Using a Superconducting Magnetic Energy Storage Coil to Improve Efficiency of a Gas Turbine Powered High Speed Rail Locomotive

Brian K. Johnson and Joseph D. Law

Abstract— **The US Federal Railroad Administration has been pursuing the use of locomotives with an on-board prime mover for high speed rail. Such systems would not require the added cost of rail electrification on top of the rail bed modifications. The prime mover runs a synchronous generator, with the output rectified to feed a dc bus. Adjustable speed drives control the traction motors. However, gas turbines run efficiently over a narrow speed range and a relatively narrow power range. The additional of a superconducting magnetic energy storage coil can improve overall system performance. The SMES coil is charged whenever the locomotive is in regenerative braking mode and whenever the prime mover is producing more power than is needed to maintain the desired speed down the track. The chief benefits to such a scheme are: 1) better acceleration at high speeds, 2) reduced prime mover power rating and weight, 3) reduced rail bed cost due to reduced weight 4) reduced trip time and 5) improved fuel efficiency.**

Index Terms—**Superconducting Magnetic Energy Storage, High Speed Rail, Rail Transportation**

I. Introduction

The US Federal Railroad Administration has been pursuing the use of locomotives with an on-board prime mover for high speed rail. Such systems would not require the added cost of rail electrification or catenaries on top of the rail bed modifications. Gas turbines are preferred over diesel engines as prime movers for high speed rail in order to stay within weight restrictions. The prime mover runs a synchronous generator, with the output rectified to feed a dc bus. Adjustable speed drives control the traction motors supplied by the dc bus. Gas turbines only run efficiently over a narrow speed power ranges. This places severe restrictions on the use of gas turbines for high speed rail.

The additional of a superconducting magnetic energy storage (SMES) coil can improve overall system performance by allowing the turbine to operate within its ranges for peak efficiency. The SMES coil is charged when the locomotive is in regenerative braking mode or when the prime mover is producing more power than is needed to maintain the desired speed down the track. The SMES coil can also be charged while the train is in the station. The stored energy is then used for acceleration.

The addition of energy storage to a high speed rail locomotive has the following potential benefits: 1) better acceleration at high speeds, 2) reduced prime mover power rating and therefore reduced weight, 3) reduced rail bed cost due to reduced weight, 4) decreased trip time and 5) improved fuel efficiency.

This paper presents the results of study of the impact of energy storage on the rating and performance of high speed rail locomotives.

II. Background

A. High Speed Rail

Rail has long been a transportation option for both passengers and freight. Early locomotives were based on a steam boiler fired by either wood or coal. The steam pressure was used to turn the drive wheels. These were eventually replaced with the diesel-electric locomotives commonly used in North America today. The diesel-electric locomotive consists of a diesel engine that is the prime mover for a synchronous generator. Modern locomotives have a 3-5000 HP synchronous generator, with the output rectified by a diode rectifier. The resulting dc bus then supplies dc traction motors. A locomotive is a small (roughly 4~MW) power system on wheels.

Most of the rail traffic in North America consists of freight trains, which tend to be long, heavy and slow. There is some passenger travel in the form of light rail and commuter rail systems around urban areas and some government controlled long distance travel along lines owned by the freight railroads.

Nearly all of these passenger systems are constrained by the civil speed limits for US rail lines of 78 miles per hour. The chief exception to this rule is the Northeast Corridor, where 120 mile per hour travel is allowed on limited access sections of track.

High speed rail transportation is getting increased attention as a possible alternative to air travel for business travel between cities that are between 150 and 400 miles apart. The chief objective is to provide transportation between cities that are far enough apart to discourage automobile travel and too close together for air travel to be efficient, generally in the

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range of 150 to 400 miles. Rail service would avoid the congestion and delays often present at major airports. Reducing the traffic at the airports will also relieve some of the airport congestion.

Fast, efficient high speed rail systems already exist in Europe and Japan. Examples would be the TGV in France and the TransRapid in Germany where trains often exceed 150 miles per hour. The European rail infrastructure is designed around all-electric locomotives, where the electric power to run the traction motors is provided through a pantograph and catenary supplied from an electric power distribution grid. However, the catenary and utility interface infrastructure required for all-electric locomotives is not economically feasible in the US as studies in Florida, Texas, California, the upper Midwest, and the Pacific Northwest have all shown. However, high speed rail projects using all-electric locomotives are still being explored in the US [1].

Magnetic levitated (MAGLEV) trains are also under consideration at several sites worldwide, include sites in North America. However, MAGLEV systems also require an extensive capital investment in infrastructure, including electric power distribution along the corridor to power the train set. SMES coils have been studied to reduce the impact of the load variations as due to passing trains on the surrounding electric power grid [2].

The high capital costs of all-electric high speed rail systems has spurred development of high speed locomotives with on-board prime movers driving synchronous generators. These locomotives are typically referred to as non-electric locomotives although they use a small on-board autonomous electric power system.

B. Locomotive Propulsion Options

The typical North American locomotive is a small electric power system on wheels. A diesel engine powers a synchronous generator. The output of the generator is immediately rectified by a diode rectifier. This dc bus supplies dc traction motors. These motors have series excitation for high torque production at low speeds, ideal for freight operation. Each of these motors is capable of regenerating when the train is braking, with the energy dissipated by a braking resistor bank.

The traditional diesel electric design has several drawbacks for high speed rail applications. Foremost among these is the size and weight of the diesel engine, which effectively limits the top speeds attainable for a diesel locomotive. Gas turbines are considered to be the best option for a lightweight prime mover for high speed rail. Gas turbines have been considered for both mechanical drive systems and for electric drive systems.

The use of dc traction motors is also a limiting factor when designing high speed rail locomotives. The tractive effort applied to the rails is limited by the wheel slip on the axle with the poorest adhesion between its wheels and the rails. Once that axle starts to slip, all of the drive axles must be throttled back. Typically, this is the front axle on the lead locomotive, since it will be seeing the wettest, dirtiest rails and is thus most likely to slip.

Significant improvements in locomotive performance can results from utilizing induction motors driven by inverters. A system with a single inverter per traction motor allows for individual adhesion control for each axle, significantly improving the efficiency in transferring power to the rail. In addition, the largest dc motor that will fit on a locomotive is roughly 1000HP. However, a higher horse power induction motor will fit in the same space since it does not require space for the commutator. The majority of new freight locomotives sold in North America now us ac motors.

C. Energy Storage

Ideally, the energy storage system added to the locomotive should be lightweight and have high transfer efficiency. The energy storage system is charged whenever the locomotive is in regenerative braking mode, rather than dissipating the energy in a braking resistor, as is currently done in non-electric locomotives. Energy is also stored whenever the prime mover is producing more power than is needed to maintain the desired speed down the track. In addition, energy can be stored while the train is in the station. The stored energy is then used for acceleration, either starting from rest or increasing speed while under way. The stored energy can also be used to provide added power for climbing grades.

The use of flywheel energy storage in high speed locomotives was considered in [3]. One drawback with the use of flywheel energy storage is the weight of the containment for counter-rotating flywheels. The containment vessel is used to contain fragments if the rotor of the flywheel fails. The size and weight of the flywheel and containment needed for a high speed rail locomotive may require the addition of a separate tender to carry the flywheels.

A SMES coil provides a lighter option for on board energy storage. The SMES coil is able to store significant amounts of energy and transfer energy into and out of the coil with high round trip efficiency. In addition, rapid charging and discharging is possible, provided the power converter has sufficient current and voltage capabilities. The SMES coil is interfaced to the common dc bus of the locomotive though a dc/dc converter as shown in Fig. 1. The dc/dc converter rating will be based on the peak energy transfer rate desired for either acceleration or regenerative braking.

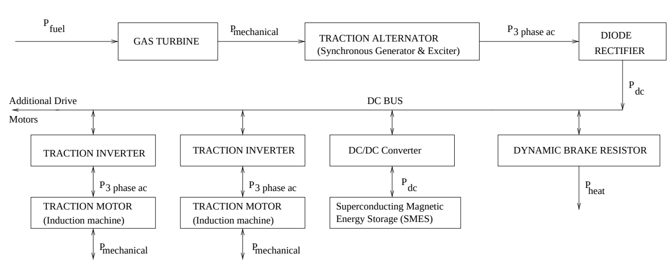

Fig. 1. Block diagram of the power train for a high speed rail locomotive with energy storage.

III. System Model

A computer simulation was developed to study the impact of the energy storage on the power output of the prime mover during normal operation of a train set. Therefore models are needed to represent the locomotive and the route itself.

A. High Speed Rail Corridors

Ideally the high speed rail train sets will operate on a dedicated route, where they won't have to be scheduled around freight trains. However, this does not mean that the train simply accelerates to 120 MPH and stays at that speed until the next stop. A typical route, such as the Northeast Corridor or the Empire Corridor in New York will have a wide range of speed limits as shown in Fig. 2. Each track section has speed limits determined by curvature, grade crossings, slope, condition of track, and other. Therefore, the train will vary its speed as it covers the route.

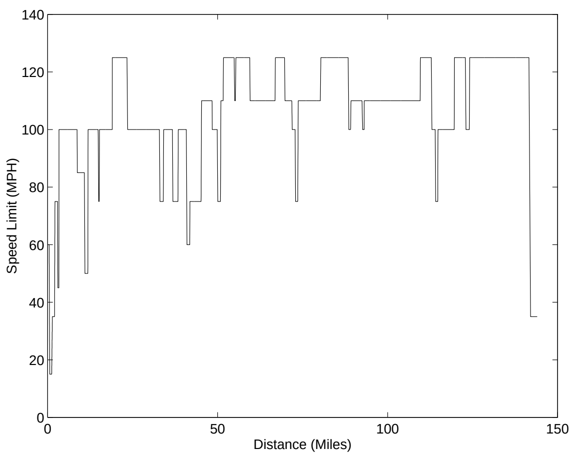

Fig. 2. Example route speed limit profile.

B. High Speed Train Set

The high speed locomotive studied consists of a gas turbine prime mover powering a synchronous alternator. The output of the alternator is rectified to create a dc bus, as shown in Fig. 1. The dc bus will be connected to four traction inverters which drive induction motors. These motor drives are capable of regenerative braking operation, where energy is transferred back to the dc bus. The bi-directional dc/dc converter for the SMES coil is also connected to the dc bus. A braking resistor is still needed on the dc bus for cases where the braking energy transfer rate exceeds the capacity of the dc/dc converter.

The train being studied will have two locomotives, each rated at about 4000 HP, and 6 passenger cars (50 tons each). Each locomotive weighs 100 tons, The top speed is 150 miles per hour. Each locomotive has a SMES coil on it, capable of transferring 2MW peak, and storing 1gigaJoule. Note that this may be accomplished with several smaller SMES coils.

C. Simulation Model

A simulation was developed using Matlab to model the locomotive propulsion system as it travels the length of the route. The objective of this simulation is to develop a basis for performing the design and control optimizations for sizing the prime mover, the energy storage system, and computing energy and fuel needs.

The models for the power converters and the rotating machines represent input/output energy flow. The system energy flow is driven by the power requirements of the traction inverters, which drive the motors to run the locomotive at the desired speed.

The simulation consists of several layers, as shown in Fig. 3. The inner layer of the simulation is the propulsion model for the locomotive. The propulsion model uses the commanded motor torque and train speed to compute the energy efficiency of the locomotive. This module has energy efficiency models for the alternator, rectifier, inverters, traction motors and other components. Many of these loss components have already been quantified in other areas, especially for diesel locomotives [4].

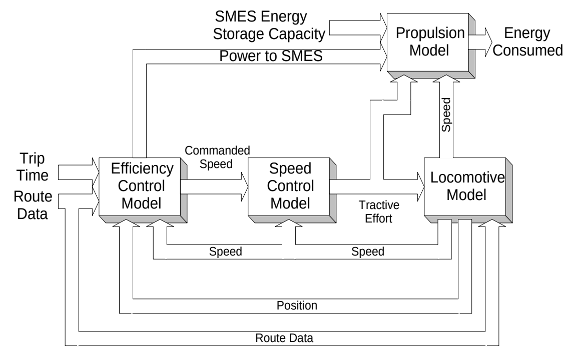

Fig. 3. Program flow diagram for system simulation.

The locomotive model uses the commanded tractive effort (real power) from the speed control module and combines it with route data to determine where the train is on the route and to output that position and speed and acceleration to the other modules. The speed control model determines the tractive effort command needed to get the train to run at the requested speed over the next segment of track. It uses information from the efficiency control model and the locomotive control model to determine this setting.

The efficiency control model is the key to the simulation. It determines a speed command for the next segment of track, based on the current position of the train and with knowledge of what's ahead on the track. This is also the module that will control the energy stored in the SMES and will make decisions based on the available stored energy.

IV. SIMULATION RESULTS

The high speed rail set was simulated as it covered a segment of track where the speed limit changed several times over the distance. Fig. 4 shows the variation in train velocity versus the time in minutes. The speed is initially zero, the increases to about 120 miles per hour following the speed command. The next section of track has a lower speed limit, requiring a change in speed command. Following this, the train enters another section of track with a higher speed limit. Fig. 4 allows a comparison between the commanded speed and the actual velocity. Note that the speed must always be under the speed limit. Fig. 4 also shows the overall distance covered versus time. Notice that the slope of this curve is steeper when the speed limit is higher, and is zero when the speed is zero.

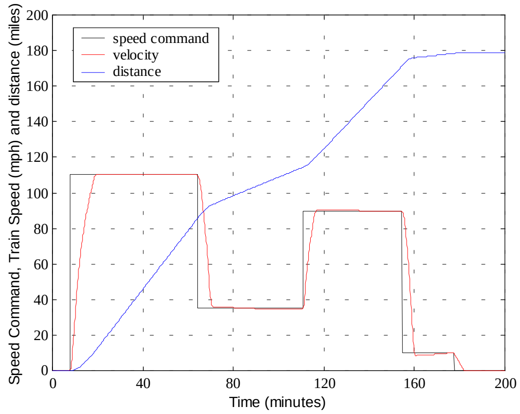

Fig. 4. Commanded speed, velocity and distance versus time.

Next Fig. 5 shows both the torque applied to the drive motors and the commanded speed versus time. Notice that the applied torque spikes when the locomotive is accelerating, and has a negative spike when the locomotive enters regenerative braking. The applied torque stays relatively constant at a lower level once the train is up to speed. There will normally be some torque variations due to grade inclines. Note that a large torque is needed to accelerate to a higher speed limit, whether the train is moving or already at speed. The figure shows total torque, for both locomotives.

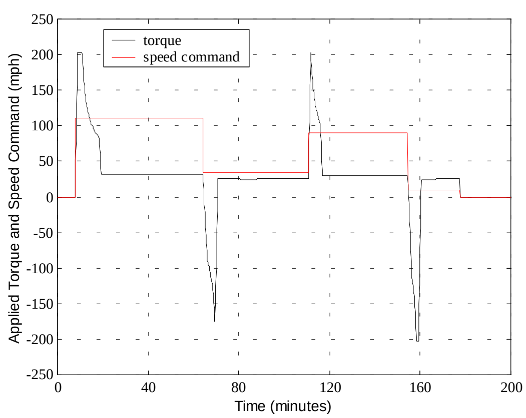

Fig. 5. Applied torque and commanded speed versus time.

The negative energy from braking torque would normally be dissipated in the braking resistor. But in this case, that energy can be stored in the SMES coil, and then later used for acceleration. Fig. 6 shows the effect SMES coil on the energy required from the prime mover. The simulation starts out with the train stationary, as shown by the distance down the track staying at zero miles. The gas turbine is used to charge the SMES before leaving the station. This is shown with positive power from the turbine and negative power out of the SMES. When, the train starts to accelerate down the track, the SMES is discharged to help supply the traction motors, reducing the power demanded from the turbine relative to that that demanded by the motors. Notice that almost all of the power delivered from the motor during braking is transferred to the SMES. The figure shows the total energy for both locomotives, with a SMES on each. The power transfer in excess of the dc/dc converter rating was dissipated in the braking resistor.

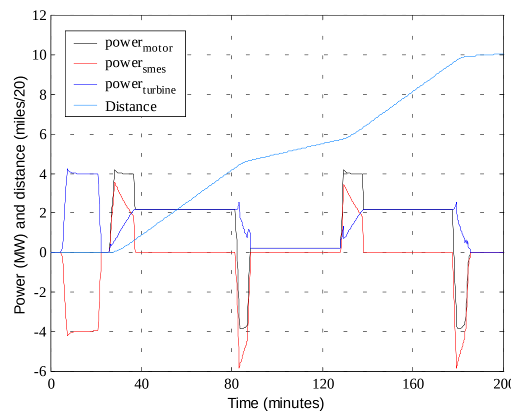

Fig. 6. Power flow from prime mover, SMES, traction motor and distance versus time

The addition of the SMES coil to the locomotive allows the prime mover to run at lower power output levels. If the initial charging of the SMES had been at a lower power level, a turbine with a lower overall Horsepower rating could have been used.

V. Conclusion

A system for improving the efficiency of high speed rail locomotives has been presented. An overview of high speed rail locomotives was presented. The addition of energy storage to the locomotive allows optimization in the design and operation of the locomotive, saving both capital and operating costs.

A system model to use in simulation of the high speed rail locomotive was presented, along with simulation results. The results of simulation can be used to design the locomotive itself. The required power rating for the prime mover can be determined, as well as both energy storage capacity SMES and the power rating for the dc/dc converters transferring energy into and out of the SMES.

Acknowledgment

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