Regenerative Braking of Traction Motors

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BY

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SUMMARY

This work deals with the theoretical and experimental investigation of the dynamic response of d.c. machine during regenerative braking.

A scheme employing a parallel stabilising resistance in the main circuit is built and studied experimentally. A mathematical model of the system has been derived and analysed on the digital computer. The effect of the stabilizing resistance is studied and a modification of the scheme is introduced to prevent remotoring after regenerative braking. Illustrations of the whole traction cycle are photographed with the aid of a storage oscilloscope, and camera.

Another scheme has been built in the laboratory for the purpose of experimental study of the operation of the machine when being supplied from a 2-quadrant converter. The specially designed electronic control circuit of the converter enables the motor to be anutomatically started, to have adjustable and

compensated speed drive and to be braked regeneratively. Photographs of the currents, voltages and signal proportional to the speed have been taken with the aid of the same storage oscilloscope and camera. The regenerative braking period is specially emphasized. Analytical study of the biphase converter circuit with a back e.m.f and inductive load, (resistance and inductance in series), during discontinuous and continuous modes of operation has been performed on the computer. The relation between the extinction and firing angles during the discontinuous mode of operation has been studied. Moreover, the wave shape of the starting current pulses, the relation between the regenerated peak current and the firing angle as well as, the threshold angle and the inversion region as a function of the firing angle have been also obtained.

The thesis consists of six chapters: Chapter (1) is an introduction to define and review regenerative braking phenomina and systems. Chapter (2) is an experimental and analytical study of the dynamic response of a d.c. traction motor during regenerative braking. The adopted scheme in this investigation is Dover's scheme employing the parallel stabilizing resistance in the main circuit. Chapter (3) deals with the experimental study of the characteristics of a 2-quadrant converter equipped with an electronic control circuit which is specially designed for affecting regenerative braking. Chapter (4) is an analytical study of the biphase circuit performed on the digital computer of Ain Shams University. Chapter (5) is the conclusion. Chapter (6) is a collection of appendices.

LIST OF SYMBOLS

Chapter (2)

R_1, L_1	:	resistance and inductance of traction motor armature and d.c. generators
R_2, L_2	:	resistance and inductance of the exciter armature.
R_S, L_S	:	resistance and inductance of traction motor series field.
R_{Sr}	:	stabilizing resistance.
E_g	:	d.c. supply voltage.
E_b	:	back e.m.f. of traction motor.
E_{ex}	:	exciter voltage.
T_o	:	no load torque.
T_b	:	mechanical braking torque.
W	:	the speed of the traction motor.
W_{o_1}	:	speed resulting from regenrative braking.
W_{o_2}	:	speed resulting from coasting.
J	:	polar moment of inertia of rotating parts.
V_d	:	diod forward voltage drop.
I_1, I_a	:	the armature current.
I_2, I_{sf}	:	the series field current
$I_2+I_3, I_{R_{sr}}$	:	the stabilizing resistance current.

SS	:	steady state.
S	:	starting period.
F.R	:	free running period.
R.B	:	regenerative braking period.
C & B	:	coasting and braking periods.

Chapter (3) and (4)

e_p	:	supply voltage.
v_{s_1}, v_{s_2}	:	voltage of secondary windings.
$E_m, \hat{E}$	:	the maximum input voltage per phase.
i_p	:	primary current.
i_{s_1}, i_{s_2}	:	secondary currents.
i_L, I_a	:	load and armature currents.
R_L, R_a	:	load and armature resistances.
L_L	:	load inductance.
E_L	:	back e.m.f. of the traction motor.
l_p	:	leakage inductance of primary winding.
l_s	:	leakage inductance of each secondary winding
l_M	:	$(M_{ss} - M_{sp})$
M_{ss}	:	mutual inductance between the two secondary windings.
M_{sp}	:	mutual inductance between the secondary and primary windings.
U_1, U_2	:	unit step functions.

x	:	any angle, $x = x_f + wt$.
x_f or GM	:	firing angle.
β or ALFA	:	extinction angle.
α_p	:	the angle at which the peak value of the current occurs.
$i(\alpha_p)$	:	the instantaneous peak value of the current
X	:	the inverse time constant, $X = R_L/L_L$
η	:	the speed factor, $\eta = E_L/E_m$
$\cos \theta$	:	the power factor of armature circuit, $\cos \theta = wL/R$
δ	:	the initial current constant, $= (L_L\ I(0))/E_m$
$I(0)$	:	the initial current.
P_{av}	:	the average regenerated power.
G	:	the per-unit average regenerated power .
p	:	the differential operator.

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CHAPTER 1

INTRODUCTION

Electric traction possesses advantages over other systems practically on railways having heavy gradients and long tunnels. In deciding upon the system of electrification to be adopted for a railway with heavy gradients considerations would naturally be given to those systems in which electric regenerative braking could be used. The trains descending the gradients would be braked electrically, so that, instead of the kinetic energy of the train being dissipated in the brakeshoes and wheel tyres, it would be converted into electrical energy and returned to the supply system. Thus, in addition to the saving in the power consumption, the maintenance of the brake shoes, wheel tyres, and track rails would be reduced. The reduction in the latter items alone may be sufficient to cover a fair percentage of the costs of electrification. The energy output from the motors of an electric train, operating on a level track is expended in accelerating the train as well as it supplies the losses due to the resistances to motion. When the train is running at constant speed, the kinetic energy which it possesses is equal to the energy expended in acceleration. During coasting a portion of this energy is utilized for propulsion. Hence, coasting may be considered as a form of mechanical regenerative braking or recuperation of energy. If reductions are to be effected in the energy consumption of level-track surface lines by means of regenerative braking, the electrical equipment must be utilized for this purpose, the motors being operated as generators during the period of retardation, and the power generated being returned to the supply system.

1.1 Electric Regenerative Braking Systems:

The operating conditions on main-line railways having long gradients and on mountain railways are very favourable to electric regenerative braking owing to the relatively large amount of energy available during the descent of the gradients. Moreover, the operating conditions permits the use of motors having constant speed characteristics. In these cases, even when d.c. series motors are employed, the additional equipment necessary for regenerative braking adds but a small percentage to the cost of the locomotive. Systems of railway electrification comprise:

(i) the direct current system; (ii) the single phase alternating-current system operating at low frequency (e.g. 16 $\frac{2}{3}$ Hz) and the standard industrial frequency (50 Hz); (iii) the three-phase alternating-current system.

1.1.1 The d.c. traction motors:

Before discussing why the series motor is prefered for traction it is worthwhile to mention the properties of the traction motor. The chief requirements of a satisfactory traction motor are:-

Electrical features:

- High starting torque.
- Series speed torque characteristics.
- Simple speed control.
- Possibility of dynamic braking.
- Good commutation under rapid fluctuations of supply voltage.