FINDING THE OPERATING WINDING INDUCED EXCESS VOLTAGE DURING THE THREE-PHASE SHORTENING OF THE SYNCHRONOUS GENERATOR

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This work presents two methods to find the induced excess voltage in a synchronous generator operating winding during a sudden three-phase shortening of the fixed coil winding. The accidental occurrence of this working state leads to high value flask currents which, due to heat density and dynamic loading, affect the fixed coil windings. These currents induce excess voltages that negatively influence the measuring equipment. We establish in this work equations to determine this excess voltage when the synchronous generator's parameters are known. The equations were validated by shortening tests on the synchronous generator.

Keywords: circuit faults, electrical safety, generators, short-circuit currents, software testing

1. Introduction

To validate the design of a synchronous generator, in special its parameters, it is necessary to simulate and test it [1, 2]. The characteristics obtained and the parameters determined by running these tests give us essential information about the performance of the analysed synchronous generator [3].

This work presents the phenomena happening in the exciter circuit of a synchronous generator when a sudden three-phase short circuit occurs at its terminals. Specific measures must be taken already in the design phase to counter the effects of the phenomena occurring in the short circuit working regime.

The phenomena occurring in the operating winding are less studied, researching their behaviour in cases of three-phase sudden short circuit was triggered by the observation that, after the short circuit transitory effects, the measuring equipment of the operating winding is damaged.

Since the choice of the measuring apparatus was done based on the stationary regime, the fact that they are damaged when a sudden three-phase short

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circuit occurs indicates that excess voltage appears in the operating winding of the synchronous generator. Therefore, it is essential to know the value of the induced off-load voltage of the operating winding and the value the current given by the voltage sum in the exciter circuit.

The current trend in the transformer design and validation observe mainly the dynamic regimes of the electrical machines, regimes that define their performances [4, 5]. At the same time, the devices used to assess the most important parameters must be able to measure the maximum values that can occur during transient regimes.

The control of the stationary and dynamic process variables is done using different, adaptive control systems, both for the exciter circuit as well as for the armature circuit [6-14].

The authors propose a method to find the values of the induced currents in the excitation winding in case of a short circuit at the autonomous, synchronous generator terminals.

2. Finding the Induced Off-Load Voltage of the Operating Winding

We consider a synchronous generator operating in the stationary regime, with the design load. The exciter circuit, powered with the U_{En} voltage rating, has the rated current I_{En}. The I_{En} current flowing through the operating winding produces the flux Ψ_{E0} which, compared to the rotor, it is a flux constant in space and time. Compared to the fixed coil, this flux, mechanically rotated, is variable in space and time during the no-load operation of the synchronous generator, being the only existing flux in the machine.

To analyse the phenomena occurring in the operating winding during a sudden three-phase short circuit we use the equations of the synchronous generator that has a damper winding. The equations for the synchronous generator, written following the two-axis theory, are [15-19]:

$$\begin{cases} u_d = -R_s \cdot i_d - \dfrac{d\Psi_d}{dt} + \omega \cdot \Psi_q \\ u_q = -R_s \cdot i_q - \dfrac{d\Psi_q}{dt} - \omega \cdot \Psi_d \\ 0 = R_D \cdot i_D + \dfrac{d\Psi_D}{dt} \\ 0 = R_Q \cdot i_Q + \dfrac{d\Psi_Q}{dt} \\ u_E = R_E \cdot i_E + \dfrac{d\Psi_E}{dt} \end{cases}, \tag{1}$$

The total flux in the operating winding, Ψ_E, immediately after the three-phase short circuit occurred, is:

$$\Psi_E = L_E \cdot i_E + L_{dh} \cdot i_d + L_{dh} \cdot i_D + L_{DE\sigma} \cdot i_D . \qquad (2)$$

The presentation will be clear and concise, and the symbols used therein will be specified in a symbol list (if necessary). In the paper it will be used the measurement units International System. In the paper, there will be no apparatus or installation descriptions.

All other variables and notation in equations (1) and (2) should be known to the reader.

The three-phase sudden short circuit is realised with a block schema as in Fig. 1.

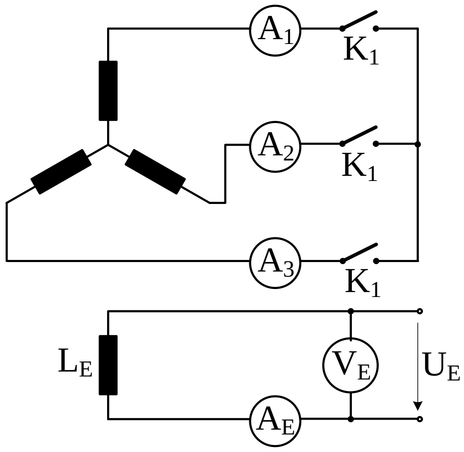

Fig. 1. The synchronous generator block schema for the sudden, symmetric, three-phase short circuit

The enduring short circuit current depends on the direct-axis synchronous inductance, X_d:

$$I_{sc3(t\to\infty)} = \frac{U_{eE}}{X_d} , \qquad (3)$$

where U_{eE} is the pole off-load voltage, in stationary regime, given by the rated field current.

During the sudden short circuit [1], the excess transient current, I''_{sc3}, is calculated using the synchronous, direct-axis, transient excess inductance, X''_d, and the same pole off-load voltage:

$$I''_{sc3} = \frac{U_{eE}}{X''_d} , \qquad (4)$$

When writing equations (3), (4) the synchronous generator parameters were considered constant, ie X_d and X''_d corresponded to a point on the linear zone of the magnetization characteristic. If these reactants are saturated, their value decreases, which leads to the occurrence of short-circuit currents of slightly higher values. At the occurrence of the short-circuit on the three phases, the operating points for each phase may be on the linear or saturation zone of the magnetization characteristic, which explains the different values of the currents at the time of the short circuit.

The three-phase, sudden short circuit current takes its maximal value immediately after time t=0, its real value, I_{sc3}, being [20]:

$$I_{sc3(t=0)} = \sqrt{3}\cdot I''_{sc3}, \tag{5}$$

For the three-phase, sudden short circuit of the synchronous generator, voltages u_d şi u_q in equations (1) are null. The only significant equation remains the one corresponding to the exciter circuit.

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At the moment t=0 the stator currents have, for each phase, a different value, each depending on the angle between the winding' axis and the respective phase axis. These currents have an inductive degaussing characteristic, the generator's load, at this moment being composed of the windings' specific inductivities.

The machine degaussing cannot be made instantly, the flux prior to the moment t=0, determined by the field current and the rotor's reacting currents, has the same final value established by the long-term short circuit. From the moment the sudden three-phase short circuit occurs the machine flux is composed of the flux Ψ_E, given by relation (2), the flux Ψ_{ead}, caused by the rotor's reaction, and the flux Ψ_{E0}. The excess transitory currents through the three phases, with values close to those given by relation (4), determine the rotor's magnetic field, whose flux Ψ_{ead} is in the opposite direction to the flux Ψ_{E0} and approximately equal to it in absolute value. We justify this statement below.

Before the moment t=0, the voltage at the generator's terminals is:

$$\underline{U} = \underline{U}_{eE} + \underline{U}_{ead} + \underline{U}_{eaq} - \underline{Z}\cdot\underline{I}, \tag{6}$$

This terminal voltage corresponds to the off-load voltage, U_e, induced in the stator windings by the total flux Ψ_t, vectorised as follows:

$$\overline{\Psi}_t = \overline{\Psi}_E + \overline{\Psi}_{ead} + \overline{\Psi}_{eaq}, \tag{7}$$

Fluxes Ψ_E and Ψ_{ead} are oriented along the fore-aft (direct) axis, d, and the flux Ψ_{eaq} is oriented along the cross axis, q. Using the synchronous direct-axis reactance, X_d, and the cross-axis reactance X_q, from (7) we have:

$$\underline{U} = \underline{U_{eE}} - jX_d \cdot \underline{I_d} - jX_q \cdot \underline{I_q}\,, \tag{8}$$

The sudden short circuit (U=0) has a degaussed, inductive character, that is I_q=0, and I_d= I"$_{sc3}$. Therefore, at the moment t=0, from (8) we have:

$$\underline{U_{eE}} = X''_d \cdot \underline{I''_{sc3}}\,, \tag{9}$$

For the fluxes, from (7) and (9) we have:

$$\overline{\Psi_E} + \overline{\Psi_{ead}} = \overline{\Psi_{E0}}\,, \tag{10}$$

Immediately after the three-phase sudden circuit occurred, at the exciter circuit terminals we measure the voltage u_E, composed of:

- Continuous power feed voltage U_E, of the exciter circuit;
- Alternate harmonic dampened voltage, u_{E1}, induced by the electric field given by the stator short circuit currents, that is:

$$u_E = U_E + u_{E1}\,, \tag{11}$$

To these voltages we have the following, corresponding currents:

- Continuous current, I_E, given by the direct power feed voltage;
- Alternate harmonic dampened current, i_{E1}, given by the three-phase sudden short circuit in the stator.

The current measured in the operating winding, i_E, is:

$$i_E = I_E + i_{E1}, \tag{12}$$

The second Kirchhoff theorem for the exciter short circuit is:

$$U_E + u_{E1} = R_E \cdot I_E + R_E \cdot i_{E1} + \frac{d\Psi_E}{dt}\,, \tag{13}$$

In the stationary regime, prior to the three-phase sudden short circuit occurrence, the following equation holds:

$$U_E = R_E \cdot I_E\,, \tag{14}$$

From relations (14) and (15) we have:

$$u_{E1} = R_E \cdot i_{E1} + \frac{d\Psi_E}{dt}\,, \tag{15}$$

If we ignore the resistor value, R_E, from (15) we have:

$$u_{E1} = \frac{d\Psi_E}{dt}\,, \tag{16}$$

For short, measurable, time intervals, Δt, relation (16) becomes:

$$u_{E1} = \frac{\Delta\Psi_E}{\Delta t}\,, \tag{17}$$

Equation (17) expresses the alternate instant voltage that occurs in the exciter circuit at the moment immediately following the three-phase sudden short circuit moment. This instant voltage overlaps the continuous power feed voltage of the operating winding.

The flux Ψ_E can be determined with the relation:

$$\Psi_E = L_E \cdot I_E, \tag{18}$$

Knowing L_E and I_E, the voltage induced into the operating winding during the sudden three-phase short circuit can be now computed.

Following the reasoning expressed in relations (4)-(10) we can infer that:

$$U_{ead} \cong 2 \cdot U_{eE(t=0)} \cong 2 \cdot I''_{sc3} \cdot X''_d, \tag{19}$$

The absolute values of the voltages u_{E1} and U_{ead} should be approximately equal, since in relation (15) the resistor R_E has been removed. The instant voltage, u_{E1}, must be transformed into its real value.

For the long-term short circuit, we have:

$$U_{ead} \cong U_{eE(t\to\infty)} \cong I_{sc3} \cdot X_d, \tag{20}$$

This, the value of the off-load voltage, induced in the operating winding can be determined:

- In the design phase or by measuring the short circuit currents and computing the excess transitory direct-axis inductance [18, 21-25];
- By measuring the current in the operating winding and by finding the Ψ_E flux. This method is harder to apply because of the difficulties in measuring the currents in the dampening winding.

If, at the same time as the short circuit current occurrence we measure the voltage at the exciter circuit terminals, we can directly find the alternate voltage of the exciter circuit.

3. Case study

To validate the relations presented above we tested a three-phase synchronous generator with the following nominal data: S_n = 353 kVA, U_n = 400 V, I_n = 509 A, n = 300 rpm, cos φ = 0.85, f = 50 Hz, Y connection. The operating winding was powered by an exciter with the following nominal values: P_n = 7 kW, U_n = 47 V c.c., I_n = 150 A c.c., n = 300 rpm.

To find the u_{E1} voltage appearing in the exciter circuit of the synchronous generator at the three-phase sudden short circuit we used the first method. The currents were measured with a data acquisition system with 15 channels, using the Fastview module of the LabView software.

During the short circuit test we measured the following parameters: the field voltage, the field current and the currents in the stator winding (Fig. 2 – stator currents i_E, u_E).

Using the different testing methods for the synchronous generator, we can determine its parameters [22-25]. Upon processing the measurements taken during the three-phase, sudden, symmetric short circuit we found the synchronous generator's parameters.

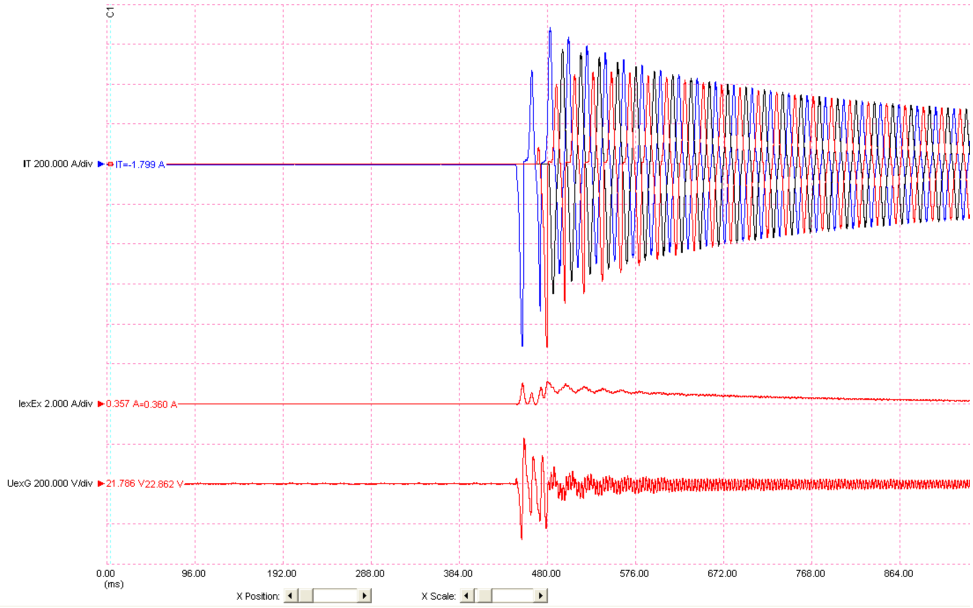

Fig. 2. Stator current variations, operating winding current and voltage variations during the sudden, three-phase, symmetric short circuit

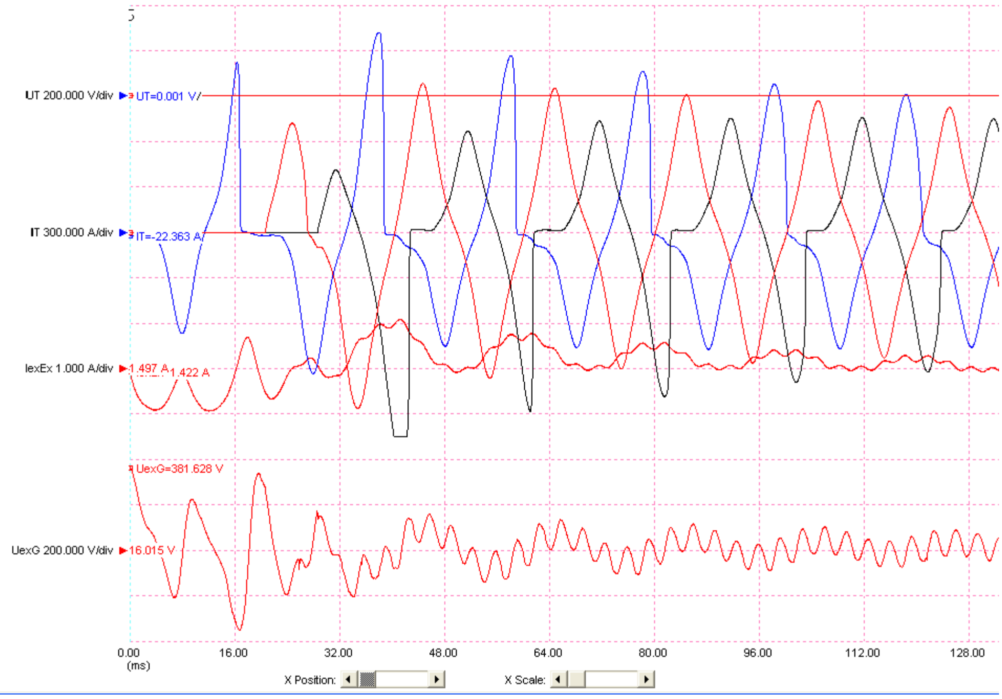

Fig. 3. Maximal voltage of the operating winding after the sudden, symmetric three-phase short circuit

Analysing the recordings, we found that a power surge in the operating winding with a maximum value of 381.628 V (Fig. 3 – detail).

Counting in the continuous component of the direct power feed voltage of the operating winding of 22.404 V d.c. (Fig. 2) we have that the value of the excess voltage in the operating winding at the sudden, symmetric three-phase sort circuit is 359.224 V, which is 7.64 times bigger than the nominal power feed voltage.

Parameters of the synchronous generator were determined by testing it in a idle, load, symmetrical short and unsymmetrical test [18]. The necessary parameters to determine the voltage u_{E1} in the operating winding are:

- The fore-aft axis inductance X_d = 0.391 Ω (0.86 u.r.);
- The exceed transient fore-aft axis inductance X''_d = 0.0646 Ω (0.142 u.r.);
- The sudden, symmetric, three-phase short circuit I_{sc3} = 916.2 A;
- The excess transient, sudden, three-phase symmetric short circuit current I''_{sc3} = 2748.6 A.

From (19) we have:

$$u_{E1} = U_{ead} = 2 \cdot I''_{sc3} \cdot X''_d = 355.12 \text{ [V]}, \qquad (21)$$

Therefore, the u_E voltage at the exciter circuit's terminals is:

$$u_E = U_E + u_{E1} = 377.523 \text{ [V]}, \qquad (22)$$

For the long term three-phase short circuit, from (20) we have:

$$u_{E1} = U_{ead} = I_{sc3} \cdot X_d = 358.234 \text{ [V]}, \qquad (23)$$

And the u_E voltage at the exciter circuit's terminals is:

$$u_E = U_E + u_{E1} = 380.638 \text{ [V]}. \qquad (24)$$

The difference between the u_E voltage value measured by the acquisition system (381.628 V – Fig. 3) and the computed value is due to the simplifying hypotheses taken in this paper.

4. Conclusions

Analysing the measurements done in the frame of our tests we establish that at the time of a sudden, symmetrical three-phase short circuit, in the exciter circuit we have a voltage with a value considerably higher than the nominal voltage, namely about 7.64 times higher. When we count in the d.c. voltage as well, the total voltage value in the exciter circuit is then 8.12 times higher than the nominal voltage.

According to our computations, the power surge value that occurs in the moment immediate to the short circuit occurrence is 355.12 V, which is more than 7 times higher than the nominal power feed voltage. The difference between the computed and measured voltage values is determined by the values of the parameters obtained from the graphical processing of the three-phase short-circuit test.

The power surge in the exciter circuit can lead to punctures in the spire insulation in the operating winding.

Knowing the synchronous generator’s parameters (inductances, currents) already at the design phase engineers can correspondingly size the exciter system and device it with appropriate protection.

At the same time, it is necessary that the power surges occurring in the exciter circuit are kept at limited values.

R E F E R E N C E S

[1]. *S. Berhausen, A. Bobon,* "Determination of high power synchronous generator subtransient reactances based on thewaveforms for a steady state two-phase short-circuit", Applied Mathematics and Computation, Volume 319, pp. 538-550.

[2]. *S. Nuzzo, M. Galea, C. Gerada, and N. Brown,* "Analysis, Modeling, and Design Considerations for the Excitation Systems of Synchronous Generators", IEEE Transactions on Industrial Electronics, Volume 65, Issue: 4, pp. 2996-307.

[3]. *I. Ilina, T. Tudorache,* "Determination of Operation Characteristics of a Synchronous Generator by StaticExperimental Tests," Advances in Electrical and Computer Engineering, Volume 16, Number 2, pp. 93-100, 2016.

[4]. *I. Vlad, A. Campeanu, S. Enache and G. Petropol,* "Operation Characteristics Optimization of Low Power Three-Phase Asynchronous Motors", Advances in Electrical and Computer Engineering, Volume 14, Number 1, pp. 87-92, 2014.

[5]. *A, Campeanu, A., A.I. Ionescu, I. Vlad, and S. Enache,* "Prediction through Simulation of the Optimal Behavior of the Induction Machine in Complex Process", International Symposium on Power Electronics, Electrical Drives, Automation and Motion, Ischia, Italy, Jun 11-13, 2008.

[6]. *I. Filip, O. Prostean, C. Vasar and I. Szeidert* , "An Improved Structure of an Adaptive Excitation Control System Operating under Short-Circuit", Advances in Electrical and Computer Engineering, Volume 16, Number 2, pp. 43-50, 2016.

[7]. *D. Vukadinovic, Dinko, S. Grbin and M. Basic,* "Experimental Method of Determining the Equivalent Circuit Parameters of a Switched Reluctance Machine", Advances in Electrical and Computer Engineering, Volume 15, Number 3, pp. 93-98, 2015.

[8]. *I. C. Petrea, C. Marinescu,* "Autonomous Three-Phase Induction Generator Supplying Unbalanced Loads", Advances in Electrical and Computer Engineering, Volume 13, Number 2, pp. 85-90, 2013.

[9]. *NF. Jiao, WG Liu, T. Meng, JC. Peng and S. Mao,* "Detailed Excitation Control Methods for Two-Phase Brushless Exciter of the Wound-Rotor Synchronous Starter/Generator in the Starting Mode", 31st Annual IEEE Applied Power Electronics Conference and Exposition (APEC), Mar. 20-24, 2016, IEEE Transactions on Industry Applications, Volume: 53, Issue: 1, pp. 115-123, 2017.

[10]. *YG. Li, MH. Ma, YC. Wu, GB. Ban,* "The New Criterion of Brushless Excitation Generator Rotor Winding Inter-Turn ShortCircuit Fault Diagnosis Based on Reactive Relative Deviation", 19th International Conference on Electrical Machines and Systems (ICEMS), Chiba, Japan, Nov 13-16, 2016.

[11]. *C. Popescu, L.G. Popescu and C.Racoceanu,* "The New Criterion of Brushless Excitation Generator Rotor Winding Inter-Turn Short Circuit Fault Diagnosis Based on Reactive Relative Deviation", 16th International Multidisciplinary Scientific GeoConference SGEM 2016, SGEM2016 Conference Proceedings, ISBN 978-619-7105-56-8 / ISSN 1314-2704, June 28 - July 6, 2016, Book1 Vol. 2, pp. 827-832, 2016.
[12]. *M. Samiei Moghaddam , M. Tavakoli Bina, M. Aliakbar Golkar and S. Shokri Kojori,* Optimal design of voltage regulators for static excitation system in synchronous generator to reduce shaft-induced voltage", Turkish Journal of Electrical Engineering & Computer Sciences, Turk J Elec Eng & Comp Sci 25: 1827 – 1839, doi:10.3906/elk-1602-184, 2017.
[13]. *C. Ting, L. Wei, S. Yuanzhang, X Jian and Z. Huakun,* "Excitation Voltage Control for Emergency Frequency Regulation of Island Power Systems With Voltage-Dependent Loads", IEEE Transactions on Power Systems, Vol. 31, Issue 2, March, pp. 1204 – 1217, 2016.
[14]. *N. Diga, C. Ghita, B. A. Enache and S. M. Diga,* "Considerations on the Command and Analysis of the Low Speed Permanent Magnet Synchronous Machines Operating", International Conference on Applied and Theoretical Electricity (ICATE), Oct. 06-08, Craiova, Romania, 2016.
[15]. *T. Dordea*, Maşini Electrice (Electrical Machines), Editura Didactică şi Pedagogică, Bucureşti, 1970 (in Romanian).
[16]. *I. Piroi*, Maşini Electrice (Electrical Machines), Editura Didactică şi Pedagogică, Bucureşti, 2004 (in Romanian).
[17]. *I. Boldea*, The Electric Generators Handbook - Synchronous Generators, Taylor&Francis, 2006.
[18]. *E. Spunei*, "Optimizarea proiectării unui generator sincron ce echipează o microhidrocentrală" - Teză de doctorat (Optimal design of synchronous generator for micro hidropower plant - Doctoral Thesys), Universitatea din Craiova, Facultatea de Inginerie Electrică, 2012 (in Romanian).
[19]. *V. S. Malyar, V.S. Maday and I. R. Kens,* "Resonant Processes in Starting Modes of Synchronous Motors with Capacitors in the Excitation Windings Circuit", Electrical Engineering & Electromechanics, Issue: 4, pp. 21-25, 2017.
[20]. *E. C. Teodoru, M. Gogu,* Maşini Electrice (Electrical Machines), Universitatea Tehnică "Gh. Asachi, Iaşi 2000 (in Romanian).
[21]. *E. Spunei, I. Piroi, F. Piroi,* “Rapid Determination of the Over-Transient Longitudinal Reactance”, Analele Universităţii din Craiova, Seria Inginerie, Anul 37, Nr. 37, ISSN 1842-4805, pp. 116-123, Craiova, 2013.
[22]. *M. M. Ali, S.M. Allam, T. H. Abdel-Moneim,* "Dynamic characteristics of an isolated self-excited synchronous reluctance generator driven by a wind turbine, " Turkish Journal of Electrical Engineering and Computer Sciences, Vol: 24, Issue: 6, pp: 5238-5250, ISSN: 1300-0632, Turkey, 2016.
[23]. *E. Rebollo, C. A. Platero, F. Blazquez, R. Granizo,* "Internal sudden short-circuit response of a new HSBDS for brushless synchronous machines tested on a 15 MVA generator," IET Electric Power Applications, Vol. 11, Issue: 4, pp: 495-503, April 2017.
[24]. *M. Yu. Frolov, A. G. Fishov,* "Electric parameters identification of synchronous generator connecting to the grid, " 11th International Forum on Strategic Technology (IFOST), Electronic ISBN: 978-1-5090-0855-1, 1-3 June 2016.
[25]. *M. Ghomi, Y. Najafi. Sarem,* "Review of synchronous generator parameters estimation and model identification," 42nd International Universities Power Engineering Conference, UPEC, Print ISBN: 978-1-905593-36-1, 4-6 Sept. 2007.