ON THE LARGE SYNCHRONOUS MACHINE PARAMETERS CALCULATION

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Summary The large synchronous generators were intensively studied, but not so many papers are entirely dedicated to the analytical calculation of the generator's parameters. Therefore any contribution should be welcomed if it offers an improvement in the existing procedures or formulae. The paper is dealing with the large synchronous generators' magnetizing and leakage inductances calculation. A coherent algorithm is presented and the calculated parameters for a generator are given.

1. INTRODUCTION

There have been published an extremely large number of papers and books on the steady-state and dynamic behaviour of synchronous machines. Many of these works are dealing only, or implicitly, with the machine parameters. Needless to say that accurate analysis of the synchronous generators behaviour can be almost entirely jeopardised if the parameters to be inserted in the analytical equations or equivalent circuits are quite inaccurate.

The synchronous machine mathematical model and implicitly its parameters were introduced, almost as they are used now, long time ago [1, 2, 3]. Quite in the same time Wieseman performed an extremely accurate graphical calculation of the magnetic field in the salient-poles synchronous generator air-gap [4]. A basic book on the synchronous machine mathematical model and on the study of its steady-state and transient behaviour was published by Concordia [5]. Rankin [6] and Talaat [7] developed and improved Kilgore's work [3] and Canay [8, 9] brought an important contribution to the synchronous machine transient study. From the extremely large number of published works dealing with the synchronous machine equivalent circuits and corresponding parameters two seems to have an impact nowadays [10, 11], even other tens can be considered as important in the domain. General design aspects are covered quite well by Walker's book [12] and elements concerning the magnetising and the stator leakage inductances' calculation are given in [13, 14].

The parameters are usually obtained either by analytical or 2D-FEM calculation within the design stage or by means of measurements at the factory or on the site.

In this paper only the analytical calculation of inductances will be discussed. The results obtained for an example considered will be compared with the values obtained by tests or by performing a 2D-FEM magnetic field computation.

All the given formulae were developed without considering the saturation other way than by introducing the usual enlarged equivalent air-gap. The saturation factor employed in the equivalent air-gap calculation takes into account a global phenomenon not the specific effects.

2. ROTOR'S ORTHOGONAL MODEL

Only the salient poles rotor is considered. It has two types of windings:

- The field winding which is a concentrated type winding and produces flux on the D-axis.
- The damping cage winding which has identically bars uniformly distributed only in the rotor pole tips.

The general two phase machine model is given in Fig. 1, [5]. For the specific case of the synchronous generator $v_D = v_Q = 0$, since the *D and Q* rotor windings are the equivalent of a damping cage winding.

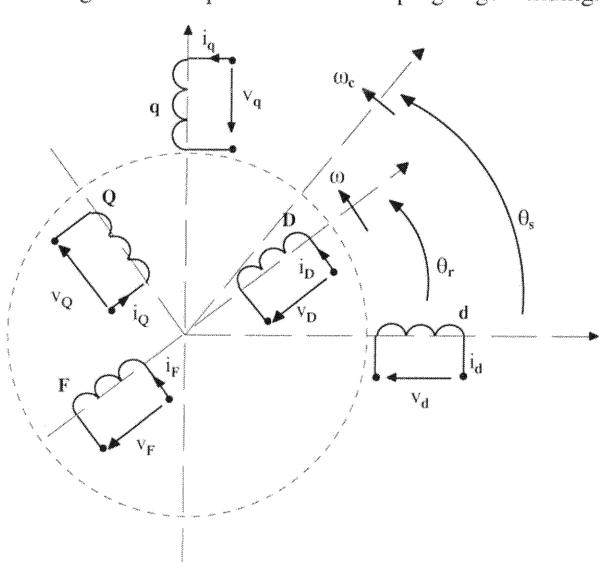

Fig. 1. The general two phase model.

In order to simplify the machine equations and to avoid any duplicity in choosing the "per-unit" base values all the rotor windings parameters are referred to the stator windings. The orthogonal rotor axes are named *D* and *Q* and consequently all their values will have these suffices, but for the field winding where will be used the suffice *F*. All the actual (physical) rotor values will be symbolised with "*" and all the referred to the stator values will have no special notations. As example i_F^* and i_F represent the actual field current and the field current referred to the stator winding respectively.

Since the frame is fixed in the rotor there is no cross coupling between D and Q axis, neglecting the one which is due to the rotor iron core saturation.

The main overall simplifying assumptions are the usual ones:

The magnetic coupling between the field, damping and stator windings is done only by the fundamental wave of the main field, so no field harmonics are to be considered.

The magnetising curve is unique.

The air-gap length under the rotor pole is constant.

The field winding will be considered as example of the way the rotor parameters are computed.

The field winding is on D-axis, then it is coupled with the stator equivalent d-axis phase.

The fundamental MMF produced by the field winding is:

$$F_{F1} = A_1 N_F I_F^* \tag{1}$$

where A_1 is the coefficient computed by Wieseman [4] for the flux distribution in the air-gap of a salient poles machine at no load, only field coil excited, N_F is the field winding number of turns and I_F^* is the actual value of the field current.

An equivalent current I_F flowing through d-axis stator winding produces the same MMF, hence:

$$A_1 N_F I_F^* = \frac{3}{\pi}\frac{k_{WS} N_S}{p} A_{d1}\sqrt{2} I_F \tag{2}$$

where

- A_{d1} is the Wieseman factor for the air-gap field produced by the d-axis stator winding,
- k_{WS} is the stator winding factor,
- p is the number of pole pairs and N_{Sd}, N_S,

$$N_{Sd} = \sqrt{3/2}\cdot N_S,$$

are the d-axis stator winding number of turns and the total stator number of turns respectively.

The current ratio k_{IF} is:

$$k_{IF} = \frac{I_F^*}{I_F} = \frac{3}{\pi}\frac{k_{WS} N_S}{p N_F}\frac{A_{d1}}{A_1}\sqrt{2} \tag{3}$$

Consequently the referred to the stator field winding resistance R_F and leakage inductance $L_{F\sigma}$ are:

$$R_F = R_F^* k_{IF}^2 = \frac{18}{\pi^2}\left(\frac{N_S k_{WS} A_{d1}}{p N_F A_1}\right)^2 R_F^* \tag{4}$$

$$L_{F\sigma} = \frac{18}{\pi^2}\left(\frac{N_S k_{WS} A_{d1}}{p N_F A_1}\right)^2 L_{F\sigma}^*. \tag{5}$$

The input power should be the same in both windings, consequently,

$$V_F^* I_F^* = V_F I_F \tag{6}$$

where V_F^*, V_F are the actual and the referred to the stator value of the input voltage of the field winding.

3. MAGNETIZING INDUCTANCES

The magnetising inductance calculation will be given considering the field winding referred to the stator as in the previous chapter.

The air-gap flux produced by the field winding is:

$$\Phi_F = C_\Phi B_{gF}\frac{Dl}{p} \tag{7}$$

$$B_{gF} = \frac{\mu_0}{g^*} F_F^* = \frac{\mu_0}{g^*} A_1 N_S\left(\frac{I_F^*}{I_F}\right) I_F \tag{8}$$

Finally the inductance M_{dF} is:

$$M_{dF} = \frac{3}{2}\frac{2}{\pi} C_\Phi Dl \frac{\mu_0}{g^*} A_{d1}\left(\frac{k_{WS} N_S}{p}\right)^2, \tag{9}$$

where C_Φ is a flux distribution coefficient [4] D and l are the air-gap average diameter, respectively, the equivalent active length of the machine iron core [3, 12, 13, 14, 15].

The inductance on the d-axis M_d considering the field produced by the d-axis stator current I_d is:

$$M_d = \frac{E_d}{\omega_S I_d} = \frac{\omega_S}{\sqrt{2}}\frac{\sqrt{\frac{3}{2}} N_S k_{WS}}{\omega_S I_d}\Phi_d \tag{10}$$

where

$$\Phi_d = C_\Phi \frac{rl}{p}\frac{\mu_0}{g^*} A_{d1}\sqrt{\frac{3}{2}}\frac{N_S k_{WS}}{p}\frac{2}{\pi}\sqrt{2} I_d \tag{11}$$

and as expected

$$M_{dF} = M_d \tag{12}$$

The equivalent air-gap length g^* is [14, 15]

$$g^* = K_{CS} k_{sat} g \tag{13}$$

where the Carter's factor can be calculated by

$$K_{CS} = \frac{\tau_S}{\tau_S - kg} \tag{14}$$

with:

$$k = \frac{4}{\pi}\left(u\,tg^{-1}u - \ln\sqrt{1+u^2}\right),\quad u = \frac{b_{0S}}{2g}, \tag{15}$$

τ_S being the stator pole pitch and b_{oS} the stator slot opening.

The stator magnetic field density should be reduced by a factor K_{Cl} due to the presence of the vent ducts in the stator iron core [16].

4. LEAKAGE INDUCTANCES

The stator phase leakage inductance is given by:

$$L_{S\sigma} = 2\mu_0 l N_S^2 \frac{1}{pq} p_C + L_{S\sigma ew} \quad (16)$$

where [3, 13, 14, 15]

$$p_C = p_{sS} + k_x p_{tS} + p_{ghS} \quad (17)$$

and the signification of the notations are:

- p_{sS} - the specific stator slot permeance,
- p_{tS} - the slot top specific permeance,
- p_{ghS} - harmonic differential leakage specific permeance,
- k_x - a coefficient which considers the presence of two currents in the slot [3, 13],
- $L_{S\sigma ew}$ -stator end winding inductance [3, 17],
- q – stator number of slots per pole and phase.

The field winding leakage can be computed by using the equation [3].

$$L^*_{F\sigma} = \mu_0 N_F^2 \left(l_{Fcp} p_{F\sigma p} + l_{Fce} p_{F\sigma e}\right), \quad (18)$$

where:

- l_{Fcp}, l_{Fce} are the average length of a conductor on the pole side respectively on the pole end,
- $p_{F\sigma p}$, $p_{F\sigma e}$ are the specific permeances for the side coil and respectively end coil leakage.

In the salient poles' rotor the damping cage is considered as constituted from independent groups of bars when the rings connect separately each group of bars placed on a pole.

The basic element for the damping cage is the rotor loop, on each pole existing the same number of loops. Each loop contains two consecutive bars and the corresponding parts of the end ring. The loop leakage inductance is [14, 15]:

$$L^*_{l\sigma} = 2\left[L^*_{b\sigma} 4\sin^2\frac{\alpha}{2} + L^*_{r\sigma}\right] \quad (19)$$

where $L^*_{b\sigma}$ and $L^*_{r\sigma}$ are the bar and end ring leakage inductance respectively, and α is the electrical angle between two consecutive bars.

If Q_{Rp} is the number of bars per pole, the number of loops is Q_{Rp}-1 equal with the number of rotor phases m_R.

The D-and Q-axis leakage inductances are [18]:

$$L^*_{D\sigma} = \frac{1}{2}\frac{L^*_{l\sigma}}{\cos^2\gamma}, \quad L^*_{Q\sigma} = \frac{1}{2}\frac{L^*_{l\sigma}}{\sin^2\gamma} \quad (20)$$

where electrical angle γ is:

$$\gamma = \frac{Q_{Rp}-1}{2}\frac{\alpha}{2} \quad (21)$$

The D-and Q-axis leakage inductances referred to the stator winding are:

$$L_D = \frac{1}{2}\left(\frac{2\sqrt{3}N_S k_{WS}\cos\gamma}{\sqrt{m_R}(1+k_{dm})}\frac{A_{d1}}{A_1}\right)^2 L^*_{l\sigma} \quad (22)$$

$$L_Q = \frac{1}{2}\left(\frac{2\sqrt{3}N_S k_{WS}\sin\gamma}{\sqrt{m_R}(1+k_{dm})}\frac{A_{q1}}{A_1}\right)^2 L^*_{l\sigma}, \quad (23)$$

where [18]

$$k_{dm} = \frac{\sin\left(\frac{m_R}{2}\alpha\right)}{\frac{m_R}{2}\sin\alpha} \quad (24)$$

relations which are different of that given in [6, 7].

5. RESULTS AND CONCLUSIONS

The above given analytical formulae were applied to calculate the inductances for a large synchronous generator which has the following main data:

- rated power S=83 MVA,
- rated voltage V=17.5 kV,
- rated frequency f=50 Hz,
- number of pole pairs p=5,
- number of stator slots Q_S=120,
- stator interior diameter D=3.2 m,
- stator length l=1.9 m,
- minimum and maximum air-gap length:

  g_m=25 mm, g_M=32.5 mm,

- number of bars per pole Q_{Rp}=7,
- rotor cage slot pitch τ_R=83.8 mm,
- number of conductors/slot N_{CS}=2.

The Wieseman coefficients are[4]:

C_Φ=1.0135, A_1=1.11, A_{d1}=0.896, A_{q1}=0.51

The stator Carter's factor is:

K_{CS}=1.0048

The equivalent air-gap length is:

g^*=25.12 mm

The saturation was not considered since the comparison is made with the inductance values obtained on the non-saturated machine by tests or by 2D-FEM analysis [16].

The calculated values are:

- Magnetizing inductances on d-axis:

M_d=11.076 mH, X_{dm}=3.48 Ω, m_d=0.94

- Stator phase leakage inductance:

$L_{S\sigma}$=1.5639 mH, $X_{S\sigma}$=0.489 Ω, $l_{S\sigma}$=0.133

- Rotor field winding leakage inductance:

$L^*_{F\sigma}$=0.179 H, $L_{F\sigma}$=1.07 mH, $l_{F\sigma}$=0.091

- Rotor damping cage *D*-axis leakage inductance:

$L_{D\sigma}$=0.15 mH, $X_{D\sigma}$=0.047 Ω, $l_{D\sigma}$=0.0128

- Rotor damping cage *Q*-axis leakage inductance:

$L_{Q\sigma}$=0.0298 mH, $X_{Q\sigma}$=0.0094 Ω, $l_{Q\sigma}$=0.0025

- Synchronous d-axis inductances [3]:

$$l_d = m_d + l_{S\sigma} = 1.073$$

$$l_d'' = l_{S\sigma} + l_{F\sigma} = 0.1458$$

- Damping cage loop leakage inductance:

$$L^{*}_{l\sigma} = 11.007 * 10^{-7}\ \mathrm{H}$$

The "per-unit" values measured and respectively computed via 2D-FEM, are,[16], unsaturated machine,

$$(l_d)_{test} = 0.986\ ; (l_d)_{FEM} = 0.934$$

$$(l_d'')_{test} = 0.1633 ; (l_d'')_{FEM} = 0.1849$$

The base impedance for "per-unit" system is

$$X_b = 3.69\ \Omega$$

The value obtained during the design stage of the generator was l_d=1.139 [16].

It is clear that by using the algorithm proposed in this paper the results are quite closer to that obtained by test or by 2D-FEM analysis.

A further improvement, to consider adequately the saturation, is required and this would be the direction to continue the actual work.

REFERENCES

1. Doherty, R.E., Shirley,O.E., "Reactances of synchronous machine and its applications" AIEE Transactions, Vol. 37, Part 2, 1918, pp. 1209-1297.
2. Park, R.H., Robertson B.L., "The reactances of synchronous machines" AIEE Transactions, Vol. 47, Part 2, 1928, pp. 514-535.
3. Kilgore, L.A., "Calculation of synchronous machines constants" AIEE Transactions, Vol. 50, Part. 2, 1931, pp. 1201-1214.
4. Wiesemen, R.W., "Graphical determination of magnetic fields" AIEE Transactions, Vol. 46, Part 2, 1927, pp. 141-154.
5. Concordia,C., "Synchronous machines. Theory and performance" John Wiley 1951.
6. Rankin, A.W., "The direct – and quadrature – axis equivalent circuits of synchronous machine" AIEE Transactions, Vol. 64, Part. 2, 1945, pp. 861-868.
7. Talaat, M.E., "A new approach to calculation of synchronous machine reactances" Part. I AIEE Transactions Part II, Vol. 74, pp. 176-183, 1955.
8. Canay, I.M., "Causes of discrepancies in calculation of rotor quantities and exact equivalent diagrams of the synchronous machine" IEEE Trans. on PAS, PAS-88, pp. 1114-1120, 1969.
9. Canay, I.M., "Extended synchronous machine model for the calculation of transient processes and stability" Electric Machines and Electromechanics, Vol. 1, no. 2, pp. 137-150, 1977.
10. Kamwa, I., Viarouge, P., "On equivalent circuit structures for empirical modeling of turbine-generators" IEEE Trans. on Energy Conversion, Vol. 9, no. 3, pp. 579-592, 1994.
11. Slemon, G.R., Awad, M.L., "On equivalent circuit modeling for synchronous machines" IEEE Trans. on Energy Conversion, Vol. 14, no. 4, pp. 982-988, 1999.
12. Walker, J.H., "Large synchronous machines. Design, manufacture and operation" Clarendon Press, 1981.
13. Alger, P.L., "Induction machines. Their behaviour and uses" Gordon and Breach Science Publisher, 1970 (second edition).
14. Chalmers, B., Williamson, A., "A.C. machines: Electromagnetics and design" John Wiley 1991.
15. Viorel, I.A., "The influence of the number and the shape of the slots and of the windings' distribution on the induction machine parameters and on its operating characteristics"(in Romanian), PhD Thesis, Technical University of Timişoara, Romania, 1978.
16. Ramirez, C., "Plate-forme numérique d'essais pour machines électriques de puissance", PhD Thesis, EPF Lausanne, 2003.
17. Carpenter, C. J., "The application of the method of images to the machine end winding field" Proc. IEE, Part 4, 1960, pp. 487-493.
18. Viorel, I.A., Simond, J.-J., Tuxuan, M., "On the synchronous machine mathematical model, parameters and equivalent circuits" (to be published).