3 and 4 are presented IM full current and electromagnetic torque characteristics at rundown regime.

Rundown regime currents and flux linkages curves analysis showed that in rotor circuit at IM switching off moment rotor current changes step-wise (Fig.5) in contrast to stator circuit current, which drops to zero (Fig.6). Rotor flux linkages at IM switching off moment have damping nature (Fig.7) but stator flux linkages drops to zero instantaneously (Fig.8).

As far rotor current swift increase at IM power supply interruption at rundown process at the matter of this current change there inducts EMF, which phase and value in aggregate with network voltage might have negative impact on IM at rapid reclosing.

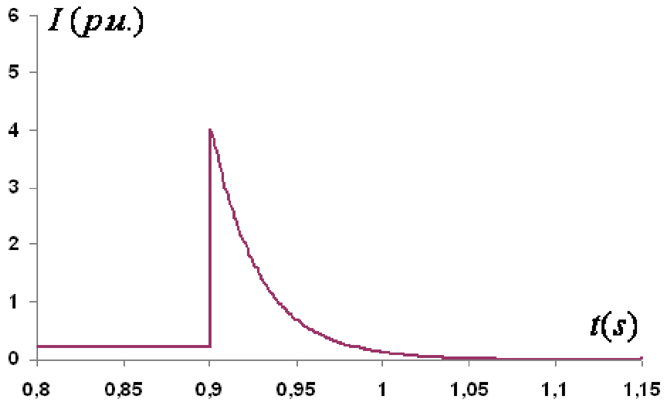

Fig.3. IM current curve at rundown regime.

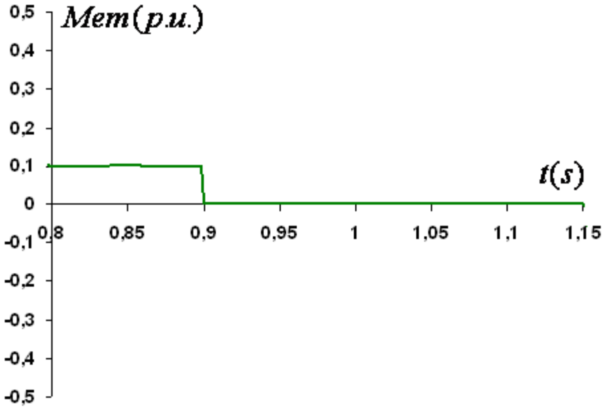

Fig. 4. IM electromagnetic torque curve at rundown regime.

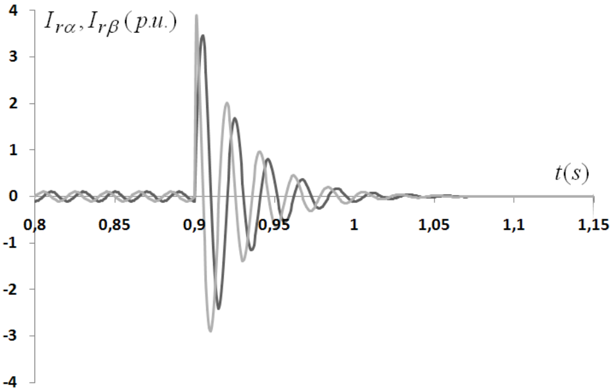

Fig. 5. IM rotor current curve at rundown regime.

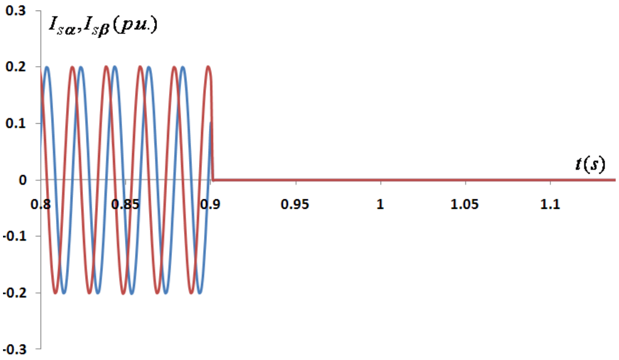

Fig. 6. IM stator current curve at rundown regime.

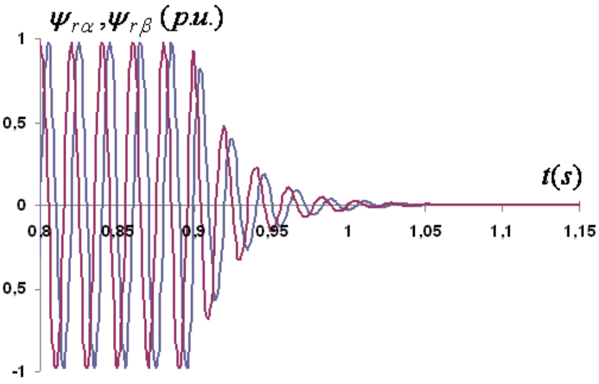

Fig. 7. IM rotor flux linkages curve at rundown regime.

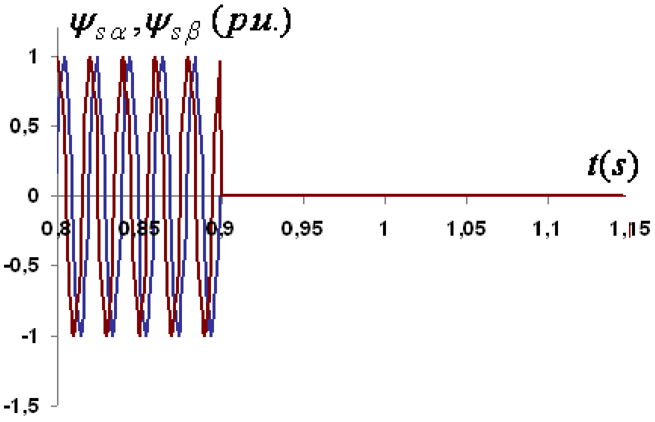

Fig. 8 IM stator flux linkages curve at rundown regime.

To estimate validity of characteristics got by mathematical modeling it was made experiments for rotation frequency, residual voltage characterization for motor with squirrel cage rotor (Fig.11 and 12). Also it was made experiment to get IM with wound rotor stator and rotor currents at rundown regime (Fig. 9 and 10).

At figure 9 it is clear seen that at motor switching off moment stator current drops to zero instantly but rotor current changes by step (Fig.10). Comparison of rundown regime curves received in mathematical modeling way and in oscillographing way shows that experimental characteristics completely concur with characteristics got by modeling.

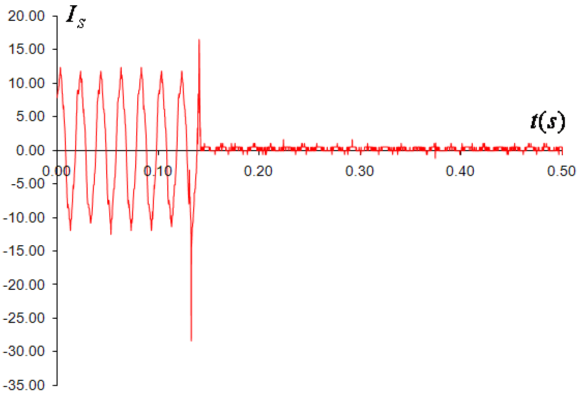

Fig. 9 Stator current oscillogram at IM with wound rotor rundown regime.

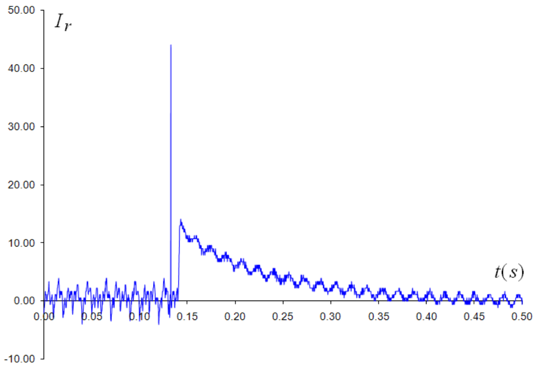

Fig. 10 Rotor current oscillogram at IM with wound rotor rundown regime.

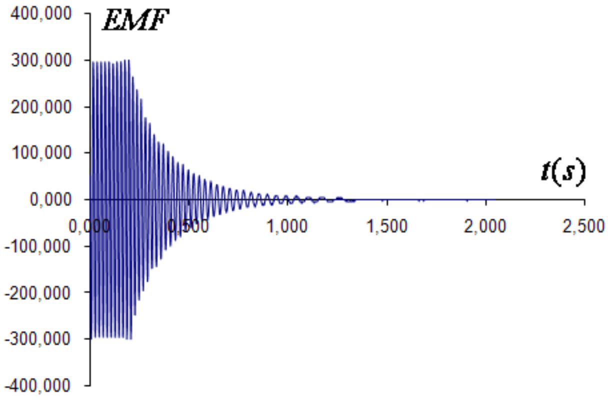

Fig. 11 Residual voltage oscillogram at squirreled cage rotor IM rundown regime.

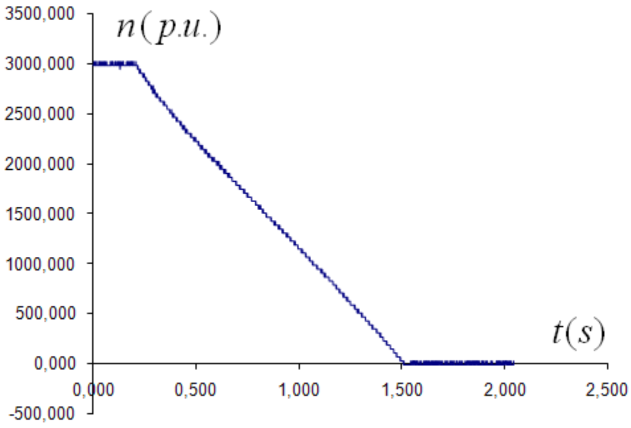

Fig. 12. Rotation frequency oscillogram at squirreled cage IM rundown regime.

VI. CONCLUSIONS

Presented induction motor mathematical model in two phase coordinate system α,β, really allows to analyze rundown processes concomitant electromechanical processes. With the help of this model there is opportunity to find out rotation frequency, residual voltage, electromagnetic torqu, currents and flux linkages curves for any certain IM capacity with different load torques and different load characteristics.

Received characteristics analysis will give an opportunity to define residual rotation torque, permissible stator residual voltage value to ensure safe repeated IM closing at regimes like: self start, wye-delta start-up, reverse etc.

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Koņuhova Marina, Orlovskis Guntis. Asinhronā dzinēja izskrejas režīmu pavadošo elektromehānisko procesu analīze divfāžu koordinātu sistēmā α,β.
Šajā darbā aprakstīts asinhronā dzinēja (ADz) matemātiskais modelis koordinātu sistēmā α,β. Koordinātu sistēmas α,β izmantošana ir vēlama, jo ļauj bez papildus pārveidojumiem salīdzināt rezultātu vienai no fāzēm. Izmantojot šādu modeli tika veikta izskrejas režīmu pavadošo ADz elektromehānisko procesu analīze. Tā izrādījās, ka rotora ķēdē brīdī, kad ADz tiek atslēgts no barošanas avota, rotora strāva pieaug un izskrejas procesā ar laika konstanti nokrītas līdz nullei. Šīs strāvas dēļ statora tinumā tiek inducēts EDS, kas tāpat rimst laikā. Tomēr paliekošais spriegums statora tinumā var norimt pēc vairākiem periodiem mazas jaudas mašīnās, bet var arī ilgt 5 un vairāk sekundes lielas jaudas mašīnās. Tādā veidā izmantojot aprakstīto modeli pastāv iespēja noteikt laiku pa kuru paliekošais spriegums statora tinumā sasniegs drošu vērtību, lai nodrošinātu drošus turpmākos ADz darbības režīmus, tādus kā: pašpalaide izmantojot ARI, AAI, reversu, palaide no zvaigznes uz trīsstūri uc.
Raksturlielumi, kas iegūti izmantojot modeli ADz izskrejas režīmā, tika salīdzināti ar raksturlielumiem, kas iegūti eksperimentālā ceļā. Tādā veidā aprakstītais ADz matemātiskais modelis koordinātu sistēmā α,β ir adekvāts un ļauj veikt elektromagnētisko pārejas procesu analīzi asinhronās mašīnas izskrejas režīmā.

Марина Конюхова, Гунтис Орловскис. Анализ электромеханических процессов, сопровождающих режим выбега асинхронного двигателя в двухфазной системе координат α,β.
В данной работе представлена математическая модель асинхронного двигателя (АД) в координатной системе α,β. Использование координатной системы α,β является предпочтительным, т.к. позволяет без дополнительных преобразований сравнить результат одной из фаз. С помощью такой модели был проведен анализ электромеханических процессов АД, сопровождающих режим выбега. Так оказалось, что в роторной цепи в момент отключения АД от источника питания, ток ротора возрастает и в процессе выбега с постоянной времени обмотки ротора падает до нуля. За счет этого тока индуктируется ЭДС на обмотке статора, которая так же затухает во времени. Однако остаточное напряжение на статорной обмотке может затухнуть через несколько периодов в машинах малой мощности, но может продлиться и более 5 секунд в машинах большой мощности. Таким базом, с помощью представленной модели, имеется возможность определить время, за которое остаточное напряжение на обмотке статора достигнет безопасного значения, для обеспечения безопасных последующих режимов работы АД, таких как: самозапуск с использованием АРВ, АПВ, реверс, пуск со звезды на треугольник и пр.
Характеристики, полученные на модели для АД в режиме выбега, были сопоставлены с характеристиками, полученными экспериментальным путем. Таким образом, представленная математическая модель АД в координатной системе α,β является адекватной и позволяет производить анализ электромеханических переходных процессов в режиме выбега асинхронной машины.