UPR/MIT/TU Professional Development Program
Transportation Technology Transfer Center
University of Puerto Rico at Mayagüez
Mayagüez, P.R.

Executive Summary

Regenerative Braking System for Tren Urbano

by

Jorge L. ColónValentín
e-mail: jorge@ieee.org
Electrical and Computer Engineering Department
University of Puerto Rico at Mayaguez

Advisor
Dr. Gerson Beauchamp
e-mail: gerson@ece.uprm.edu

Executive Summary

1. Introduction

Heavy-Rail trains such as Tren Urbano have an electrical motor that is able to regenerate energy during the braking periods. The polarity of the motor is reversed to produce an inverse torque that converts kinetic energy in electrical energy, hence braking the train. The energy generated is then dissipated in the braking resistor. This is known best as Dynamic Braking (DB). In addition to the DB system, a friction brake is used to provide emergency braking and a faster response from the DB drive. The dissipation of energy creates heat, decreases overall efficiency of the system, and also implies wasting of recoverable energy and resources. This research deals with the evaluation of a Regenerative Brake (RB) system as an alternative for improving the energy consumption of Tren Urbano. The RB system must be able to stop the train in the time and distance required, guaranteeing the passengers a safe and comfortable ride. During braking, the RB system produces a coasting effect due to the inability of the motor to generate once it has reached a speed of about 7 mph. This is why a friction brake system is required. The RB system should be integrated with an energy storage system, which must be able to handle the considerable amounts of energy generated by the motor.

2. Objectives

The main objectives of this research are: 1) To study electrical braking systems, specifically the Dynamic Brake (DB) and the Regenerative Brake (RB). 2) To design and develop a RB control system that guarantees the anti-slip/slide of the train during braking. 3) Determine the feasibility of implementing the RB technology in Tren Urbano.

3. Methodology

Case studies are of great importance in this research. It was necessary to review the literature about several cases. The cases studied include the Line B of the City of Rome [1] and that of Australia [4]. Both of these systems were initially designed with DB. Studies are now being conducted to determine the feasibility to include RB as an energy conservation alternative. In the literature review was also found information of existing electric trains that use technologies similar to those that will be implemented in Tren Urbano. From these references the fundamental differences between RB and DB systems were established [1,2,3,4]. The RB options were determined and found to be the same as those used in DB systems. After evaluating the RB options, a mathematical model that describes the system response will be developed. It will be necessary to design a RB controller that guarantees braking in the time and distance required for a heavy-rail train as Tren Urbano. The system will be designed and simulated using Matlab in order to validate the model, making sure that the wheels won't slide during braking.

The resources that are being used as part of this research are: 1) Dr. Gerson Beauchamp; EE-UPRM. 2) Dr. Iván Baigés; ME-UPRM. 3) References in the last section. 4) Eng. Chris Fonta; STT-SJ. 5) Eng. Dirk Rosler; STT-Sacramento. 5) TUO.

4. Up to date conclusions

Dynamic Braking is very effective in terms of braking ability and independence in overcharge situations on the lines that feed the train (3^{rd} rail). The implementation of a DB system costs less since it requires components that perform simple and unidirectional tasks as for example the dissipation of energy. On the other hand. Regenerative Braking has the same efficiency as the DB has in terms of braking and in addition its efficiency from an energy consumption standpoint makes it technologically superior. The RB lowers the average temperature of the system. producing an improvement in the temperature of the stations. which consequently will require less energy for air conditioning devices. The Total Harmonic Distortion (THD) of the current during RB is comparable to the distortion of the current produced by the motoring action [2].

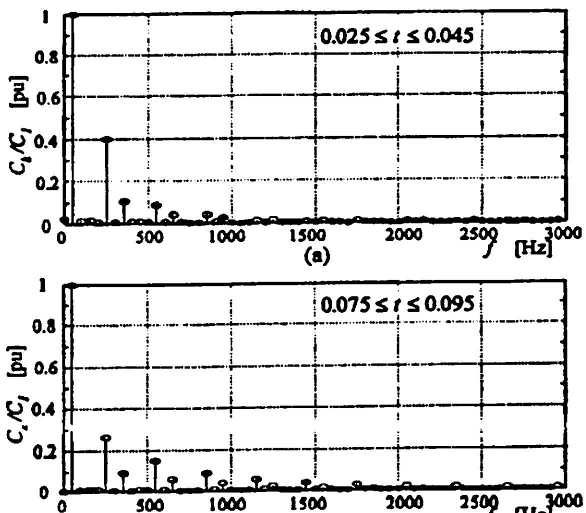
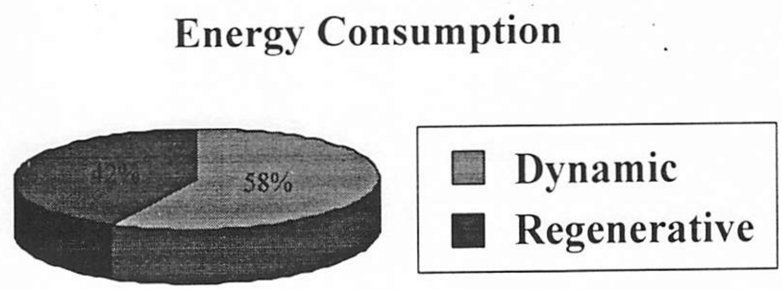


Fig. 11. Spectrum C_k, k=0..60 of the current I_{al} in Fig. 10 during (a) motoring and (b) regenerating of the drive

Simulations made elsewhere [1, 4] show that Regenerative Braking is capable of producing a 15% average daily savings and up to a 19% savings during peak hours. This implies that the cost of usage of a RB is considerably lower than that of the DB.



As part of our analysis, it was concluded that a RB module used with a pneumatic brake should prove to be the best option for Tren Urbano. Since the train is designed to use a Dynamic/Pneumatic module, it would produce a lower cost of implementation to use the existing system with the addition of a Regenerative drive capable of being used as an add-on unit.

5. Research Plan

August, 1999 – October, 1999

Literature Review on DB systems, RB systems, electric trains and energy storage systems.

October, 1999 – December, 1999

Determine RB options, compare the available technologies and recommend a system. Progress Report writing.

January, 2000 – February, 2000

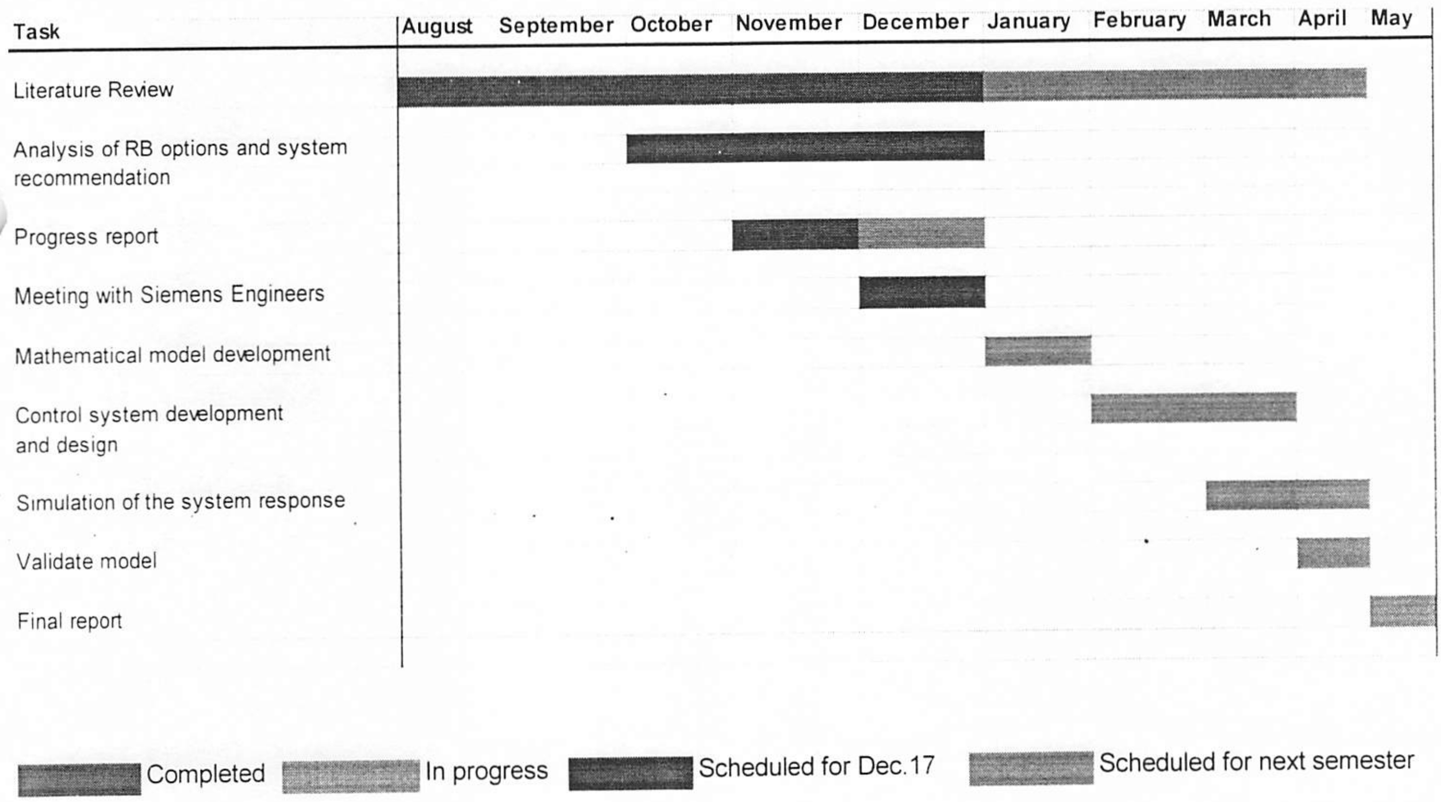
Analysis of the system and development of a mathematical model that describes the train's performance using RB.

February, 2000 – April, 2000

Control system design for anti slip/slide brakes.

March, 2000 – May, 2000

Simulation of the system response using Matlab and model design revision. Progress Report writing.



Literature Review
INEL 4998
UPR/MIT/TUO Professional Development Program
Dr.Gerson Beauchamp Báez – Advisor

[1] A. Adinolfi, R. Lamedica, C. Modesto, A. Prudenci, S. Vimercati, "Experimental assessment of energy saving due to trains regenerative braking in an electrified subway line," *IEEE Annual Meeting*, pp. 211-216, May 1997.

[2] V. Blasko, "Power conditions and control of a regenerative brake," *IEEE Industry Applications Conference, 1998.Thirty-Third IAS Annual Meeting*, Vol. 2, pp. 1504-1510.

[3] T.H. Pham, P.F. Wendling, P. Lombard, S.J. Salon, H. Acikgoz, "Dynamic braking of a voltage supplied induction motor using finite element analysis," *IEEE International Electric Machines and Drives Conference Record, 1997*, pp. WB3/3.1-WB3/3.3, May 1997.

[4] F. Flinders, R. Mathew, W. Oghanna, "Energy savings through regenerative braking using retrofit converters," *1995 IEEE / ASME Joint Proc.-Railroad Conference*, pp. 55-61, April 1995.

[5] D.P. Madau, F. Yuan, L.I. Davis Jr., L.A. Feldkamp, "Fuzzy logic anti-lock brake system for a limited range coefficient of friction surface," *Second IEEE International Conference on Fuzzy Systems*, Vol. 2, pp. 883-888, April 1993.

[6] J. Paterson, M. Ramsay, "Electric vehicle braking by fuzzy logic control," *IEEE Industry Applications Society Annual Meeting, 1993*, Vol. 3, pp.2200-2204, October 1993.

This paper [1] deals with a research done on the subway line B in the city of Rome, whose trains are equipped with drives providing the regenerative braking (RB). The trains are also equipped with a pneumatic braking system completely substitutive of the regenerative one without any limitations of speed or duration.

Simulations were conducted of the electric power system and the results were tabulated and compared with experimental tests showing a satisfactory matching in the results. It was concluded that the regenerative braking system produced energy savings of about 19% during the traffic peak hours and average daily savings of about 15% as well as improvement on the subway environmental thermal conditions.

In [2] a complete analysis of a standard regenerating drive is discussed and a robust and simple solution of control of RB with an analysis of power conditions is provided.

The differences between dynamic and regenerative braking systems are detailed and it was concluded through simulation that a RB system can be used as a stand alone, add-on unit to the standard drive. It can be built into the drive becoming a part of a regenerative "integrated drive". The Total Harmonic Distortion (THD) of the current of RB is comparable to the distortion of the current of the standard drive during motoring.

[3] Presents the simulation of the dynamic braking of a voltage supplied induction motor from Turk Elektrik Endustrisi using the software Flux 2D.

The motor is polyphase and it operates in three modes: motor, generator and reverse-rotation braking. The reverse-rotation-braking mode consists of reversing any two phases of the three-stator leads, resulting in reversing the phase sequence and thus the direction of the rotation of the magnetic field. This mode of operation effectively brakes the speed of the rotor and is called "plugging". The simulation results showed the variation of the torque and the rotor velocity during the dynamic braking. After the initial strong braking time steps where the rotor velocity decreases sharply, the rotor is accelerated again due to a swinging effect. It is initially when the heat losses peak.

Paper [4] explores the benefits and feasibility of retrofitting existing phase controlled DC motor drives in a rail transport in Australia using PWM rectifier technology, whose major benefits would be the replacement of the dynamic brake with a regenerative system and unity power factor operation.

Even though that this research work is at very early stages, it was demonstrated via simulation, using SIMULINK, that a full scale program such as the one proposed may be both economically and technically feasible.

In [5] a preliminary research on and implementation of a fuzzy logic controller to control wheel slip for an antilock brake system is described. Since the dynamics of braking systems are highly nonlinear and time-variant, a simulation was used to derive an initial rule base, which was then tested on an experimental brake system. Varying operating conditions and external environmental variables further tested the robustness of the fuzzy logic slip regulator.

In conclusion, the research showed that fuzzy logic supplies a framework for quick development of prototype controllers without the need of detailed understanding of the internal plant dynamics.

[6] Shows that, by exploiting the inherent tolerances in the braking system, a fuzzy logic controller can be used to achieve a more comfortable ride for the vehicle operator. Binary switching of braking action from regenerative to mechanical causes an unpleasant sudden jolt, which could be smoothed using fuzzy logic. The fuzzy controller model reduces the velocity error but does not eliminate it completely. These errors are due to the time variables of temperature, brake pad wear, brake pad temperature and the mechanical frictions in the system. It is expected that with the addition of an adaptive control scheme to monitor these time constants and predict them will reduce the unwanted jerks in the switching of brake modes.

Regenerative Braking System for Tren Urbano

Jorge L. Colón Valentín
(Undergraduate Student)

Electrical and Computer Engineering Department
University of Puerto Rico
Mayaguez Campus

Dr. Gerson Beauchamp (Advisor)

Statement of Purpose

Although dynamic braking systems are predominantly used in train technologies because of their dependability in line overcharge situations, their performance is inefficient and often contributes to the premature deterioration of the train.

The main objective of this research is to study regenerative braking systems of trains that are similar to those of Tren Urbano and determine the feasibility of implementing such a system. A regenerative braking system should use **energy storage** instead of dissipation. The regenerative braking system would provide, given the proper control system, the same dependability in line overcharge situations and the efficiency that energy recovery and storage implies.

Once an appropriate regenerative braking system is identified, a control system will be designed to assure the anti-slip/slide braking of the train. The performance of the control system will be evaluated via simulation.

Objectives

- Study of electrical braking systems
  - Dynamic (Resistive) Brake (DB)
  - Regenerative Brake (RB)
- Develop a RB control system
- Determine feasibility of implementation

General Findings

- System options
  - Regenerative / Pneumatic
    - Fast Response

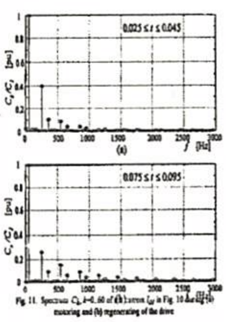
  - Regenerative / Hydraulic
    - Constant applied pressure

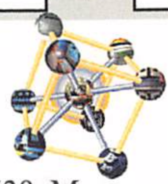
General Findings

•Dynamic braking causes the average temperature of the system to raise and could produce an uncomfortable environment in the stations

General Findings

•Total Harmonic Distortion (THD) of the current of RB during braking is comparable to the distortion of the current during motoring.





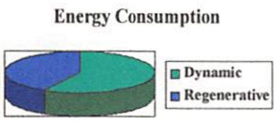
TREN URBANO

Jorge L. Colón Valentín PO Box 5539, Mayaguez, PR, 00681-5539 jorgec@ieee.org

Regenerative Braking System for Tren Urbano

General Findings

- Regenerative drive
  - 15% average daily savings
  - 19% savings in peak hours
  - High percentage of energy can be recovered



General Findings

- The braking system of Tren Urbano is a combination of multiple brake systems
  - Regenerative-Dynamic brake system
    - The generated energy is feed into the power supply system (catenary or third rail).
  - Friction brake system
    - The friction brake system is mainly used to support (blending) the regenerative brake system at the following conditions:
      - -Stopping at low speeds and parking brake
      - -Deceleration at high loads and high braking rates
      - -Emergency brake operation
      - -Disabled regenerative braking

Note: Track brakes are used for light rail applications only

Results

- Dynamic Braking
  - Effective
  - Lower cost of implementation
- Regenerative Braking
  - Effective
  - Energy efficient
  - Station environment improvement
  - Cost of implementation could be a factor
  - Significantly lower cost of usage

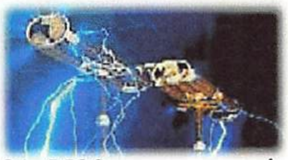
Results

- A regenerative / pneumatic drive that utilizes an in-station energy storage system should prove to be the best option since the pneumatic brakes are already being used for Tren Urbano and the RB with energy storage could be used as an add-on unit to the existing DB drive.

Future Work

Primary Sources

- *Dr. Gerson Beauchamp*
  Professor, EE, UPR-Mayaguez Campus
- *Dr. Iván Baigés*
  Professor, ME, UPR-Mayaguez Campus
- *Eng. Dirk Roesler*
  Siemens Transit Team, Sacramento,CA
- *Eng. Christian Fonta*
  Siemens Transit Partnership, San Juan,PR
- *Eng. Lorraine Z. Lerman*
  Siemens Transit Partnership, San Juan,PR
- Literature from *IEEE* publications



TREN URBANO

Jorge L. Colón Valentín PO Box 5539, Mayaguez, PR, 00681-5539 jorgec@ieee.org