UDC 621.31 DOI:10.30724/1998-9903-2019-21-3-4-90-99

ASSESSMENT METHODOLOGIES FOR SYNCHRONOUS MOTORS STABILITY UNDER THREE-PHASE FAULTS IN POWER SUPPLY GRIDS

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Abstract: *This article presents research of three-phase short circuit impact on synchronous motors stability in external power supply grids. The analysis of the work performed on this topic revealed that the following issues in motor operation during the fault are not taken into account: voltage sag on busbars occurred during short circuit; the relationship between busbars voltage and distribution of currents in the elements of the power supply system; the impact of sag through excitation system. As part of the work, short circuits in adjacent lines are considered and the law of voltage sag on the busbars of the backbone substation during short- circuit is revealed. A synchronous motor model was developed to take into account the impact of neglected factors on the motor stability. The article proposes the methodology developed to assess synchronous motor stability under three-phase short circuit faults occurring in electric grids. Research results could be used to calibrate protective relays used in power supply grids with powerful synchronous motors.*

Keywords: *Short-break power supply; short circuit; stability; synchronous motor; critical fault duration; methodology.*

Acknowledgments: *This research was funded by the Ministry of Education and Science of the Russian Federation as a part of federal targeted programme "Research and Development in Priority Areas of Development of the Russian Scientific and Technological Complex for 2014-2020". Grant subsidy agreement № 075-02-2018-190 – 1 stage, unique ID of applied scientific research (project) is RFMEFI57418X0188.*

For citation: Fedotov A.I., Abdullazyanov R.E., Mudarisov R.M. Synchronous motors stability estimation methodologies under three-phase faults in power supply grids. *Proceedings of the higher educational institutions. ENERGY SECTOR PROBLEMS*. 2019; 21(3-4):90-99. (In Russ). doi:10.30724/1998-9903-2019-21-3-4-90-99.

The motors stability maintenance during short-break in power supply resulting from short circuits (SC) in electric grids is one of the key problems in power supply systems equipped by synchronous motors (SM). This problem is solved by the installation and correct regulation of fast automatic load transfer switches (FALTS) and by the electric transmission line relay protections that detect the fault and restore electric power supply before motors lose their synchronism [1, 2].

In both cases the stability of motors can be provided only if critical fault duration is calculated using correct methodologies. Critical fault duration is the maximum time interval corresponding to the operation of SM under the short-break power supply caused by the three-phase short circuits without the loose in synchronism.

The existing practical criteria and methodologies used to assess stability of motors [3, 4], and researches which are performed to calculate the critical fault duration for the motors operating under the short circuits are based on assessment of motors stability with the following assumptions: it is performed under electric power supply interruption and the subsequent supply recovery [1, 2, 5]; it neglects the transient DC component of the voltage sag [6-9]; it doesn`t take into account real distribution of symmetrical current and voltage components over the elements of power supply grid [7,10]; it doesn`t take into account the operation of excitation system i.e. neglect the impact of sag on the motors excitation winding [3–6].

However, short-break in power supply mainly occurs because of short circuits in the transmission lines connected to the same busbars of the backbone substation as the synchronous motors [12].

At the same time, all the above-mentioned assumptions affect the assessment of the reliable duration of a power failure, since during short circuits appearing in the electric grids, motors operate under the voltage sags with transient DC component, moreover distribution of current over the power supply elements during sag effects the motors voltage value and phase. Besides that, powerful synchronous motors are mainly equipped with static excitation systems that are connected to the same busbars as the motors which they excite, and it means that voltage sag also affects the operation of motors through their excitation.

Fig. 1. shows synchronous motors electrical power supply system schematic diagram. It has the following elements: *EG* – Electric grid; L_1 – electric transmission line feeding the motor; L_2 – transmission line with short-circuit (*SC*); T_1 – step down transformer of industrial substation with SM; *BUS–1* – busbars of the backbone substation; *BUS–2* – busbars of the industrial step-down substation.

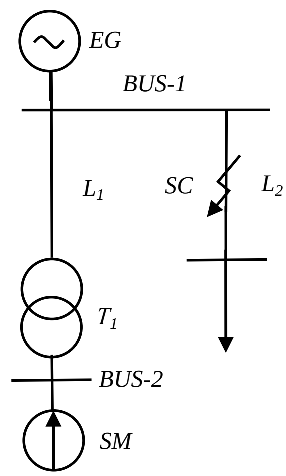

Fig. 1. Power supply grid schematic diagram

Further we consider voltage sags appearing in power supply grids those load consists of synchronous motors by 25–30 % of transformers power (T_1 in fig. 1). According to the Russian state standard GOST 52735-2007 “Short circuits in electrical installations” that defines the methods of short circuit current calculations in the electric grids, when calculating the initial effective value of AC component of the three-phase short-circuit current, it is allowed to neglect synchronous motors if they are separated from the short-circuit point by power transformers. Therefore equations of the periodic AC component of the current and the voltage of phase A on busbars of backbone substation (BUS-1 in fig.1) during the 3-phase short circuit in the line L_2 can be expressed as follows:

$$i_P(t)=\frac{E\sqrt{2}\sin(\omega t+\alpha-\varphi_K)}{\sqrt{3}\sqrt{(R_1+R_2)^2+(X_1+X_2)^2}}=\sqrt{2}I_P\sin(\omega t+\alpha-\varphi_K), \quad (1)$$

$$u_P(t) = \frac{E\sqrt{2}\sqrt{\left(R_2^2 + X_2^2\right)}\sin\left(\omega t + \alpha - \varphi_1\right)}{\sqrt{3}\sqrt{\left(R_1 + R_2\right)^2 + \left(X_1 + X_2\right)^2}} = \sqrt{2}U_P \sin\left(\omega t + \alpha - \varphi_1\right). \quad (2)$$

Transient DC-components of the current and the voltage on the busbars of backbone substation can be calculated by equations:

$$i_A(t) = I_A e^{-t/T}, \quad (3)$$

$$u_A(t) = (R_2 i_A(t) + \frac{X_2}{\omega}\frac{di_A(t)}{dt}) = (R_2 - \frac{X_2}{\omega T}) I_A e^{-t/T}. \quad (4)$$

Symbols used in equations (1–4) have the following meanings: R_1 and X_1 are active and reactive resistances of the electric grid (*EG* in fig.1), respectively; R_2 and X_2 are active and reactive resistances of the line with fault (L_2 in fig.1); E is electromotive force (EMF) of electric grid; T is transient time constant of DC component ; ω is angular frequency of electric grid voltage and current; α is short circuit appearance angle; φ_1 and φ_K are phase angles related to the scheme diagram resistances; I_A is initial value of short circuit current transient component. Value of the current I_A can be calculated as the difference between current AC-component before fault and immediately after it:

$$I_A = I_M \sin(\alpha - \varphi) - \sqrt{2} I_P \sin(\alpha - \varphi_K) \quad (5)$$

Symbols in the equation (5) are: I_M is magnitude of current periodic AC component before the fault; φ is phase angle related to current AC component before the fault. It is clear that the DC component of current and voltage achieve their maximum if the magnitude of current before the fault in the equation (5) equals to zero. This corresponds to case when transmission line with fault doesn`t have the load in prefault conditions. If we rewrite equation (4) by using equation (5) for the conditions with the maximum DC component when I_M is zero we obtain equation (6):

$$u_A(t) = -(R_2 - \frac{X_2}{\omega T})(\sqrt{2} I_P \sin(\alpha - \varphi_K)) e^{-t/T} = -U_A e^{-t/T}. \quad (6)$$

Then the residual voltage (u_R) of the backbone substation busbars (BUS-1 in fig.1) will be written as equation (7) and have periodic (U_P) and transient DC (U_A) components:

$$u_R(t) = \sqrt{2} U_P \sin\left(\omega t + \alpha - \varphi_1\right) - U_A e^{-t/T}. \quad (7)$$

Figs. 2–3 show relationships between DC-component residual voltage (U_{A*}) and phase angle φ_1 and AC-component residual voltage (U_{P*}). Table 1 shows phase angles φ_K corresponding to various values of the DC component transient time constants varying from 0,02 s to 0,2 s. In figs. 2–3 and table 1 transient DC-component voltage (U_{A*}), periodic AC-component voltage (U_{P*}) and DC component transient time constant (T_*) are expressed in relative units. AC current period (0,02 s) is taken as the base unit for the transient time constant. These calculated values are given for 6 values of voltage DC component time constants and correspond to electric grids with 110–220 kV voltage ratings those 3-phase short circuit currents on the backbone substation busbars vary from 4 to 40 kA. Dependencies in figs. 2–3 show that for the considered classes of power supply systems, the DC-transient component of voltage is greater, the greater the voltage sag and the shorter the decay time constant are.

Table 1

Phase angle φ_K for various time constants T_*

T_*, r.u.	1	2	3	4	5	10
φ_K, °	81	85	87	88	88	89

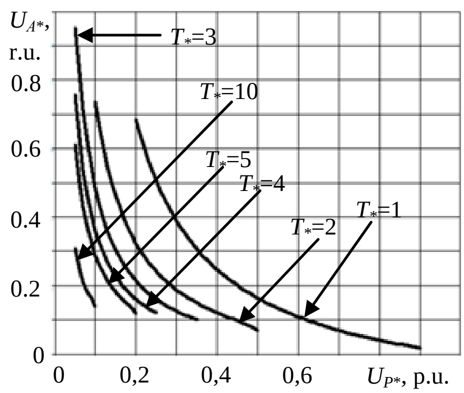

Fig. 2. Relationship between voltage of DC-component (U_{A*}) and voltage of AC-component (U_{P*})

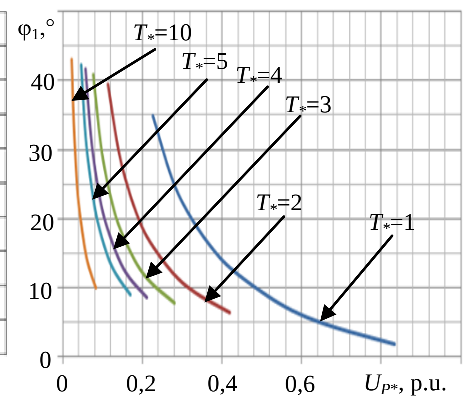

Fig. 3. Relationship between phase angle φ_1 and voltage of AC-component (U_{P*}).

The synchronous motor model shown in fig. 4 is developed to assess motors stability. The distinct feature of this model from its analogues is that it takes into account features in motors operation under 3-phase short circuit conditions such as: sag is described by residual voltage equation (7) with DC-component; it calculates current flow in power supply grid elements and therefore accounts the influence of current on the motor voltage; it calculates the impact of voltage sag on the motors excitation winding.

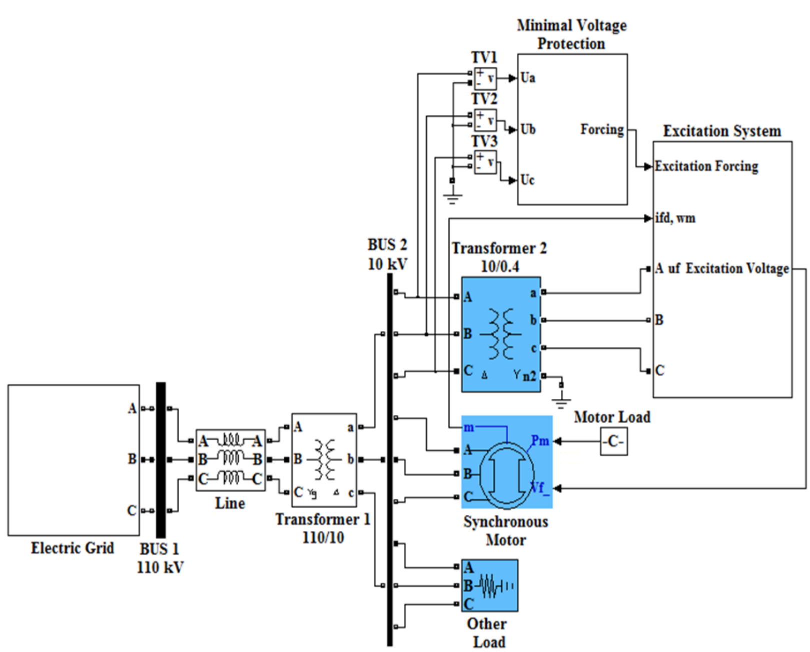

Fig.4. The Simulink model of SM and its power supply grid

In order to calculate the influence of voltage sag on the motors excitation winding the model includes elements of “TE8-320” excitation systems (“Excitation System” element in fig. 4). These elements implement the basic functions of exciters such as: field forcing, switching on the starting resistor that limits voltage surges on the rectifier and starting resistor circuit switching off function.

In order to prove advantages of aforementioned model we have calculated critical fault duration of SM under 3-phase short circuits. Calculation was done using practical criteria and motor models, designed by other researchers. Calculations were performed for the STD-8000 synchronous motor with the following properties of prefault conditions: equivalent load moment of inertia J_{LOAD}=250 kg·m^2, load factor m_L=0,7 r.u., system voltage U=0,997 r.u. (SM voltage U_{SM}=1,081 r.u.), synchronous EMF E_q E_q=1,598 r.u., load angle δ=62,8°. Motor is connected to 110 kV electric grid (Z_1=j15,88 Ohm) through TDN-16000/110 transformer.

Table 2 shows results of critical fault duration research that was carried out using simplified motor models from other researchers.

Table 2

Calculation of stability using simplified motor models

Residual voltage properties (U_{P*}, U_{A*}, T_*, r.u.)		Calculation 1: U_{P*}=0, U_{A*}=0, $T*$=0 (SC on backbone substation busbars)		Calculation 2: U_{P*}=0,111, U_{A*}=0,256, T_*=5 r.u. (U=110 kV, SC in transmission line: AS-240, L=4,7 km)		Calculation 3: U_{P*}=0,227, U_{A*}=0,579, T_*=1 (U=110 kV, SC in transmission line: AS-70, L=7,1 km)		Calculation 4 :U_{P*}=0,431, U_{A*}=0,217, T_*=1 (U=110 kV, SC in transmission line: AS-185 L=26,3 km)		Total error of all calculations Δ t_C, %
№	Motor model type	t_C, ms	Δ, %	t_C, ms	Δ, %	t_C, ms	Δ, %	t_C, ms	Δ, %	
1	Test model	160	0,0	211	0,0	231	0,0	831	0,0	0,0
2	Model 1	172	7,5	215	1,9	232	0,4	932	12,2	22.0
3	Model 2	172	7,5	206	2,4	217	6,1	698	16,0	31,9
4	Model 3	178	11,3	210	0,5	223	3.5	933	12,3	27.5
5	Model 4	245	53.1	314	48,8	1249	440,7	3934	373,4	916,0

Explanations for table 2:

- Test model is full model of the electrical power supply system diagram, shown in fig. 1, that includes electric grid (*EG*), electric transmission line feeding the motor (L_1), step-down transformer (T_1), synchronous motor (*SM*), excitation system, adjacent transmission line with short circuit (L_2) and the element that simulates the 3-phase short circuit fault;
- Model 1 is a developed model, which, instead of a three-phase circuit system and unit in an adjacent line, takes into account the law of change of residual voltage on busbars of backbone substation (*BUS*-1 in fig. 1.) according to expression (7). The model also includes feeding transmission line (L_1), step-down transformer (T_1), motor (*SM*), operation of excitation system under voltage sag.
- Model 2 is the same as the model 1, but doesn’t take into account the transient DC component of the residual voltage equation (7);
- Model 3 is the same as the model 1, but doesn’t take into account the transient DC

component of the residual voltage equation (7) and the impact of sag on the operation of the excitation, exciter voltage is assumed to be constant and equal to exciter voltage before the fault;

- Model 4 is based on distribution of currents in the elements of the power supply system depending on the busbars voltage of backbone substation (*BUS*-1 in fig. 1), electric grid, adjacent transmission line with fault (L_2), feeding transmission line (L_1), step-down transformer (T_1) are simulated as voltage source that generates voltage sag without transient DC component on the busbars of industrial step-down substation, i. e. this model neglects the impact of current flow over the power supply grid elements on the value and phase of motor voltage.

Results of research show that correct stability assessment over full range of voltage sag is possible only within the full model (test model in table 2) and within the developed models (models 1 and 2 in table 2) which are based on distribution of currents in the elements of the power supply system depending on the busbars voltage of backbone substation (*BUS*-1 in fig. 1), which take into account: equation of voltage on the busbars of backbone substation, impact of current flow over the power supply grid elements on the motor voltage, and operation of excitation system under voltage sag. The developed model also has the following advantages when comparing it with full models: it accounts less elements, which results in reduction of time needed to prepare electrical power supply system model, and enables to calculate critical fault duration relatively to the voltage sag values which is used to adjust adaptive relay protection systems.

Table 3 shows critical fault duration that were calculated by practical criteria used to assess motors stability such as: method of equal areas, criterion of transient stability under break in power supply [3, 4]. These results are calculated for the motor with decelerating torque (m_D) caused by excitation field and with field forcing (synchronous EMF of motor with field forcing E_q =1,75$E_{q,\text{NOM}}$=4,0 r.u.). In calculations it is assumed that motor is working under voltage sags described in the calculations 3 and 4 presented in table 2 (in calculation 3 U_{P*} =0,227 r.u., in calculation 4 U_{P*} =0,431 r.u.).

Table 3

Calculation of SM stability using practical criteria

Criterion	Method of equal areas t_A, s			Transient stability under break in power supply t_{CR}, s		
Calculation assumptions:	E_q=const	$E`_q$=const	$E``_q$=const	m_D=0 E_q=E_{q1}	m_D≠0, E_q=4 r.u.	m_D=0, E_q= 4 r.u.
Critical fault duration in calculations 3/4, s	0,151/ 0,209	0,233/ 0,.095	0,083/ 0,047	0,232/ 0,232	0,213/ 0,213	0,292/ 0,292
Errors of calculations 3/4, %	34,6/74,8	0,9/88,6	64,1/94,3	0,4/72,1	7,8/74,4	26,4/64,9

Results of research prove that aforementioned practical stability criteria don`t assure accuracy requirements in calculations of critical fault duration over full range of voltage sag values caused by 3-phase short circuits appearing in the electrical grids. Further we consider characteristic properties of stability assessment in the synchronous motor models that take into account the aforementioned recommendations.

In order to observe the impact of fault appearance time on the motor stability under three-phase short circuit, the motor operation is simulated with 0,001 s shift in fault appearance time which is determined by the phase angle α in the voltage equation (7). The results of this research are presented in fig. 5 as a critical duration vs fault appearance time curve. These results are obtained for the STD-8000 synchronous motor model operating at previously mentioned prefault conditions and under voltage sags described for the calculation 3 presented in table 2 (U_{P*} =0,227 r.u). In fig. 5: curve 1 corresponds to the results obtained using the full model (testing model in table 2), when motor is connected to the electric grid through the transformer (TDN-16000/110); curve 2 corresponds to the results obtained using the full model (test model), when motor is connected to the electric grid through the transformer (TDN-16000/110) and feeding transmission line (conductor of AS-70 type, length 20 km); curve 3 corresponds to the results obtained by the developed model (model 2 in the table 2) that doesn`t account the transient DC-component of the voltage equation (7) for the motor connected to the electric grid through the transformer (TDN-16000/110) and feeding transmission line (conductor of AS-70 type, length is 20 km).

As it is seen from fig. 5, the distinction between the minimum and the maximum critical fault durations is less than 2 % (approximately 3 ms). This result assures that fault appearance time could be neglected during the assessment of SM stability under 3-phase short-circuit faults.

Fig. 6 shows relationship between critical fault duration and residual voltage obtained in the developed model of the STD-8000 synchronous motor connected to 110 kV electric grid through the transformer (TDN-16000/110) and feeding transmission line (conductor type is AS-70) of 20 km length. Motor operates with the following prefault conditions: equivalent load moment of inertia J_{LOAD}=250 kg·m^2, load factor m_L=0,7 r.u., system voltage U=0,995 r.u. (SM voltage U_{SM}=1,07 r.u.), synchronous EMF E_q =1,587 r.u., load angle δ =64,8°. In fig. 6: curve 1 corresponds to the results obtained by the developed model (model 2 in table 2) that doesn`t account the transient DC-component of the voltage equation (7); curves 2–6 correspond to the results obtained by the developed model (model 1 in table 2) that takes into account the transient DC-component of the voltage equation, transient time constants of these curves are equal to (1–5) periods of voltage AC-component consequently.

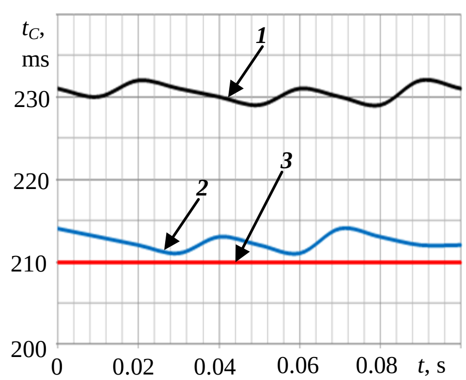

Fig. 5. Critical duration vs fault appearance time

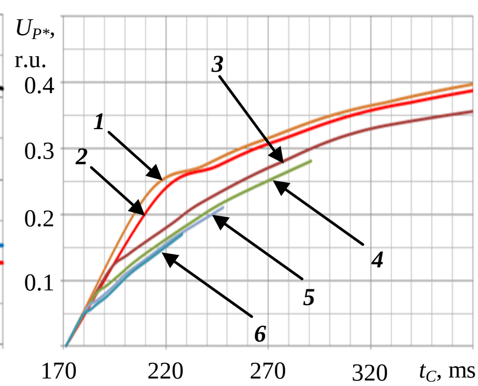

Fig. 6. Critical duration vs residual voltage

It is seen from fig. 6 that transient DC-component of voltage increases the critical fault duration. Thus stability assessment without transient DC-component of voltage sag equation provides calculation of the combined stability zone that includes stability zones with all transient time constants of transient voltage DC-component.

Fig. 7 shows relationship between critical duration and phase angle φ_1 obtained without transient DC-component of the voltage sag equation. Calculation is carried out for the STD-8000 synchronous motor model, prefault condition of which are described in the previous research presented in fig. 5. During the fault motor operates under the voltage sag without transient DC voltage component described in calculation 3 presented in table 2 (U_{P*} =0,227 r.u.).

As it seen from fig. 7, critical fault duration calculated for the fault with the fixed value of AC-component residual voltage (U_{P*} =0,227 r.u.) can change up to 36 % depending on the phase angle φ_1. It should be noticed that real values of φ_1 phase angle vary from 0 to 90° and that increase in this angle increases the critical fault duration. Hence critical fault duration should be calculated for the possibly lower values of the phase angle φ_1.

Fig. 8 shows relationship between phase angle φ_1 and AC-component residual voltage for various values of electric grid resistances and types of transmission line conductor. This curves are plotted for the 110–220 kV electric grids for which three-phase short circuit currents vary from 4 to 40 kA. In fig. 8: curve 1 corresponds to 110 kV transmission line with AS-70 conductor type; curve 2 corresponds to 110 kV transmission line with AS-95 conductor type; curve 3 corresponds to 110 kV transmission line with AS-150 conductor type; curve 4 corresponds to 110 kV transmission line with AS-300 conductor type; curve 5 corresponds to 220 kV transmission line with AS-300 conductor type; curve 6 corresponds to 220 kV transmission line with AS-400 conductor type. From fig. 7–8 it can be concluded that motors stability assessment must be calculated for φ_1 phase angles corresponding to transmission lines with higher cross-section area of conductors and according to curves in fig. 8.

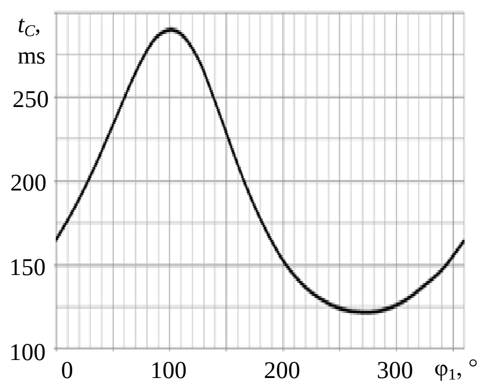

Fig. 7. Relationship between critical duration and phase angle φ_1

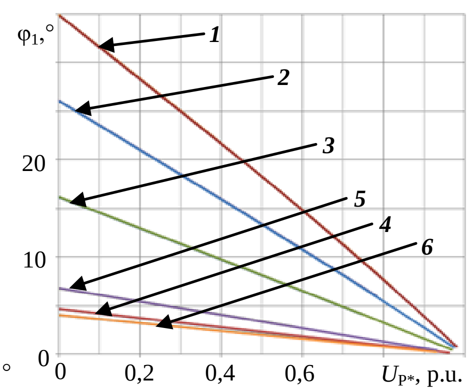

Fig. 8. Relationship between phase angle φ_1 and AC-component voltage (U_{P*})

All results obtained in studies described above are used to develop stability assessment methodology. Methodology assures calculation of critical fault duration of SM under three-phase short circuits appearing in the electrical grids and consists of the following principles:

1) SM computing model should take into account the distribution of currents in the elements of the power supply system depending on the busbars voltage of backbone substation (*BUS*-1 in fig. 1), electric grid and transmission line with the fault can be simulated as voltage source that generates voltage on the busbars of backbone substation according to equation (7). The model must also take into account feeding transmission line (L_1), step-down transformer (T_1) of industrial substation and excitation system operating under voltage sag.

2) Stability assessment of synchronous motors for full range of residual voltage and possible values of transient time constants should be carried out in the form of combined stability zone (fig. 6) which is computed by the developed SM model (fig.4) according to the residual voltage equation (7) without transient voltage component.

3) Calculation of critical fault duration of synchronous motors operating under three-phase short circuit faults appearing in the electric grids could be done without regard to the fault appearance time (angle α in the equation (7));

4) Assessment of stability of synchronous motors should to be done with regard to real values of phase angle φ_1 according to the curves in fig. 8, corresponding to transmission lines connected to the backbone substation busbars and having higher cross-section area of conductors.

The developed methodology could be used during designing and adjustment of protective relays used in electric grids and designing the elements of power supply grids with regard to the stability of synchronous motors. This will enhance reliability of SM operation under short-break power supply caused by the three-phase short circuits in electric grids.

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Received ***March,10 2019***