A MATLAB/Simulink Model of a Self Excited Induction Generator for an Electrical Brake Application

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ABSTRACT

This paper presents a MATLAB®/Simulink dynamic model of an induction generator, which makes simulation studies possible for the design of fuzzy logic controllers for the purpose of controlling the retarding torque output of the generator in an electrical brake application, using the fuzzy logic toolbox of MATLAB®. Electrical braking has been proposed in the literature as an alternative to the mechanical braking systems with an advantage of providing lower maintenance costs. An induction generator, acting as a brake, converts the kinetic energy of a vehicle to electrical energy, which can be dissipated in a resistor bank or used in a regenerative mode.

The Simulink model developed will be used to design and test controllers for an effective control of the output torque of the electrical brake system.

1. INTRODUCTION

The Centre for Railway Engineering (CRE) at Central Queensland University (CQU), in conjunction with Commonwealth Sugar Refineries (CSR), has been engaged in a project to investigate the use of electrical braking for the cane trams used to transport the raw product to the sugar mills for refining. Currently, brake vans coupled to the end of cane trains are used by the sugar cane industry in Australia to produce a given constant braking torque, keeping the trams in tension to reduce the derailment risk. The brakes on these vans operate using compressed air, which is supplied by an onboard compressor. The compressed air activates a brake calliper, which clamps a ventilated disc rotor present on each of the four wheel sets. This system has high maintenance requirements due to the wear on the brake pads and rotors, and associated maintenance of the compressor and pneumatic equipment.

This project was established to investigate electrical braking as an alternative to the existing mechanical system. As a low cost alternative, it would be preferable to use induction machines due to the lower maintenance requirements and robustness of the machines. An induction generator converts the kinetic energy of the train to electrical energy, which is dissipated in a resistor bank, acting as a brake [1].

A major component of the system is the controller, which is required to ensure that the generator stays in excitation and maintains the required braking torque to the tram. In order to design and test suitable controllers for this system, proper models of the components must exist. This paper details the development of a MATLAB®/Simulink model, based on an available mathematical model for Self-Excited Induction Generators [2]. MATLAB®/Simulink is chosen as the platform due to its common availability across almost all universities and its flexibility in integrating the models with suitable control systems and other system models.

The Simulink model developed may then be used to design and test controllers, e.g. fuzzy logic controllers, for an effective control of the output torque and voltage of the electrical brake system. Although a dynamic model of an induction generator for this application has been developed by Seyoum and Wolfs [3], but since it has used a Simnon software package, its integration with the Fuzzy Logic Toolbox of MATLAB® is not easily possible.

Models of induction machines are also available in the literature (e.g. [4] to [6]) and in the power system blockset of MATLAB®/Simulink. However, the development of a custom model has been deemed necessary because the existing models do not offer the flexibility required to represent specific dynamic behaviour of the induction generator with variable parameters, which would be dependent on the operating condition of the machine.

It is anticipated the model presented in this paper would be broadly applicable in any system where the induction machine is used as a generator.

2. ELECTRICAL BRAKING SYSTEMS

Electrical brakes are used in electrically driven utilities and machines in industries and, mainly, in electric vehicles. An electrical brake system is mainly based on the ability of electrical machines, to run as generators when the torque gets reversed. The generated energy may be either stored in a battery or sent back to the grid as in electric locomotives or converted into heat using a bank of resistors, thereby wasting the energy to the drive in the form of heat and gradually decreasing its speed. Therefore, the electrical brakes are classified in two types as follows [7].

2.1. REGENERATIVE BRAKING

It is a braking technology, where the vehicle is allowed to recapture and store a part of the kinetic energy instead of wasting it as heat. This technology converts the kinetic energy back into electrical energy. It is sometimes known as dynamic braking. A common application of dynamic braking is in electric locomotives and hybrid vehicles.

2.2. RESISTIVE BRAKING

It is a braking method where the mechanical energy is first converted into electric energy and then this electrical energy is converted into heat. Actually the useful electrical energy generated in the process is wasted in this process hence the efficiency is not as good as regenerative braking. Also, this system needs an additional cooling system in order to cool the resistor bank which dissipates the heat.

3. SELF EXCITATION AND LOAD CONTROL OF INDUCTION GENERATORS

Any induction machine requires excitation current to magnetise the core and produce a rotating magnetic field. An isolated induction generator without any excitation will not generate voltage and will not be able to supply electric power irrespective of the rotor speed. In other words an induction machine requires reactive power for its operation. Three initially charged capacitors connected to the stator terminals of a three phase induction machine can supply the reactive power required. The charged capacitors cause the terminal voltage to build up at the stator terminals of the induction generator. This process is called self-excitation of induction generators [3].

Capacitor banks are normally connected across the stator terminals of an induction generator to provide a source of reactive power for providing the excitation needed for the operation of the generator. When the charged capacitors are connected to the terminals, a transient exciting current will flow and produce a magnetic flux. This magnetic flux will generate voltage and the generated voltage will be able to build the charge in the capacitors. As the charge increases, more exciting current is supplied to the induction generator. The magnetic flux continues to increase hence producing a higher generated voltage. In this way the voltage is built up. However, some conditions must be met for this self-excitation to occur! For a given capacitor value, self-excitation can only be achieved and maintained under certain load and speed combinations. Therefore, the capacitor bank has to be dimensioned according to a defined narrow range of speed and load values [8]. When the speed falls below certain values, the machine demagnetizes and stops generating. This means that an additional control mechanism has to be added in order to avoid demagnetization and to accept the full scale of the output voltage [3].

On the other hand, the output voltage of the induction generator depends greatly on its shaft speed and load; this will cause a significant variation in the power consumption in the load of the machine and, therefore, a variation in the retarding torque produced by the machine during braking. Thus, the power dissipated in the load must be adjusted with speed so that a constant braking torque is generated.

In order to develop controllers for both self excitation and load control, a suitable dynamic model of an induction generator in the environment of MATLAB®/Simulink is required. This paper has proposed such a model, which has the feature of a nonlinear variation in the machine parameters that are dependent on the operating condition of the machine.

4. THE PROPOSED MODEL

The proposed dynamic model of an induction generator is shown in the Appendix. This is a block diagram of the MATLAB/Simulink model, which has been developed to simulate the operation of the induction generator. The following Sections explain the main blocks of this model.

4.1. INPUTS AND OUTPUTS

Three inputs are defined for this system as follows.

4.1.1. SHAFT SPEED

The shaft speed in rpm is dependent on the train speed. The output voltage and the generated power (and hence the braking torque) of the machine are dependent on this speed.

4.1.2. LOAD CONTROL

This input represents the duty cycle of a PWM inverter, which will control the load on the machine. The load control input can be any value between 0 and 1. This represents the output of a controller, which will be designed to change the machine load as the train speed changes.

4.1.3. CAPACITANCE CONTROL

This input represents a binary-switched capacitor bank, which is used to maintain the self-excitation of the induction machine. A controller will be designed to determine a value for this capacitor bank as the operating condition of the machine changes.

4.1.4. OUTPUTS OF THE MODEL

The outputs of the model are the d-q values of the stator and rotor currents and the d-q values of the machine terminal voltage.

4.2. MAIN DYNAMIC BLOCKS

The main dynamic blocks of the proposed model are designated as IG_AB_Lm and IG_stateSpace blocks, as shown in the Appendix.

The IG_AB_Lm block gets the values of the capacitor bank, the electrical angular velocity of the machine, the load value, the initial voltage across the capacitor bank, and also the current values of the outputs of the machine (as described in Section 4.1.4) to calculate the matrices A and B of the machine state space model and also to obtain the magnetising inductance (L_m) of the machine, which is a nonlinear function of the magnetising current of the machine.

The IG_stateSpace block, receives the A and B matrices in addition to L_m and the initial values as inputs, and calculates the new state (output) of the machine. Then, the rms terminal voltage of the machine and the retarding torque produced by the induction machine are computed accordingly.

4.3. THE PERFORMANCE OF THE MODEL

Fixed values for the inputs 'Load Control' and 'Capacitance Control' are used with a shaft speed of 1300 rpm for 3 seconds. The load is applied to the machine at the 3rd second and the speed is gradually decreased from the 6th second to check the performance of the model. The variation in the magnetising inductance of the machine, the rms terminal voltage and the retarding output torque are obtained, which are then compared with the output responses of the Simnon model for the same machine provided by Seyoum and Wolfs [3].

Figure 1 shows the voltage buildup process, which demonstrates the variation of the quadrature component of the terminal voltage (V_q) within 0.8 seconds of the startup of the generator.

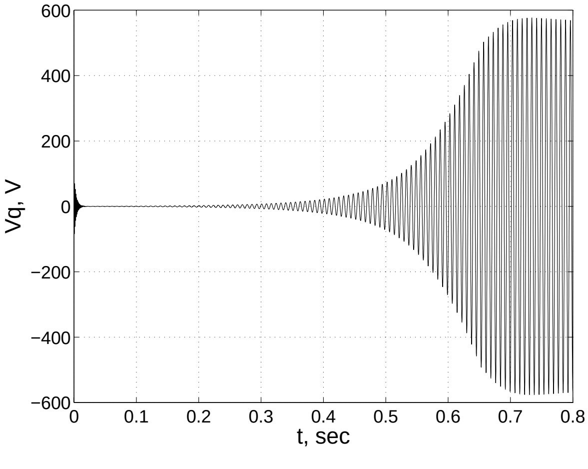

Figure 1: The voltage buildup process

After the generated voltage has settled down to a stable value, in t = 3 sec the load on the machine is increased. This affects both the terminal voltage and the braking torque. Then, in t = 6 sec the speed is gradually decreased from its initial fixed value of 1300 rpm to a value of 1225 rpm in one second (from the 6th to the 7th seconds). Figures 2 and 3 show how the rms value of the terminal voltage and the braking torque respond to these changes. Figure 4 shows the variation of L_m within the 7 seconds of simulation. The magnetising inductance varies nonlinearly, as the magnetisation current changes with time.

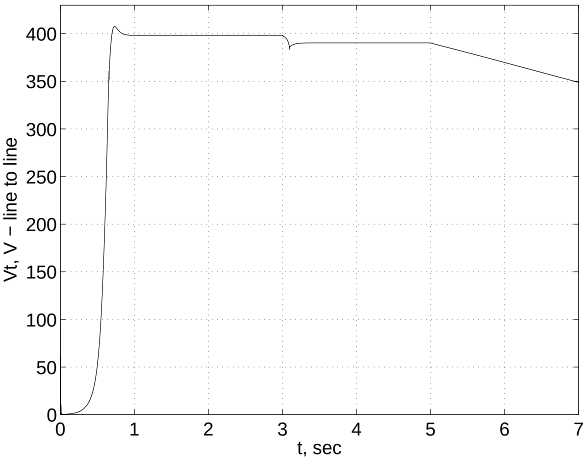

Figure 2: The rms value of the terminal voltage

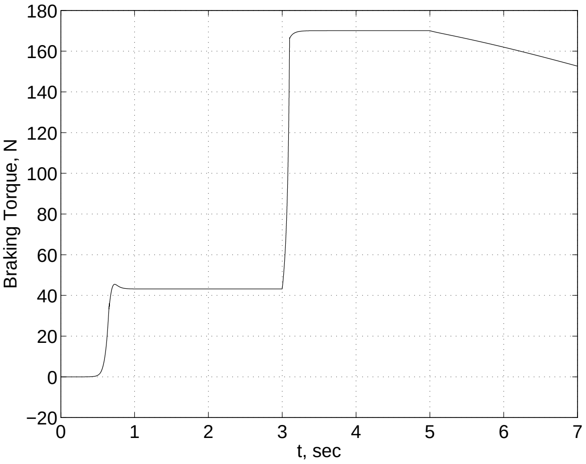

Figure 3: The braking torque output of the induction machine

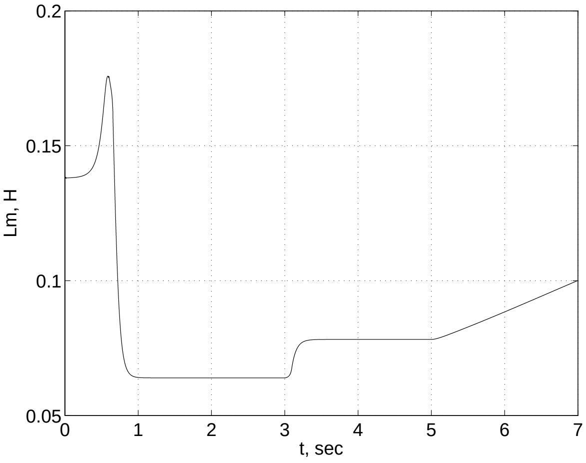

Figure 4: Variation of the machine magnetisation inductance

The purpose of the control elements, which will be designed using the proposed model, is twofold. The first aim is to maintain the excitation of the induction machine, as the speed and other operating conditions of the machine change. The second aim is to produce a fixed output torque in spite of the variations in speed and the operating condition.

For instance, Figure 5 shows how by controlling the load, which has been applied by a gradual increase in load from t = 7 seconds, and simultaneously increasing the capacitance value, by switching the capacitor bank to a bigger value to retain adequate excitation, the braking torque response can be corrected. Note that the speed is still decreasing from the 7th to the 9th seconds.

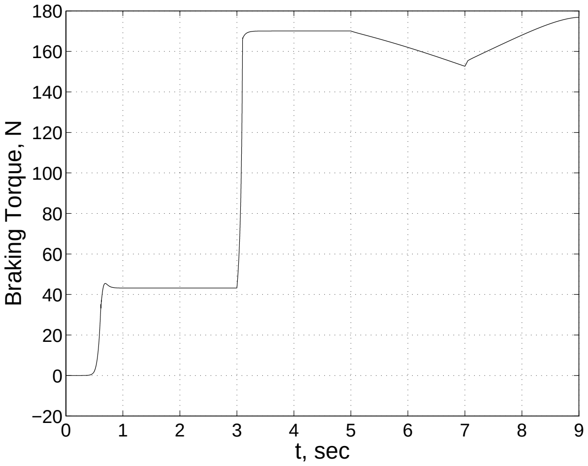

Figure 5: The correction of the braking torque output response by controlling the load from t = 7 sec

Of course, to keep both torque and voltage in a predetermined band of values in a dynamic operation of the machine, sophisticated control schemes are required. The authors are working on the design and development of these controllers.

5. CONCLUSIONS

This paper described a dynamic model for an induction machine in the generating mode, which has the feature of a nonlinear variation in the machine parameters that are dependent on the operating condition of the machine. MATLAB®/Simulink is chosen as the platform due to its common availability across almost all universities and its flexibility in integrating the models with suitable control systems and other system models.

The model is based on an available mathematical model for self-excited induction generators. This Simulink model may then be used to design and test controllers, e.g. fuzzy logic controllers, for an effective control of the output torque and voltage of the electrical brake system. It is anticipated that the model presented in this paper would be broadly applicable in any system where the induction machine is used as a generator.

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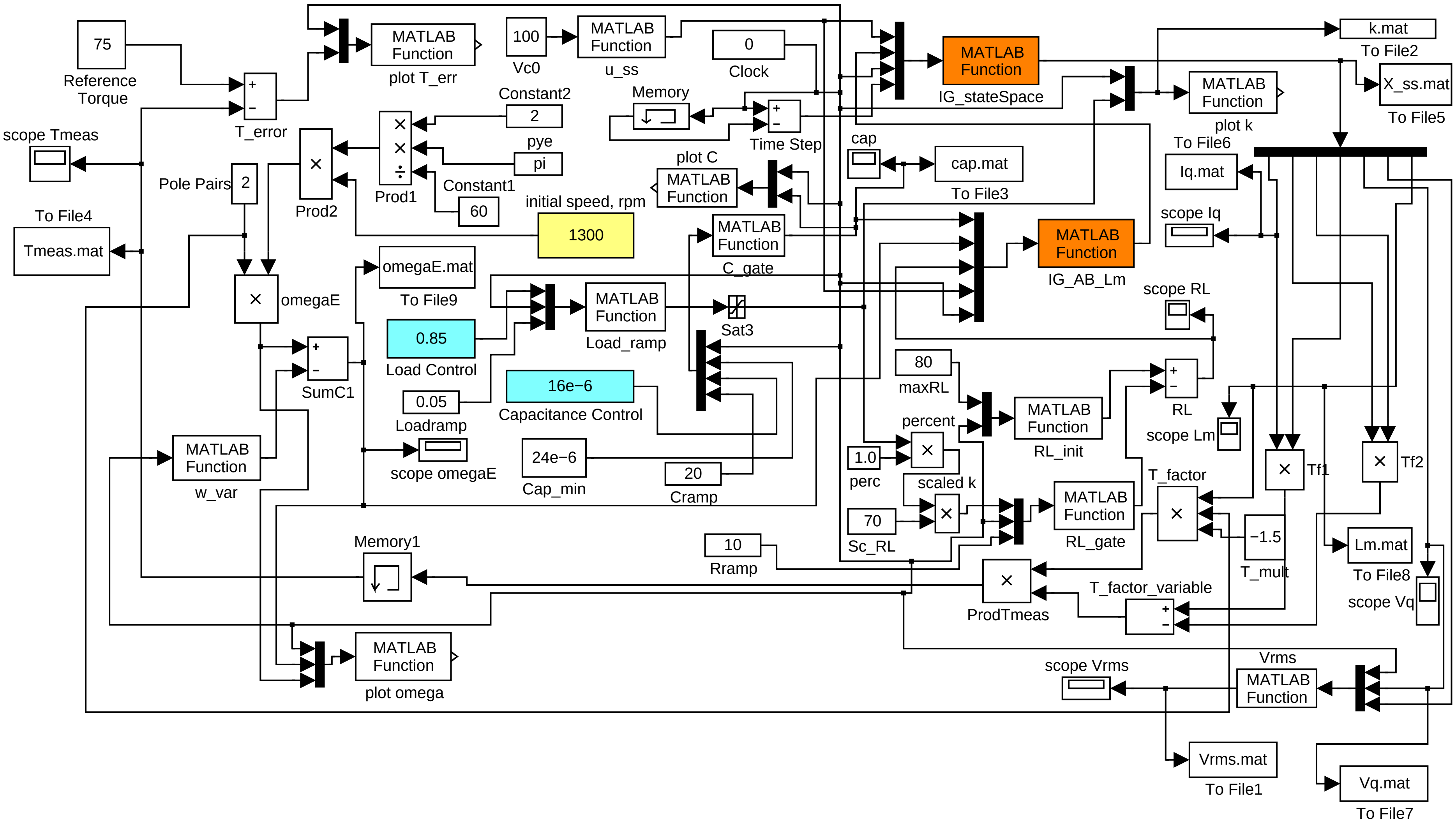
Appendix


75
Reference Torque
+
-
T_error
MATLAB Function
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Vc0
MATLAB Function
u_ss
0
Clock
MATLAB Function
IG_stateSpace
k.mat
To File2
X_ss.mat
To File5
MATLAB Function
plot k
scope Tmeas
Pole Pairs
2
×
Prod2
×
×
÷
Prod1
Constant2
2
pye
pi
Constant1
60
Memory
+
-
Time Step
cap
cap.mat
To File3
To File6
Iq.mat
To File4
Tmeas.mat
plot C
MATLAB Function
initial speed, rpm
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MATLAB Function
C_gate
MATLAB Function
IG_AB_Lm
scope Iq
×
omegaE
omegaE.mat
To File9
MATLAB Function
Load_ramp
Sat3
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Load Control
+
-
SumC1
80
maxRL
MATLAB Function
RL_init
+
-
RL
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Loadramp
16e−6
Capacitance Control
percent
×
1.0
perc
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w_var
scope omegaE
24e−6
Cap_min
20
Cramp
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×
70
Sc_RL
MATLAB Function
RL_gate
T_factor
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×
Tf1
×
Tf2
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+
-
MATLAB Function
plot omega
scope Vrms
Vrms
MATLAB Function
Vrms.mat
To File1
Vq.mat
To File7