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UNIVERSITY OF SASKATCHEWAN

Electrical Engineering Abstract #80A208

THEORETICAL AND EXPERIMENTAL INVESTIGATIONS ON THE PERFORMANCE OF SYNCHRONOUS MACHINES UNDER THYRISTOR-BRIDGE LOAD OPERATION

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ABSTRACT

In recent years, the level of harmonics in power systems has become relatively high. Meantime, there is a tendency to eliminate the filters which are usually provided to absorb these harmonics. This has triggered an interest for investigating the interaction between synchronous generators and thyristor-bridge loads and for studying the effect of the harmonics on the performance of synchronous machines.

In this thesis, a rigorous and an easily manipulated analysis has been developed for the determination of the performance of synchronous generators supplying thyristor-bridge loads. This analysis accounts for the full interaction between the synchronous generator and the thyristor-bridge load. The developed analysis is capable of predicting the waveforms of the various variables of the synchronous generator, and their harmonic contents for two cases: (i) when the resistances are neglected, and (ii) when the resistances are taken into consideration. The algorithm of solution of this analysis avoids the use of an iteration process when the resistances are neglected.

Special considerations have been given in this thesis to the design features of synchronous generators supplying thyristor-bridge loads. In this regard, a great deal of work was devoted to the investigation of the effect of the synchronous machine parameters and the system operating conditions on the harmonic levels of its various variables as well as on the copper losses in the machine windings. The findings of these studies would provide the guide lines for designing synchronous machines to cope with the thyristor-bridge loading.

In order to examine the validity of the analysis, extensive experimental investigations were carried out on a microalternator supplying a thyristor-bridge load. In these investigations, the PDP LAB-8/E minicomputer has been used for acquiring, storing and processing the experimental results. The studies have been conducted for different operating conditions as well as for various external inductances and resistances inserted in the microalternator circuits. The comparison made between the experimental and analytical results has proved the general validity of the analysis.

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LIST OF SYMBOLS

a	$\frac{L''_d - L''_q}{L''_d}$
C_o	shift angle
f	frequency
f_1	fundamental frequency
H	step of integration
I	output DC current
$[I]$	vector of synchronous machine currents
$\bar{I}_f$	average field current
$\bar{I}_{kd}, \bar{I}_{kq}$	average d- and q-axis damper winding current respectively
$\hat{I}_{a_n}$	peak value of the nth order harmonic component of the armature current
$\hat{I}_{f_n}$	peak value of the nth order harmonic component of the field current
$\hat{I}_{kd_n}, \hat{I}_{kq_n}$	peak value of the nth order harmonic component of the d- and q-axis damper winding current respectively
$\bar{I}_{kd_{eq}}, \bar{I}_{kq_{eq}}$	equivalent value of the d- and q-axis damper winding current respectively. $\bar{I}_{kd_{eq}} = \sqrt{(R_f/R_{kd})}\ \bar{I}_f$, $\bar{I}_{kq_{eq}} = \sqrt{(R_f/R_{kq})}\ \bar{I}_f$
i	transient commutation current
i_a, i_b, i_c	3-ph armature current
i_f	field winding current
i_{kd}, i_{kq}	d- and q-axis damper winding current respectively
i_{fo}	field winding current at the start of the commutation interval
i_{kdo}, i_{kqo}	d- and q-axis damper winding current at the start of the commutation interval respectively

LIST OF SYMBOLS (Continued)

$i_{f\gamma}$	field winding current at the end of the commutation interval
$i_{kd\gamma}, i_{kq\gamma}$	d- and q-axis damper winding current at the end of the commutation interval respectively
$i_{f(\pi/3-\alpha)}$	field winding current at $\omega t = \pi/3 - \alpha$
$i_{kd(\pi/3-\alpha)}, i_{kq(\pi/3-\alpha)}$	d- and q-axis damper winding current at $\omega t = \pi/3 - \alpha$ respectively
$i_{f(\pi/3)}$	field winding current at $\omega t = \pi/3$
$i_{kd(\pi/3)}, i_{kq(\pi/3)}$	d- and q-axis damper winding current at $\omega t = \pi/3$ respectively
$[L]$	synchronous machine inductance matrix
L_{aao}	average value of the stator self-inductance
L_{aa2}	difference between maximum and average value of the stator self-inductance
L_{abo}	average value of the stator mutual inductance
L_{ad}, L_{aq}	d- and q-axis magnetizing inductance respectively
L_{ae}	external inductance inserted in the armature circuit
L_{afdo}	maximum mutual-inductance between field winding and phase a of the stator
L_{akdo}	maximum mutual-inductance between d-axis damper winding and phase a of the stator
L_{akqo}	maximum mutual-inductance between q-axis damper winding and phase a of the stator
$L_{a\ell}$	armature winding leakage inductance
L_d, L_q	d- and q-axis synchronous inductance respectively
L'_d	d-axis transient inductance
L''_d, L''_q	d- and q-axis subtransient inductance respectively
L_{fdkd}	mutual-inductance between d-axis damper winding and field winding

LIST OF SYMBOLS (Continued)

L_{fe}	external inductance inserted in the field winding
L_{ffd}	self-inductance of the field winding
$L_{f\ell}$	field winding leakage inductance
L_{kde}, L_{kqe}	external inductance inserted in the d- and q-axis damper circuit respectively
$L_{kd\ell}, L_{kq\ell}$	d- and q-axis damper winding leakage inductance respectively
L_{kkd}, L_{kkq}	d- and q-axis damper winding self-inductance respectively
L_t	transformer leakage inductance
N	$\frac{L_{ad}L_{kkd} - L_{ad}^2}{L_{ffd}L_{kkd} - L_{ad}^2}$
N_c	number of channels
N_{fdl}	field winding effective number of turns
N_{kdl}, N_{kql}	d- and q-axis damper winding effective number of turns respectively
N_s	number of samples per cycle
N_{sl}	stator effective number of turns per phase
n	order of harmonic
P	$\frac{L_{aq}}{L_{kkq}}$
p	$\frac{d}{dt}$
Q	$\frac{L_{ad}L_{ffd} - L_{ad}^2}{L_{ffd}L_{kkd} - L_{ad}^2}$
$[R]$	synchronous machine resistance matrix
R_a	armature winding resistance
R_f	field winding resistance
R_{kd}, R_{kq}	d- and q-axis damper winding resistances respectively

LIST OF SYMBOLS (Continued)

R_{kde}, R_{kqe}	external resistance inserted in the d- and q-axis damper circuit respectively
R_t	transformer winding resistance
S	sampling frequency
T_E	electromagnetic developed torque
$\bar{T}_E$	average value of electromagnetic developed torque
$\hat{T}_{E_n}$	peak value of the nth order harmonic component of the electromagnetic developed torque
t	time in p.u.
[V]	vector of machine terminal voltage
$\hat{V}_1$	peak value of fundamental component of machine terminal voltage
$\hat{V}_n$	peak value of nth order harmonic component of machine terminal voltage
v_1, v_2, v_3	3-ph machine terminal voltage
v_a, v_b, v_c	3-ph voltage applied to thyristor-bridge
v_f	voltage of field winding
V_f	$\bar{I}_f \times R_f$
v_{kd}, v_{kq}	d- and q-axis damper winding voltage respectively
$\bar{v}_{DC}$	average value of output DC voltage
x_d, x_q	d- and q-axis synchronous reactance respectively
x'_d	d-axis transient reactance
x''_d, x''_q	d- and q-axis subtransient reactance respectively
$x_{f\ell}$	field winding leakage reactance
$x_{kd\ell}, x_{kq\ell}$	d- and q-axis damper winding leakage reactance respectively
x_p	potier reactance

LIST OF SYMBOLS (Continued)

$[\psi]$	vector of synchronous machine flux linkage
ψ_a, ψ_b, ψ_c	3-ph armature flux linkage
ψ_f	field winding flux linkage
ψ_{kd}, ψ_{kq}	d- and q-axis damper winding flux linkage respectively
θ	rotor position with respect to phase a
ϕ_{V1}	phase angle of the fundamental component of machine terminal voltage measured from the reference axis
ϕ_{I1}	phase angle of the fundamental component of the armature current measured from the reference axis
ϕ_1	$=\phi_{V1} - \phi_{I1}$
α	firing delay angle
δ	displacement angle
γ	commutation angle
ω	rotor speed
λ_d, λ_q	d- and q-axis equivalent permeance of the synchronous machine respectively
μ_o	permeability of space

1. INTRODUCTION

1.1 General

In the past, little attention was paid to the effect of the presence of harmonics on the operation of electrical power systems. This is because harmonic levels, in general, were found to be acceptably low. In recent years, however, the level of harmonics in power systems has become relatively high due to the use of high power converters for HVDC transmission systems[1-4] and the rapidly increasing applications[5-10] of semiconductor devices, e.g., in static excitation systems,[11,12] motor speed control,[13-16] ... etc.

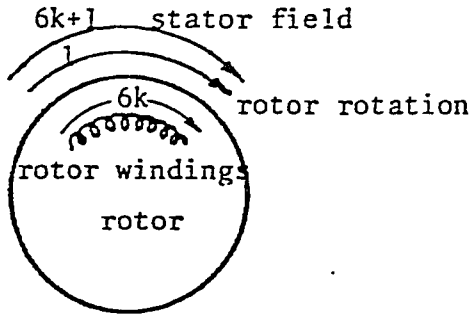
Whenever harmonics are present in high percentage, filter networks are provided to absorb them. However, these filters are relatively expensive (for example, the cost of filters in a HVDC converter station can reach up to 15% of the converter station cost) and their provision introduces many problems.[3,4] Accordingly, there is a tendency to eliminate these filters especially from systems consisting of isolated generators supplying thyristor-bridge loads, such as AC exciter systems[11,12] and unit-connection HVDC transmission schemes.[17-19] This has triggered an interest in investigating the interaction between synchronous generators and thyristor-bridge loads when the filters are eliminated, and to examine the effect of the generated harmonic currents on the performance of synchronous machines.

1.2 Effect of Harmonics on the Performance of Synchronous Machines

In all the systems which consist of synchronous generators supplying thyristor-bridge loads, harmonic currents of order 6k±1 (where k is an integer) are generated[1,2] by the thyristor-bridge. The flow of these currents in the stator windings of synchronous machines results in harmonic currents of order 6k in the rotor windings.[20-23] This is because the stator harmonic current of order 6k+1 (e.g., 7) creates an MMF with the same sense of rotation as that of the rotor, Fig. 1.1a. Therefore, the relative velocity of such an MMF with respect to the rotor is 6k times that of the rotor. On the other hand, the corresponding harmonic component of the stator phase currents of order 6k-1 (e.g., 5) creates an MMF which has also a relative velocity with respect to the rotor of the same value as that of the 6k+1 harmonic current but of opposite direction, Fig. 1.1b. These two MMFs rotating in opposite directions result in an elliptical field, Fig. 1.1c, and they induce harmonic currents of order 6k (e.g., 6) in the rotor surface and windings. In such a case, the rotor circuits will be carrying AC currents even under steady-state conditions.

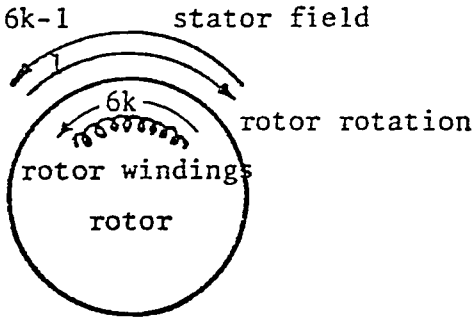
The flow of these harmonic frequency currents in the synchronous machine windings results in the distortion of the waveform of the machine terminal voltage. Such a distortion is unacceptable if the synchronous generator is supplying a load which is sensitive to harmonic voltages.

Moreover, the resultant harmonic rotating air-gap fluxes will interact with the harmonic currents of the machine and results in the production of pulsating electromagnetic torques[16,22,23,24] which add to the constant torque of the machine. These pulsating



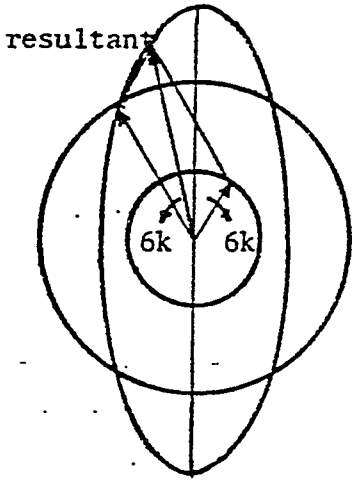
(a)

Generation of Harmonic Currents of Order 6k in the Rotor due to Harmonic Currents of Order 6k+1 in the Stator.



(b)

Generation of Harmonic Currents of Order 6k in the Rotor due to Harmonic Currents of Order 6k-1 in the Stator.



(c)

The Resultant Elliptical Field.

Fig. 1.1 Generation of Harmonic Currents of Order 6k in the Rotor

electromagnetic torques produce vibrations that could damage the machine structure, especially if their frequencies coincide with the machine natural frequencies.[25,26]

The flow of harmonic currents in the machine windings and rotor surface increases the machine losses.[2,3,18-21,27-30] With an increase in the losses, the machine efficiency[16] is reduced and the operating cost is increased. In addition, the extra machine losses result in an increase in its temperature rise, and thus the machine should be derated[18-20,27-30] to avoid any undue deterioration of the insulation.

This problem of the increase in the losses and heating of synchronous machines due to thyristor-bridge loading has been receiving the attention of many investigators[18-20,27-30] for a long time. In earlier studies,[20,29] the effort was directed towards the experimental determination of these losses and their heating effects. Few other studies[17,18,27,28] applied approximate theoretical concepts to predict the amount of these losses by representing the synchronous machine by its negative-sequence resistance and using approximate values for the rotor harmonic currents. In all these investigations, the rotor currents were calculated by assuming that the same order harmonic currents (6k), which are induced in the rotor due to the one higher (6k+1) and the one lower order (6k-1) stator harmonic currents, are in phase and add together. In this context, the rotor heating effect of rectifier loads was specified[17,18,27,28] in terms of an equivalent continuous negative-sequence current. Such a current was then compared with the generator continuous permissible negative-sequence current and reduction factors for rectifier loads were calculated. However, the results obtained from these various