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Asynchronous Generator Non-Linear Mathematical Model in Simulation of Transient State

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Abstract— *in the paper a non-linear circuital mathematical model of a synchronous generator is presented. This model takes into consideration saturation effects in magnetic cores and phenomenon of eddy currents induced in solid parts of a rotor. The methodology for the determination of the model parameter set is given, using the finite element method. Simulation investigations are carried out for the 200 MW turbogenerator to examine the effects of magnetic circuit Saturation and the ways of representing the rotor damper circuits.*

Keywords— *Non-linear circuital mathematical model; finite element method; magnetic circuit.*

I. Introduction

In simulation investigations of transients in electric power systems are more and more frequently used extended mathematical models of synchronous generators. Structures of mathematical models for synchronous generators and sets of related to them parameters depend on the method and accuracy of modeling of coupling phenomena: phenomenon of magnetic cores saturation and phenomenon of eddy currents flowing in solid elements of a rotor. Taking into consideration both phenomena in a circuit mathematical model is difficult and now is possible to take them into consideration only separately and partially. As a consequence the mathematical model of a machine is formulated in two stages. First stage consists in determination of a circuit mathematical model of unsaturated machine, in which influence of eddy currents effects in solid parts of a rotor is taken into consideration as accurately as possible. In second stage are modified these elements and parameters of the above model which are influenced by saturation phenomena in a machine cores made by the main and stator leakage field, assuming that other elements of the model are unchanged. In the paper is presented the structure of such generator model and methodology of determination of its parameters. Simulation investigations are performed for the 200 MW turbogenerator. The computation results are compared for different model types and for saturated and unsaturated machine magnetic circuit.

II. Structure and Parameters of Agenerator Non-Liner Mathematical Model

Basing on presented above methodology the mathematical model of a synchronous generator taking into consideration saturation phenomenon in magnetic cores of a machine and phenomenon of eddy currents flowing in a rotor was prepared. Principles of a model formulating and made assumptions are presented in [1], [5]. Mathematical model may be presented as the equivalent circuit as shown in Fig. 1. In the presented equivalent circuit influence of eddy currents induced in a solid rotor, in slot wedges or in a damper squirrel cage is represented by means of nd and nq equivalent damper circuits, in d and q axes, respectively. Saturation effect in machine magnetic cores is taken into account by means of non-linear static and dynamic inductances that depend on magnitudes and arguments of space vectors of appropriate currents.

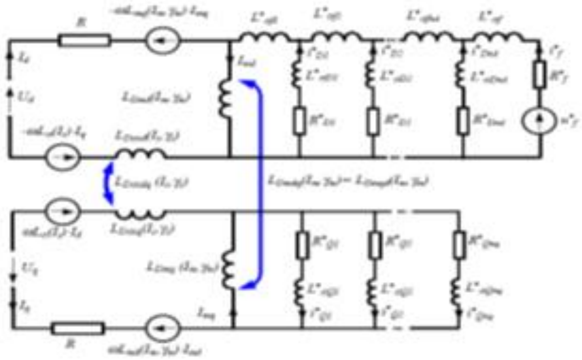

Fig. 1. Equivalent circuits of the non-linear Mathematical model of a synchronous generator taking Into consideration saturation effects.

The pair of numbers (1+*nd*, *nq)* defines the type of the mathematical model of a synchronous machine. Static and dynamic inductances of a machine related to main magnetic field and stator leakage field are determined with good accuracy by means of synthetic characteristics of flux linkages and their derivatives with respect to appropriate currents [5]. Assuming for main field simplified form of these characteristics as the non-linear functions *(¥md.q*1, *(Im*), ¥ *md*, *q3* (*Im*), and for stator leakage field the Function ¥*s* (*Is)* is obtained the following relations determining static and dynamic inductances:

A. Static inductances.

$$L_{md}(I_m,\gamma_m)=\frac{\psi_{md}(I_m,\gamma_m)}{I_{md}}=\frac{\psi_{md}(I_m,\gamma_m)}{I_m\cos(\gamma_m)}=\sum_{i=1,3}\left(\frac{\psi_{mdi}(I_m)\cos(i\gamma_m)}{I_m\cos(\gamma_m)}\right)$$
$$I_{mq}(I_m,\gamma_m)=\frac{\psi_{mq}(I_m,\gamma_m)}{I_{md}}=\frac{\psi_{mq}(I_m,\psi_m)}{I_m\sin(\gamma_m)}=\sum_{i=1,3}\left(\frac{\psi_{mq}(I_m)\sin(i\gamma_m)}{I_m\sin(\gamma_m)}\right) \quad (1)$$

B. Dynamic magnetizing inductances.

$$L_{Dmd}(I_m,\gamma_m)=\sum_{i=1,3}\left(\left(\frac{d\psi_{dmi}(I_m)}{dI_m}\cos(i\gamma_m)\cos(\gamma_m)+....\right.\right.$$

$$\left.\left.......+i\frac{\psi_{dmi}(I_m)}{I_m}\sin(i\gamma_m)\sin(\gamma_m)\right)\right)$$

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$$L_{Dmq}(I_m,\gamma_m)\sum_{i=1,3}\{\frac{d\psi_{mq}(I_m)}{dI_m}\sin(i\gamma_m)\sin(\gamma_m)+....$$

$$....+\frac{\psi_{mq}(I_m)}{I_m}\cos(i\gamma_m)\cos(\gamma_m)$$

$$L_{Dmqd}(I_m,\gamma_m)=\sum_{1=1,3}(\frac{d\psi_{mdi}(I_m)}{dI_m}\cos(i\gamma_m)\sin(\gamma_m)+... \qquad (2)$$

$$....+i\frac{\psi_{dmi}(I_m)}{I_m}\sin(i\gamma_m)\cos(\gamma_m)$$

C. Dynamic stator leakage inductances.

$$L_{D\sigma d}(I_s,\gamma_s)\frac{d\psi_\sigma(I_s)}{dI_s}\cos^2(\gamma_s)+\frac{\psi_\sigma(I_s)}{I_s}\sin^2(\gamma_s)$$

$$LD\sigma q(I_s,\gamma_s)=\frac{d\psi_\sigma(I_s)}{dI_s}\sin^2(\gamma_s)+\frac{\psi_\sigma(I_s)}{I_s}\cos^2(\gamma_s) \qquad (3)$$

$$L_{D\sigma dq}(I_s,\gamma_s)=L_{D\sigma dq}(I_s,\gamma_s)=\frac{1}{2}(\frac{d\psi_\varsigma(I_s)}{dI_s}-\frac{\psi_\sigma(I_s)}{I_s})\sin(2\gamma_s)$$

Where $I_{m\sigma}, I_{s\sigma}, \gamma_{m\sigma}, \gamma_{s\sigma}$, are magnitudes and arguments of space vectors of magnetizing current and stator current.

III. Methodology of Determintion of Model of Parameters for Non-Liner Mathematical Model of the Synchoronous

Parameters of the non-linear mathematical model of a synchronous generator may be determined on the ground of spatial electromagnetic field distributions in the machine, which are calculated by means of the finite element method using design-constructional data. In accordance with remarks from point 1, determination of electromagnetic parameters of the mathematical model was assumed in two stages. In first stage will be determined parameters of RL type assuming in field calculations linear magnetization curves of magnetic cores. In second stage will be determined synthetic characteristics of flux linkages in the machine taking into account in field Calculations non-linear magnetization curves of magnetic cores. Next, these characteristics will be approximated by spline functions. For determination of electromagnetic parameters of synchronous machine mathematical models with linear magnetic circuit the frequency method was used. It consists in determination and approximation of spectral inductances of the machine. The following relations between flux linkages and stator currents in d and q axes and the field winding define spectral inductances [1]:

$$L_{do}(v)=\frac{\psi_{do}}{L_d(v)}\Big|_{if=0} \quad L^*_{df}(v)=\frac{\psi_d(v)}{i^*_f(v)}\Big|_{I_d=0} \quad \underline{L}_q(v)=\frac{\underline{\psi}_q}{L_q(v)} \qquad (4)$$

Where v is the relative frequency?

Spectral inductances (4) are determined basing on spatial magnetic field distributions in the machine. Calculations of these field distributions are made using the finite element method, feeding successively machine windings with complex values of currents in d and q axes and with a field current at frequency of wide range, ($\nu\in(0, \infty)$) and calculating corresponding flux linkages. For the structure of equivalent circuits of the machine in d and q axes defined by type of the machine mathematical model, lumped parameters of RL type can be determined on the ground of approximation of spectral inductances expressed by rational functions. Presented here methodology of RL -type parameters determination for non-linear mathematical model of a synchronous generator is illustrated in Fig. 2. Synthetic characteristics of flux linkages are determined by calculations of spatial distribution of magnetic fields in corresponding computational models of the machine using the finite element method [4], [5]. Calculations are made by forcing appropriate DC currents in phase windings of these models.

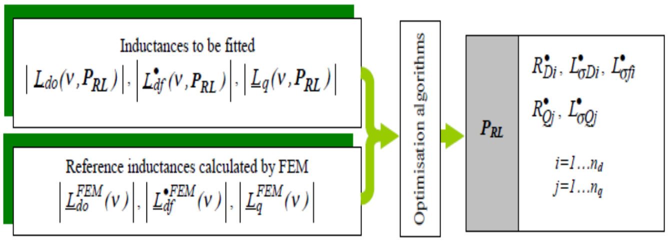


Fig. 2. Methodology of determination of RL -type electromagnetic parameters for non-linear model of asynchronous machine. *PRL* – vector of RL parameters of a rotor.

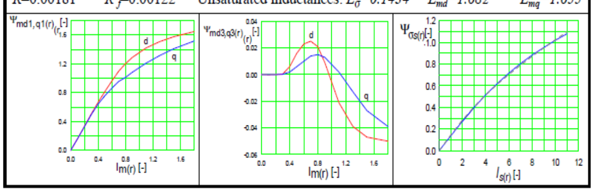
IV. Results of Simulation Investigations

Numerical computations have been carried out for the 200 *MW* turbogenerator (S_n=235.3 *MVA*, P_n=200 MW, U_n=15.75 kV, I_n=8625 A, $\cos\varphi_n$=0.85).

In the Table (1) are presented calculation results of RL equivalent circuit electromagnetic parameters (p.u.) in d and q axes for circuital models of (2, 1), (2, 2) and (3, 3) types and synthetic characteristics of Flux linkages calculated by FEM. In the Table 1 are also placed unsaturated values of magnetizing Inductances in d and q axes and leakage inductance of the stator. Table.1. Electromagnetic parameters and synthetic characteristics of flux linkages of the non-linear Mathematical model of TWW-200-2 turbogenerator and synthetic characteristics of flux.

TABLE. 1. Electromagnetic parameters and synthetic characteristics of flux linkages of the non-linear mathematical model of TWW-200-2 turbogenerator and synthetic characteristics of flux linkages (p.u.).

Para–meter	Model (2,1)	Model (2,2)	Model (3,3)	Para–meter	Model (2,1)	Model (2,2)	Model (3,3)
$L^\bullet_{\sigma f1}$	0.00719	0.00719	0.15866	$L^\bullet_{\sigma Q1}$	0.07727	0.25313	11.7925
$L^\bullet_{\sigma D1}$	$7.75\cdot10^{-6}$	$7.75\cdot10^{-6}$	21.4807	$R^\bullet_{Q1}$	0.00253	0.00268	0.00413
$R^\bullet_{D1}$	0.00128	0.00128	0.00603	$L^\bullet_{\sigma Q2}$		-0.00018	0.20827
$L^\bullet_{f\sigma 2}$			-0.1533	$R^\bullet_{Q2}$		0.033819	0.00316
$L^\bullet_{\sigma D2}$			0.00002	$L^\bullet_{\sigma Q3}$			-0.0064
$R^\bullet_{D2}$			0.00137	$R^\bullet_{Q3}$			0.04351
$L^\bullet_{\sigma f}$	0.092810	0.092810	0.09469				
R=0.00181	$R^\bullet_f$=0.00122	Unsaturated inductances: $L_\sigma=0.1434$		$L_{md}=1.682$		$L_{mq}=1.655$	



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Waves of the field current, stator currents in d and q axes and the load angle during 3-phase fault and subsequent clearing at the stator terminals, calculated for models of (2,1), (2,2) and (3,3) type, are presented in Fig. 3. The influence of magnetic circuit saturation on dynamic characteristics of the same electrical quantities calculated for the model of (3, 3) type are illustrated in Fig 4.

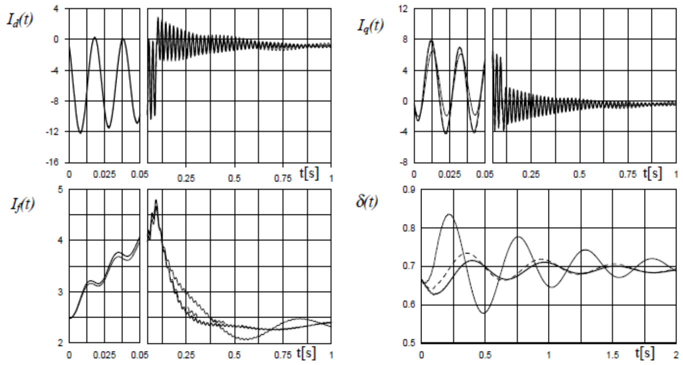

Fig. 3. Waveforms of the armature currents *Id*, *Iq*, the field current *If*, and the power angle δ during 3-phase transient short-circuit and subsequent clearing at the stator terminals for the TWW-200-2 turbogenerator (clearing time *tz*=0.1s; p.u.), Model: (3, 3) (2, 2) (2, 1).

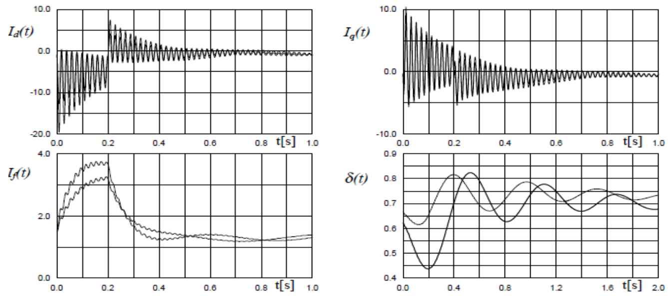

Fig. 4. Waveforms of the armature currents *Id*, *Iq*, the field current *If*, and the power angle δ during 3-phase transient short-circuit and subsequent. Clearing at the stator terminals. For the TWW-200-2 turbogenerator (clearing time *tz*=0.2s; model of (3, 3) type, p.u.), Model: linear---- non-linear.

V. CONCLUSION

Presented in the paper non-linear mathematical model of a synchronous generator and calculated set of corresponding electromagnetic parameters make possible to carry out simulation investigations of generators in various operating conditions, at small and large disturbances of equilibrium state. The presented model may be used for simulation of operating conditions of a power system both within short-circuit processes occurring in the system and for investigations of short-term and mid-term transient stability. Made by authors simulation investigations for synchronous generator mathematical model showed that taking into consideration magnetic core saturation effects resulting from stator leakage field, participates in improvement of accuracy of calculation of maximal short-circuit currents which may occur in the system, whereas taking into consideration saturation effects for main field improves accuracy of calculation of transient stability of generators. Similar influence on calculations accuracy has number of damper circuits in a rotor, which are taken into consideration in the machine model. Presented in the paper methodology of estimation of electromagnetic parameters for various types of mathematical models based on calculations of spatial distributions of electromagnetic fields in a machine by means of the finite element method may be successfully used for all generators operating in electric power system, without necessity to perform special tests on real objects

REFERENCES

[1] A., Kodak J., Żywiec A.: Parametry elektromagnetyczne maszyny synchronicznej. Wykorzystanie metody elementów skończonych. Wydawnictwo Politechniki Śląskiej "MONOGRAFIA", z. 7, Gliwice, 1998.
[2] Bubo A., Kudła J., Żywiec A.: Determination of Spectral Transfer Functions of a Synchronous Machine by the Finite Element Method. International Workshop on Electrical Machines, 7-8 Sept. 1998, Prague, pp. 102-110.
[3] Kudła J.: Obliczenia nieliniowych charakterystyk sprzężeń magnetycznych pola magnetycznego głównego w maszynie synchronicznej cylindrycznej. Zeszyty Naukowe Pol. Śl. „Elektryka" z. 149, Gliwice 1996, s. 99-110.
[4] Kudła J Model matematyczny generatora synchronicznego uwzględniający zjawisko nasycenia dla pola głównego i pola rozproszenia stojana. Politechnika Warszawska Prace Naukowe „ Elektryka" z. 111, Warszawa 1999, s. 81-90.
[5] Bobon A., Kudla J.: Badania symulacyjne stanow dynamicznych generatora synchronicznego przy wykorzystaniu parametrow wyznaczonych metoda elementow skonczonych. Zeszyty Naukowe Politechniki Slaskiej "Elektryka" z.171, Wydawnictwo Politechniki Slaskiej, Gliwice 2000, ss.215-226.
[6] Boboń A., Kudła J., Żywiec A.: Modele generatorów synchronicznych w badaniach systemu elektroenergetycznego, VIII Międzynarodowa Konferencja Naukowa "Aktualne Problemy w Elektroenergetyce", Gdańsk -Jurata, czerwiec 1997., ss.133-140.
[7] Kudla J.: Simulation investigations of induction motor start-up when using field-circuit model, Proceedings of X International Symposium on Electric Machinery "ISEM 2002" in Praque, pp. 96-104.
[8] Kudla J.: Methodology of determining static characteristics of induction motors basing on quasistatic waveforms. Use of the machine field-circuit model, Proceedings of EPVE 2002
[9] G. Eason, B. Noble, and I. N. Sneddon, "On certain integrals of Lipschitz-Hankel type involving products of Bessel functions," Phil.