Block Switches for LSM Driven Transportation System

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1. Introduction

The propulsion motor for the US Urban Maglev Demonstration System is a Linear Synchronous Motor (LSM) with long stator windings mounted on the track. During operation of the vehicle, the stator is energized but only the portion of the stator immediately coupled with the rotor on the vehicle contributes to the propulsion. The power in other portion of the windings is wasted in the form of I^2R heating. With the block switches, shorter blocks can be energized and as a consequence, the LSM efficiency will be improved. Ideally, the length of the winding energized is close to the length of the rotor and moves with rotor but there is a practical limit to the length and number of the guideway blocks that can be energized. The block length and number of blocks for a real system depend on the route layout and equipment size, etc. The block switch can be a liability to the system reliability unless the reliability of the block switch is fully assured (it is also a cost driver). A system level optimization is required.

Number and size of the block switches depend on the block length and switching scheme. Three block switching schemes are commonly known. They are:

- Sequential block switching
- Leaf frog block switching
- Series leaf frog block switching

Both leaf frog and series leaf frog switching schemes require two switches per energized block and the sequential switching requires one switch per energized block. The system architecture selected for the urban maglev demonstration system is the sequential block switching mainly because this architecture requires less switches than other schemes. Failure of a block switch in the system can lead to system failure. The LSM system is more reliable and less expensive with small numbers of block switches in the system but the thrust changes during the switching should not affect the ride quality. The goals of the present study are:

1. Determine the optimum size of the block switch for the urban maglev propulsion system
2. Find the right architecture for the sequential block switching
3. Reliability of the power hand off
4. Power efficiency improvement with Block switch
5. Verify the performances including zero current switching.

Figure 1-1 shows sequential block switching architecture and Figure 1-2 shows the thrust variation during the switch.

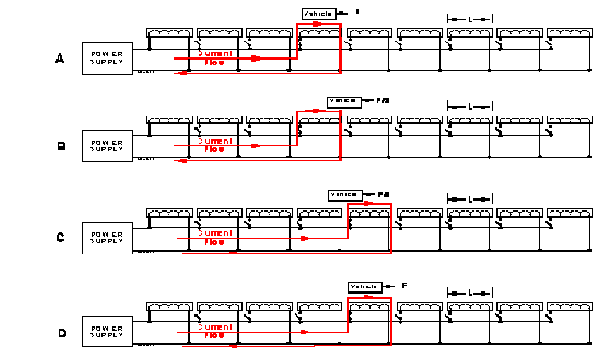

Figure 1-1 Sequential Block Switching Architecture

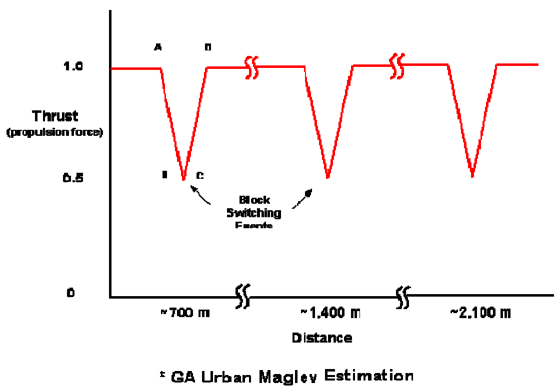

Figure 1-2 Thrust Variation during the Sequential Block Switching

2. Block Switch Hardware

The block switch is an AC power switch used to connect / disconnect the 3-phase power delivered by VVVF inverter that feeds the LSM motor blocks. One block switch feeds one motor block at a time and when the vehicle is at the interface of the motor blocks, the power is handed off to the next block switch. The block switch unit is comprised of three separate circuits, one per phase, each consisting of two thrystors, a resistor / capacitors net work and gate trigger control circuit. Figure 2-1 shows the GA block switch developed for the Electro-Magnetic Aircraft Launch System (EMALS). The capacity of the switch is established:

Max current: 10,000A
Max voltage: 5,000V

Figure 2-1 Block Switch Hardware

3. *Block Switch Test*

The block switch system operational testing on the test track was conducted in two steps:

- Step 1: Static tests without vehicle operation
- Step 2: Dynamic tests with vehicle operation

3.1 Static Test

The static tests were conducted to make sure that the cabling changes were properly done and that the required full current switching took place reliably. Also, the zero current switching and thermal characteristics of SCR were evaluated during this phase of testing. The static tests provided a more convenient atmosphere to observe the power hand off and SCR temperature monitoring.

3.1.1 Zero Current Switching

Initially, the LSM was powered with a small AC current such as 100amp and a frequency representing the vehicle speed. The LSM power was increased in steps up to 2000A. This series of tests verified that the LSM winding and block switches were safe for the full power applications.
Next, the AC current was switched from the south block to the north block by manually triggering the proximity sensor. The AC currents were measured at the outlet side of the block switches using two Rowgorski coils, one at each block switch. The SCR temperatures were monitored with a digital infrared thermometer.
The current wave forms from two switches were recorded on an oscilloscope. Figures 3-1 and 3-2 provide representative current wave forms that were recorded during the switching test. Figure 3-1 shows switching of 1000A from block #1 (south) to block #2 (north). Figure 3-2 shows the switching at 2000A. The wave form was maintained thru the switching and the switching took place when the current was near zero.

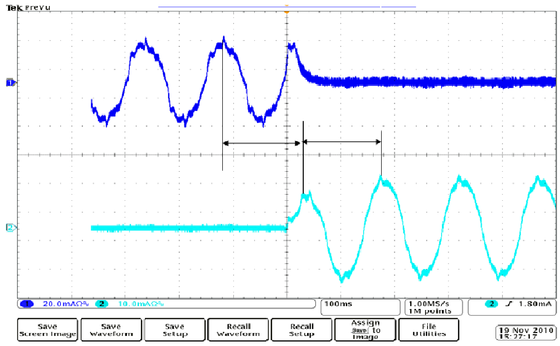

Figure 3-1 Switching of 1000A

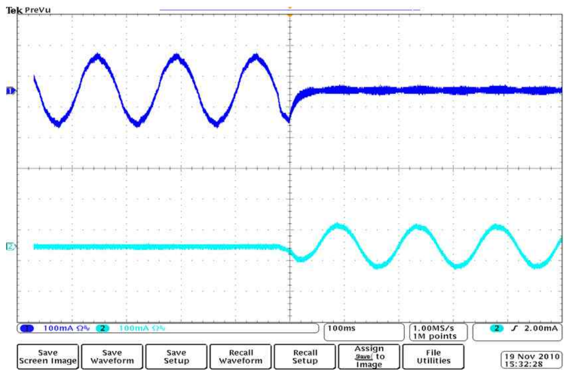

Figure 3-2 Switching of 2000A

3.1.2 SCR Temperature Characteristics

SCR temperature is an important parameter related to the reliability of the system. The block switch is physically reliable when the SCR temperature stays below 120C during the repeated switching. Infrared thermometer by CRAFTMAN was used to measure the temperature. A current of 2000A and 16.2Hz was applied to the LSM block#1 for 10 seconds and then switched to LSM block #2. The heating from 2000A current for 10 sec is considered equivalent to a heating for a normal test run. The simulated heating was repeated every 120 seconds to simulate a vehicle running with 2-min headway. The temperature monitoring resulted in the SCR temperature of BS#1 rising to 76.2C after 10 runs. The SCRs are considered safe and reliable as long as the SCR temperature stays below 120C.

3.2 Dynamic Testing

A series of tests were conducted on the system to evaluate the effects of switching on the dynamic behaviour of the vehicle. The dynamic behaviour includes the vehicle speed, acceleration, ride quality and power. The goal of this test was to verify that the dynamic response of the vehicle to switch between blocks had no negative effect on vehicle control or vehicle ride quality.

The 1st block is made of 4 track modules (60m) and the 2nd block is made of 3 modules (45m). The vehicle starts a test run from the energized block with a specified speed profile. When the center of the vehicle passes the proximity sensor on the track, power is handed off to the new block. No failure occurred during 200 test runs. In this scheme, only one half of the vehicle is powered at the time of switching. This causes the LSM thrust and vehicle speed to drop momentarily as the controller compensate for the loss of speed with an increase in current. The effect of the reduced thrust was assessed by evaluating:

- The ability of the vehicle to start from rest with only half the vehicle covered by powered LSM,
- The effect on the ride quality as the vehicle passes through the switch area.

The time through the switching area and the duration of the reduced thrust varies with vehicle speed. For a low speed run, the time through the switching area is longer and speed reduction and the command current changes are expected to be greater. For a higher speed run, the time through the switching area is shorter with speed reduction and current changes smaller. The following section discusses the testing performed to validate these issues.

3.2.1 Vehicle starts from rest with partial LSM coverage

Test runs were made to assess the vehicle starting from rest with less than 50% of motor powered. This situation arises when the vehicle stops between the two LSM blocks. Starting from 50%, the powered armature section was reduced until the vehicle was not able to move under LSM power. The smallest motor section generating enough thrust was found to be about 35%. In all cases of the test runs, the vehicle started with acceptable currents in the range of 2000 to 2500amps.

3.2.2 Effect of Switching on the Vehicle Speed and Current

Effect of switching on the vehicle speed and current is shown in Figures 3.3 and 3.4. These figures show speed decreasing during the switching due to the reduced thrust. The speed reduction, however, is relatively small since the LSM control quickly increases the current to make up for the reduced speed.

The effect of switching on the speed is higher when speed is low, and lower as the vehicle speed increases.

At 6m/s, the speed reduction is less than 2% and at 3m/s, the speed reduction is around 10%. However, the speed reduction was not noticeable to the passenger.

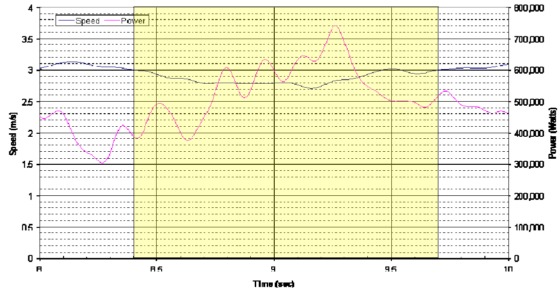

Figure 3.3 Effect of Switching on the Speed and Current (3m/s)

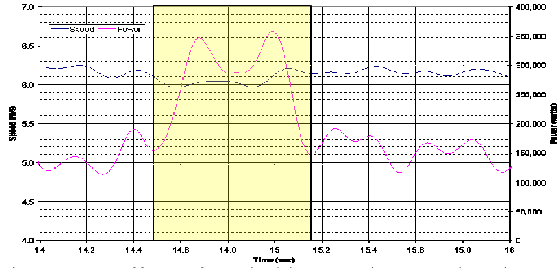

Figure3.4 Effect of Switching on the Speed and Current (6m/s)

3.2.3 Effect of Block Switching on LSM Control

Figure s 3.3 and 3.4 confirm that the control system is stable and well within its operational parameters to handle the disturbances created during the block switching. Some of the operational parameters or limits set by the control are the maximum current output and maximum current change rate. These values were set to protect the component of the inverter. Presently, the inverter operates with limit settings of a maximum current of 4000A and a maximum current change rate of 5,000A/s. No adverse effects of block switching on the LSM control were detected during this test program.

3.2.4. Effects of Switching on the Ride Quality

Ride quality is normally evaluated by measuring acceleration over a period of 10 to 15 sec during a constant speed (cruise). However, the block switching time for a 7m/s run is only 0.6 seconds. The disturbance contributed by the switching is of such a short duration that it was not detectable during normal ride quality evaluation. Figures 3.5 and 3.6 compare two ride quality plots, without and with block switching, respectively. Both ride quality plots, provide very similar results and the exposure limits for 2.5-hour reduced ride comfort. Any noticeable effects on ride quality were not detected.

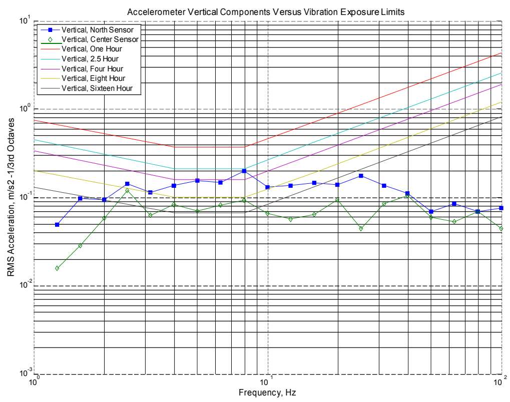

Figure 3.5 Ride Quality w/o Block Switches

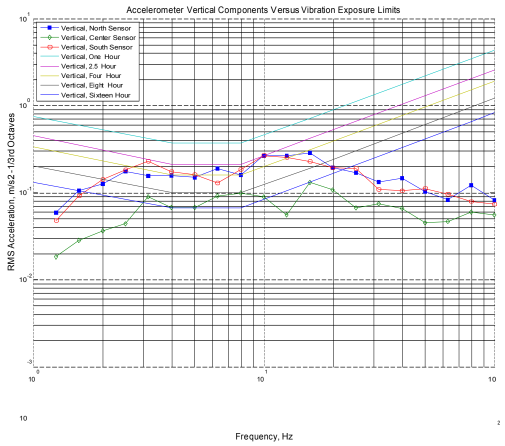

Figure 3.6 Ride Quality w/ Block Switches

3.2.5 Effect of Block Length on the LSM Power

The primary goal of the block switch in the Linear Synchronous Motor system is to improve the motor efficiency. Power in the uncovered sections provides no mechanical work and is dissipated as I^2R heating, which increases with the powered block length. Originally, our test track was powered as a single block of 7 guideway modules (105m). The re-configured track is made of two LSM blocks, one with 4 guideway modules (60m) and the other with 3 modules (45m).

It is expected that when the vehicle is on the 4-module block, the power consumption will be higher than when the vehicle is on the 3-module block. The test runs were made such that the switching took place during a cruise run. Figure 3.7 shows the power level variation during switching from the 4-module block to 3-module block. The power level decreased from about 64kW to 39kW which was close to what would be expected.

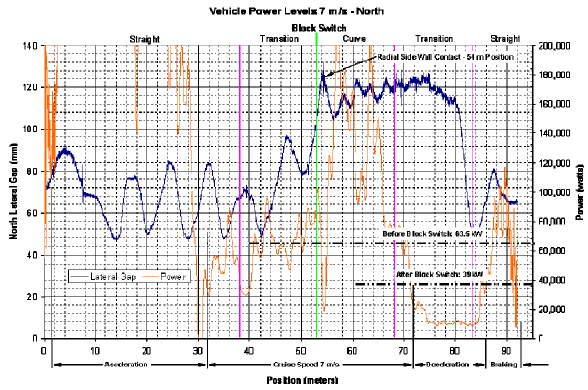

Figure 3.7 Power Level Variation between 4-Block Section and 3-Block Section

4.0 Conclusion

The block switch test confirmed that the selected block switch hardware and architecture is acceptable for a deployed urban system. The following conclusions may be made:

- The sequential block switching approach is successfully applied to the low speed urban maglev LSM system.
- The full power hand-off up to 2000A seems reliable and safe.
- The max SCR temperature was well below 120C of the maximum allowed.
- The disturbance during the switching does not cause a noticeable effect on the ride quality.
- The block switch has no ill effect on the LSM control.