

A SIMULATION-BASED DESIGN STUDY FOR A LOCOMOTIVE ELECTRIC POWER SYSTEM

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A Simulation-Based Design Study for a Locomotive Electric Power System¹

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Abstract-- This paper presents a model and simulation for a conceptual locomotive power system consisting of a gas turbine driven synchronous alternator coupled to a rectifier – dc link – variable frequency inverter configuration. This system drives four induction traction motors and is integrated with a flywheel energy storage system (FESS). Such a system is meant to meet demands for rapid acceleration, speed maintenance on grades, recovery of braking energy and overall improved fuel efficiency. This system is under investigation at the Center for Electromechanics (CEM) at the University of Texas at Austin as part of its Advanced Locomotive Propulsion System (ALPS) project. In this paper, a modular, system level simulation of the ALPS prototype is presented, with emphasis placed on the use of power flow management.

Key words: Simulation, Locomotive power systems, power system, reduced-order models, inverter, motor

I. INTRODUCTION

The University of Texas at Austin Center for Electromechanics (UT-CEM) is currently developing an Advanced Locomotive Propulsion System (ALPS) as part of the Next Generation High-Speed Rail program sponsored by the Federal Railroad Administration (FRA) [1]. The ALPS consists of a gas turbine driven synchronous alternator, and variable frequency inverters to drive four induction traction motors and an induction motor-coupled flywheel energy storage system (FESS). The turbo-alternator and FESS combine power flows to improve response and fuel efficiency.

The development of such complex power systems relies heavily on simulation to aid the component and controller design and, later, the rapid prototyping and testing. This paper presents a modular, system level simulation of the ALPS configuration; with emphasis placed on the use of power flow management. The simulation modules include: turbine system, alternator and rectifier, induction motor drives, FESS, locomotive dynamics and a power management module.

II. SYSTEM OVERVIEW

Figure-1 illustrates the basic ALPS conceptual schematic. The prime mover of the system is a gas turbine, which runs a

synchronous generator. The generator output is fed into a DC bus via an uncontrolled rectifier. Five bi-directional DC/AC converters generate variable frequency, variable voltage AC to traction and flywheel motors/generators. Another DC/AC converter supplies AC power to locomotive accessories, like lighting and fans, which are termed “head-end power,” or HEP. A resistor grid is available to dissipate any surplus energy during braking. The locomotive controller accepts the speed command and controls the traction motor to reach the target speed and thus sets the traction power requirement. The power management system tries to minimize the fuel consumption by optimally partitioning the DC power among the sub-systems. One advantage of such a system topology is that the turbine is de-coupled from the load, allowing the turbine speed and power to be optimized with respect to fuel efficiency [2]. Such a dual power source system also provides flexibility for power flow management.

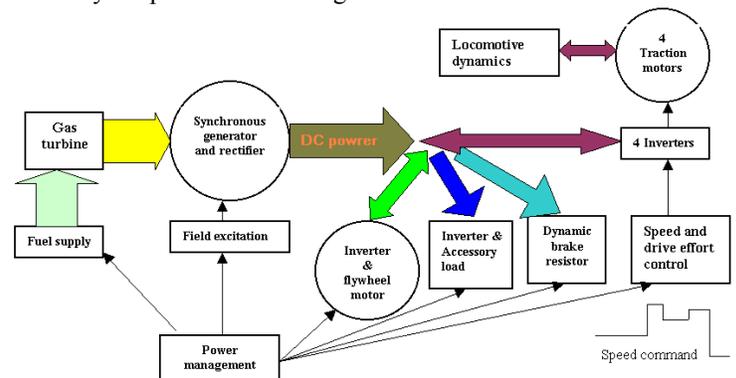


Fig. 1 ALPS concept schematic of power flow

III. SIMULATION MODELS OF THE SYSTEM

Detailed models of each component shown in Figure-1 have been studied and developed extensively [3][4][5][6]. However, due to the complexity of the system (seven inverter/rectifiers, five AC motors, one synchronous motor, etc.), it can be very time consuming if detailed models are used for simulation. In addition, because these simulations are being prepared in the design stages of this system, there can be a lack of information required to formulate detailed models. For example, the equivalent circuits of the traction motors are not yet known. To overcome these problems, reduced-order models for power flow analysis are employed. The system simulation diagram Figure-2 shows the input/output relations of each sub-system. From a power flow point of view, all the loads, including HEP, brake, flywheel and traction systems can be modeled as current

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injectors and the DC bus is the summing point of these currents.

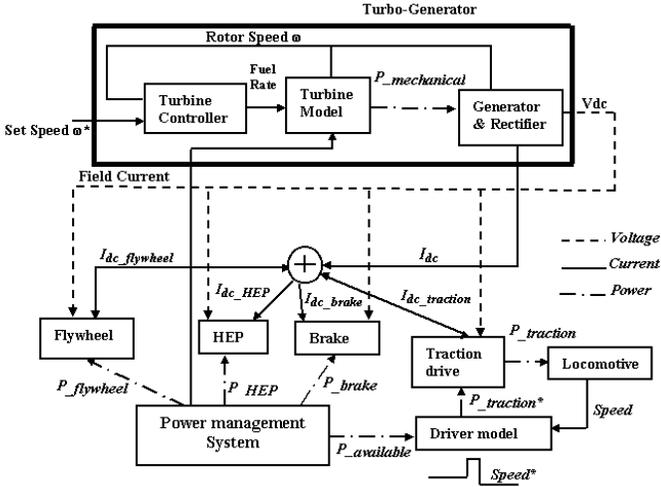


Fig.2 System simulation diagram

A. Turbo-Generator model

The Turbo-Generator is the model of the power plant of the system. It contains the gas turbine, turbine controller and the synchronous generator/rectifier unit. The inputs are the turbine speed set point, the field current, the DC bus current. The output is the DC bus voltage.

1) Gas turbine Model

The diagram and Matlab/Simulink block of the gas turbine model is depicted in Figure-3. The inputs to this model are fuel rate \dot{q} and output shaft speed ω , and the output is turbine power P_m . The turbine is modeled by combing a first order delay that represents turbine system dynamics with a performance map available from the turbine manufacturer. It shows the output shaft power P_m as a function of fuel rate and output shaft speed ω , i.e. $P_m = f(\dot{q}, \omega)$. The output shaft of the gas turbine is directly coupled to the generator, so the shaft speed ω can be determined from the generator model and fed back to the gas turbine as input.

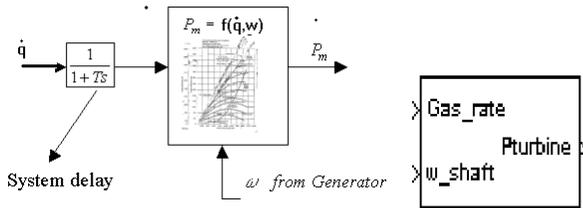


Fig.3 Gas turbine model diagram and Simulink block

2) Gas turbine controller

The gas turbine controller is modeled as a PID controller. It tries to maintain the turbine speed constant by monitoring the output shaft speed and adjusting the fuel rate.

3) Synchronous generator and rectifier model

The synchronous generator and rectifier are modeled as one

integrated module. Their diagram and Simulink block are shown in Figure-4. Each phase of the synchronous generator consists of a voltage source in series with RL impedance elements, which represent the internal impedance of the machine. The resistance R may be zero, but the inductance value L must be positive. The inputs to this module are field current I_f , mechanical power P_m , and DC current I_{dc} . The module outputs are DC bus voltage V_{dc} and shaft rotational speed ω .

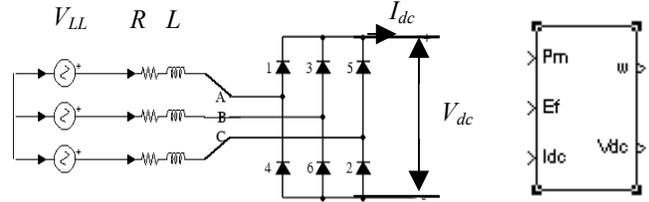


Fig.4 Synchronous generator and rectifier model

Ignoring the internal resistance R , the DC bus voltage is [7],

$$V_{dc} = \frac{3\sqrt{2}}{\pi} V_{LL} - \frac{3}{\pi} \omega L_s I_{dc}. \quad (1)$$

The RMS value of the internal voltage source V_{LL} is a function of field current I_f and rotational shaft speed ω . For a fixed I_f , V_{LL} is proportional to mechanical speed ω .

Let P denote the number of poles, f_n denotes the nominal electrical frequency, ω_n denotes the nominal shaft speed corresponding to f_n , and V_0 denotes the value of V_{LL} when the field current is at I_f and rotational speed is ω_0 . Note that the value of V_0 can be determined experimentally.

Now the voltage V_{LL} at speed ω and field current I_f can be expressed as,

$$V_{LL}(\omega, I_f) = \frac{V_0(\omega_n, I_f) \omega \frac{P}{2}}{2\pi f_0}. \quad (2)$$

The dynamics of the rotor can be calculated based on power flow balance. Figure-5 is a modified figure from [8] that illustrates the power flow diagram of a synchronous generator.

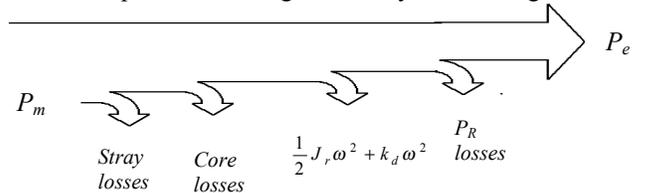


Fig. 5 The power flow diagram of a synchronous generator

By ignoring the power loss in the diode bridge, as well as core and stray losses in the generator, the power balance can be written as,

$$P_m = P_e + \frac{1}{2} J_r \omega^2 + k_d \omega^2 + P_R, \quad (3)$$

where P_m is the mechanical power from the prime mover

(turbine), P_e is the DC bus electrical power, $P_e = V_{dc} I_{dc}$, J_r is the inertia of the rotor, and k_d is mechanical friction factor. The copper losses in the stator, P_R , can be calculated using the stator phase current I_{ph} . The RMS value of I_{ph} is roughly $0.816 I_{dc}$ [7]. Thus we can then estimate the losses by,

$$P_R = 3 \times (0.816 I_{dc})^2 R. \quad (4)$$

From (3), the rotor dynamics can be described as,

$$\omega = \sqrt{\frac{\int 2(P_m - P_e - P_R - k_d \omega)}{J_r}}. \quad (5)$$

Figure-6 is the Simulink diagram of this model.

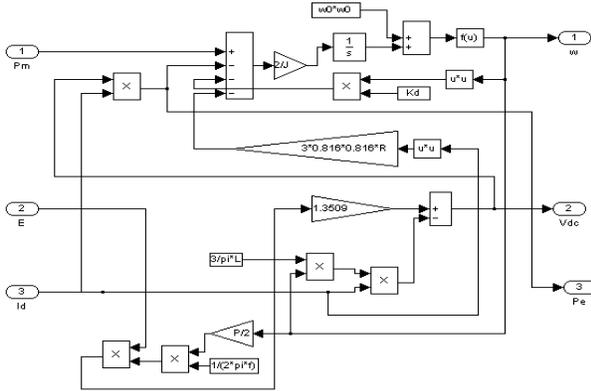


Fig. 6 Simulink diagram of generator and rectifier model

The exciter circuit for the generator is also commonly modeled based on experimentally observed behavior plus a first order delay. The open circuit terminal voltage of the generator at speed ω_0 , which is a function of field current I_f , can be measured as $V_e(\omega_n, I_f)$. Considering the delay between I_f and V_e , the terminal voltage can be written as $V_0 = \frac{V_e}{1 + T_e s}$, where T_e is the delay time. A Simulink diagram for the simplified exciter model is shown in Figure-7.

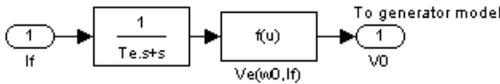


Fig. 7 Simulink diagram of exciter

Linking these three models together, we get the Turbo-Generator model.

B. HEP (Head-end power) model

The input to this model is the power to be consumed by the accessories like lights and fans. The output is the DC current injected. The power consumed by accessories like lights and fans can be treated as a constant and thus the output of HEP

$$\text{model can be calculated as } I_{dc_HEP} = \frac{P_{cons \text{ constant}}}{V_{dc}}.$$

C. Brake model

The dynamic brake resistor will dissipate any surplus energy during braking. In other words, it must make sure the DC bus current is always positive (which means power can't flow back into the generator). Thus a simple way to model the resistor grid is to use a saturation block with a lower limit of zero amps. The input of this model is the sum of DC current consumed by flywheel, traction motor and HEP. The output of this model is DC bus current or generator current I_{dc} .

D. Adjustable speed drive (ASD) model

There are five adjustable speed drives in this locomotive, one for the flywheel and four for traction purposes. Simulation of the adjustable speed drives for this locomotive can be very time consuming, even if an averaged model of the inverter is used. The simulation difficulties arise because: 1) the large inertia of the flywheel makes the transient response quite long, 2) the rated frequency of the AC motor (200Hz) is higher than ordinary AC motor (50/60Hz), and 3) the project requirements seek long simulation time-periods (order of hours). To overcome these obstacles, a 'behavior' model of the ASD based on its designed performance has been developed. In this model, the controller, inverter, and AC motor are combined together and modeled as an integrated unit, based on the assumption that a field orientation control strategy will allow a desired torque level to be accurately and nearly instantaneously achieved.

The ASD system can be described as shown in Figure-8. The input is required power (traction power or power to charge or discharge the flywheel) and the output is the corresponding output power or DC bus current injected or absorbed I_{dc_ASD} .

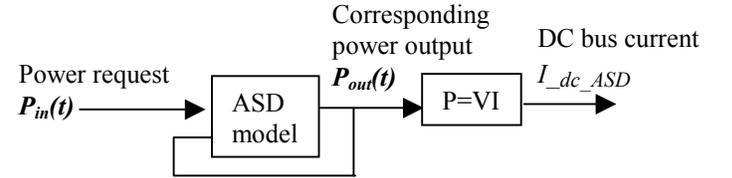


Fig. 8 ASD drive diagram

To simulate this system efficiently, a behavior model is formulated. The behavior of the ASD can be described using the torque-speed and/or power speed curve shown in Figure-9. In Figure-9, the vertical axis is the output power or torque of the drive and the horizontal axis is the speed of the drive. The dashed line is the torque-speed curve of the drive while the solid line is the power speed curve. The ASD system is controlled as follows: when the speed of the drive is under its nominal or rated speed, the drive operates within the constant torque region (1st operation region). When the speed exceeds the nominal value, the drive operates within the constant power region (2nd operation region). In the 2nd region, the torque is inversely proportional to the speed. This type of control strategy can be realized by field orientation control with field weakening.

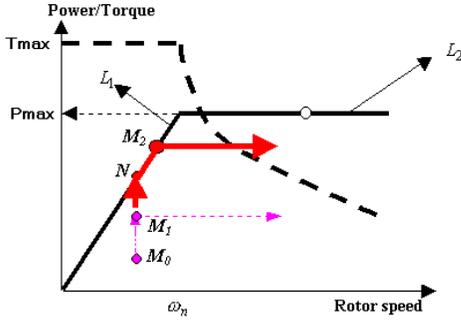


Fig. 9 ASD drive behavior

The state of the ASD can be described by two variables: speed $\omega(t)$ and output power $P_{out}(t)$. These two variables form an operating point in the power-speed plan as shown in Figure-9. The solid lines labeled L1 and L2 in Figure-9 are bounds on the ASD operating region. Assume that at time t_0 the ASD is working at point $M_0(\omega_0, P_0)$, and an input requires it to be charged with power $P_1 \leq P_{max}$. The performance of the ASD can be described as follows:

- 1) The ASD can jump to $M_1(\omega_0, P_1)$ almost instantly if $P_1 < T_{max} \omega$, and then the operating condition moves horizontally unless the input is changed. The thin dash line with an arrow shows the state trajectory. Under this condition, the output power of the FESS equals to the input power, i.e. $P_{out}(t) = P_{in}(t)$
- 2) If $P_1 > T_{max} \omega_0$, then the ASD operating condition jumps to the point $N(\omega_0, T_{max} \omega_0)$, which is on the maximum torque line L_1 (note the slope of L_1 is T_{max} .) and then climbs to point $M_2(\omega_1, P_1)$. The operating point continues to move horizontally unless the input is changed. The thick line with arrow shows the state trajectory. Under this condition, we have,

$$P_{out}(t) = P_0 + T_{max}(t - t_0) \text{ Before } P_{out} = P_{in}$$
Then $P_{out} = P_{in}$

- 3) The speed can be calculated from $P = J\omega \frac{d\omega}{dt}$

When the two variables P_{out} and ω are solved, the state of the flywheel is known. The DC bus injected or absorbed can easily

be calculated as: $I_{dc_ASD} = \frac{P_{out}}{V_{dc}}$.

Simulation speed for this behavior model of the ASD is extremely fast, making it very useful in the design stage since little to no detailed information about the drive is required.

E. Locomotive dynamic model

In this model, the locomotive is considered as a point mass and the interaction between rail and wheel is considered represented by an adhesion curve (e.g., Senini, et al [9]). The longitudinal dynamics of the locomotive can be described as,

$$M \frac{dv}{dt} = F_{tr} - R - Mg \sin \theta, \quad (6)$$

where v is locomotive speed, M is the mass of the locomotive and R is the total locomotive resistive force including aerodynamic loads, friction forces, and resistance due to curvature. The influence of grade is represented by $Mg \sin \theta$, where θ is the grade angle. The traction force, F_{tr} , is a function of slip speed of the wheel and locomotive velocity, and can be written as,

$$F_{tr} = \mu(\omega_r r - v)N, \quad (7)$$

where μ is the adhesion coefficient. A μ -slip curve is stored as a look up table, with μ a function of slip speed, $\omega_r r - v$. The rotational speed of the wheel, ω , is determined from the wheel dynamics,

$$J \frac{d\omega}{dt} = T_m - T_L - F_{tr} r \quad (8)$$

where T_m is the motor drive torque, J is the equivalent inertia of the wheel of the locomotive, r is wheel radius and T_L accounts for any other resistive loads on the wheel. The normal force, N , at the point of contact of the rail and wheel can be approximated by, $N = Mg \sin \theta$, if any dynamics in vertical direction of the locomotive are ignored.

This basic model can account for the influence of slip/spin in the traction force, which meets the need in power management study since slip/spin will heavily influence the instantaneous power flow in this propulsion system. The model in Simulink form is shown in Figure-10.

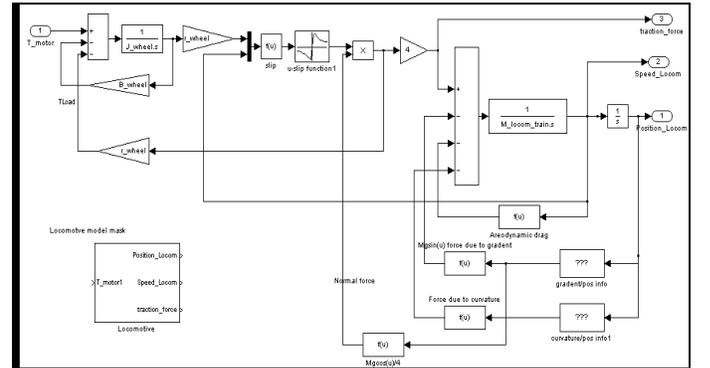
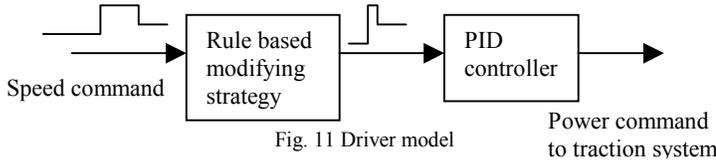


Fig. 10 Locomotive dynamics

F. Driver model and driving strategy

In the test phase, it is proposed to have a driver use two joysticks to control the locomotive. One stick will set the target speed and the other will set the maximum torque to accelerate the locomotive, using the route speed limits as guide. The driver, however, needs to brake the locomotive in advance of speed reductions to avoid overspeed. A PID controller and a rule based driving strategy are used to simulate the behavior of the driver. The idea is to modify the original speed limit profile so that the locomotive is under speed limit. Figure-11 shows the diagram of the driver's model.



G. POWER MANAGEMENT AND DRIVING STRATEGY

The success of a hybrid locomotive relies heavily on its power management scheme. Extensive study of power management of hybrid vehicle has been reported in the literature [10].

There exist several power management strategies that can be employed for simulation purposes. One example is a simple rule-based management strategy. The gas turbine provides the average power and the flywheel provides the peak power and stores the dynamic energy. Another effective energy management strategy reported in [11] involves maintaining a near constant DC bus voltage. The DC bus represents the primary power flow path of the system and the DC bus voltage reflects the power balance of the system. When the traction power is increasing the DC bus voltage tends to decrease, while when the locomotive is braking the DC bus voltage tends to increase.

From equation (1) and (2), it can be found that the DC bus voltage can be regulated by adjusting generator speed, field current I_f or DC bus current I_{dc} . Adjusting speed is not a good option because gas turbines should generally run at a constant speed to maintain maximum efficiency. Thus adjusting field current is the primary method for controlling the DC bus voltage, and adjusting I_{dc} can provide additional benefits. The DC bus current provides current to the flywheel, the traction motors, and the resistor grid. In decomposed form, this can be written as,

$$I_{dc} = I_{dc_traction} + I_{dc_flywheel} + I_{dc_brake} + I_{dc_HEP} \quad (9)$$

In (9), $I_{dc_traction}$ and $I_{dc_flywheel}$ can be both positive and negative while I_{dc_brake}, I_{dc_HEP} , can only be positive.

The traction current is set by the traction power or speed command. The HEP current is roughly a constant if DC bus is nearly constant. So only flywheel and resistor grid current can be used to regulate DC bus voltage. This is done in such a way that the resistor grid current should be minimized to save the energy.

The following management scheme has been used in simulation studies: the DC bus voltage is monitored and compared to a reference value to control the flywheel and the field current of the generator. The speed of the turbine/generator is monitored and controlled by adjusting the fuel rate of the gas turbine.

IV. SIMULATION RESULTS

A. Validation of reduced order models

1) Validation of generator/rectifier model

The simplified generator/rectifier is verified by comparing the simulation results with a more detailed model provided

in the Power System Blockset (PSB) from Mathworks®. In these comparisons, both models are used to drive the same resistive load with the same initial condition (from zero speed). Figure-12 shows the results.

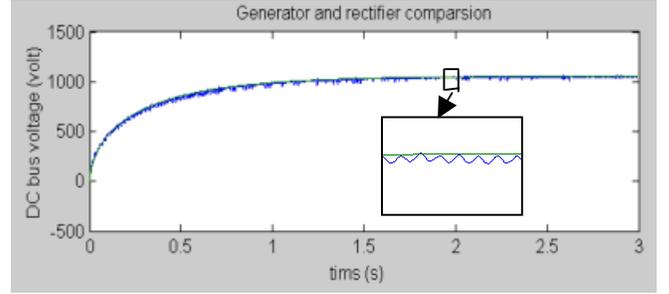


Fig. 12 Validation of Generator/rectifier model.

From Figure-12, it is found that the results from the two models are very similar. The DC bus voltage found using the simplified model is smooth with no ripple. The value is an upper bound on the result given by the PSB.

2) Validation of ASD/flywheel model

A field orientation controlled AC drive using an average inverter model is used as a high fidelity model to compare with the behavior model described earlier. In this test case, a motor is started from zero initial speed. A power command of $P=200\text{KW}$ is set at time=0 and then decreased to $P=20\text{KW}$ at time=3s.

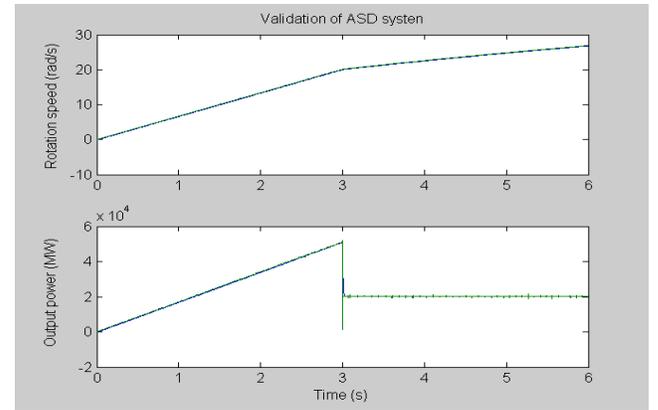


Fig. 13 Validation of ASD model

Figure-13 shows the results. The output power first approaches 200 kW along the maximum torque line and, when time =3s, it steps to 20 kW, immediately, and remains constant thereafter. The results of the two models are very close but the simulation speed of the behavior model is much faster than the average model.

B. Simulations to aid design

One purpose of this modeling and simulation study is to help make design decisions. For example, there is a need to begin determining the ratings for the gas turbine, flywheel system, DC bus power, etc. For this purpose, only the locomotive dynamics and a simple driver model need be simulated. The Simulink model is shown in Figure-14.

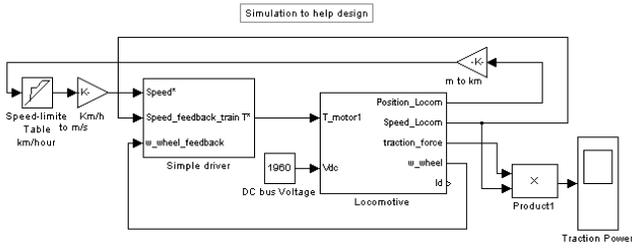


Fig. 14 Simulink Block to simulate traction power

Figure-15 shows simulation results for the traction power of the locomotive over a given route.

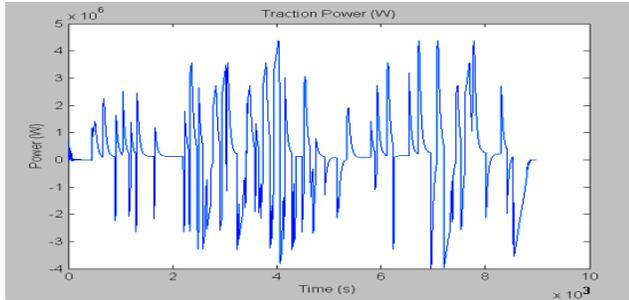


Fig. 15 Traction power simulation results

The traction power is equal to the sum of the power of the gas turbine and the power of the flywheel. The peak power in Figure-15 is about 4.35MW. If the power of the accessory equipment (about 1MW) is added to it, the peak power needs for the locomotive will be 5.35MW. If a 3MW gas turbine is used, then the maximum power of the flywheel system will be about 2.35MW. Braking is inferred when the value of traction power is negative. The negative peak point is about -4MW. The flywheel and resistor grid will absorb this power during braking. Thus the power of the resistor grid will be about 1.65MW. The time over which the locomotive stays in the peak power region can be used to set the maximum energy stored in the flywheel system. For example, the width of a “pulse” in Figure-15 is about 130 second, so the flywheel should at least be able to discharge for about 130 seconds. If the discharge power is 2MW, then the energy the flywheel can supply should be $E_{total} = Pt = 2MW \times 130s = 260 MJ$. The minimum flywheel speed to store this amount of energy is $\omega_{min} = \sqrt{\frac{2E_{total}}{J_{fw}}}$, where J_{fw} is the rotational inertia of the flywheel.

C. Full route simulations

Figure-16 shows part of the full route simulation results. The system component models discussed above are used.

These results show that the turbine power can be maintained essentially constant around 1 MW over this part of the route, while the flywheel power carries most of the load fluctuations. The DC-bus voltage is also held near constant over this run. The speed curve shows the actual speed and the original speed limit curve.

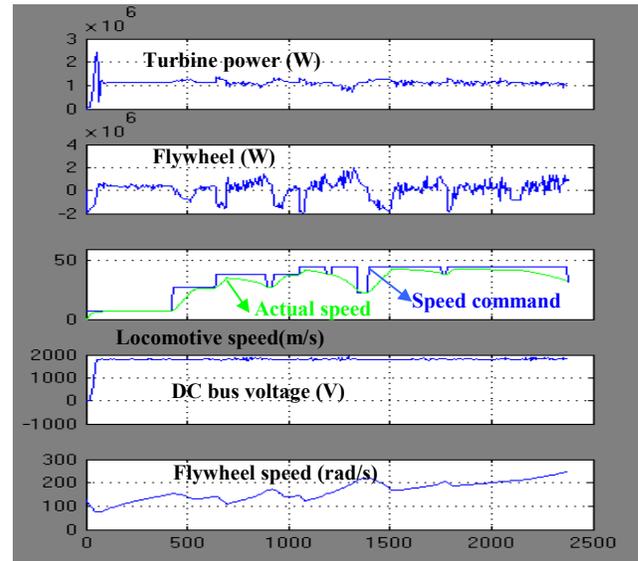


Fig. 16 Full route simulation results

V. CONCLUSION

This paper describes the modeling and simulation of a conceptual locomotive power system with a power management scheme that employs a flywheel system. Simplified models for the components are used in order to assure efficient simulation. Preliminary results indicate the models will be useful to help design such a system from the power management perspective.

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