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Electric Drivetrain Testing Using Smart Green Technology

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ABSTRACT

Electric Motor and Drivetrain (Electric Mobility) Testing is a critical part of bringing any electric drivetrain into production. In this paper the requirements for an electric drivetrain test cell are discussed. The implementations of such test cells are described and examples of test results are provided. In particular, the energy and power requirements for PM brushless DC dynamometers and a PM brushless Unit Under Test (UUT) connected through a common dc bus are described. Simulation of the set-up is developed using MATLAB/Simulink and verified using empirical data from the test bench. The data used represents various steady state load conditions during durability test cycles. This "Smart Green Technology" concept not only reduces the energy requirement from the grid but also eliminates the inefficiencies related to putting energy back on the grid.

INTRODUCTION

Electric vehicle technology can be traced back as early as the 19th century when a Frenchman Gustave Trouve built the first electric vehicle in 1881 [1]. Over the years the success of Internal Combustion Engines (ICEs) has delayed the development of electric vehicle technology. During the later part of the 20th century, increasing concerns about the environment and rising fuel costs have prompted many OEM's to switch gears towards more fuel efficient vehicles. Major technical developments have been made towards the development of energy storage systems, motors and motor controllers in recent years which have added to progress of electric vehicles and hybrid electric vehicles. One major area of development has been in the area of motors and motor controllers. The recent advancements in permanent magnet materials, solid state devices and microelectronics have considerably increased the efficiency of the electric motor drive system [2]. These components need to be tested to ensure robust and efficient performance before being used in a production vehicle.

Most of the HEV/EV drive systems in automotive traction applications use PM brushless or synchronous machines. These motors exhibit higher efficiency, power factor, power density and better dynamic performance than asynchronous motors [2]. Due to the complexity involved in operating these motors in HEV and EV applications, they must be validated by testing that involves various real-world drive cycles [3]. This testing is generally performed on test benches equipped with dynamometers that possess the capability of motoring and generation. The test benches should also be capable of re-creating road-load conditions and measuring the performance of the drive system.

One of the major challenges in an electric drivetrain test bench set-up is the efficient use of grid energy to minimize cost and hardware. The presented test set-up takes advantage of the same energy capturing techniques that help to make EV and HEV vehicles more efficient. The resistance force generates power which is fed directly back into the driving motor via a common DC bus. The power source only needs to provide the energy necessary to make up for the mechanical and electrical losses. This method of energy reuse is more efficient than feeding back to the grid as less conversion steps are required.

I. TEST CELL REQUIREMENTS

An electric/hybrid drivetrain test bench set-up depends on the type of configuration being tested. For an electric drivetrain, the test bench can be set-up for a complete front/rear wheel drive configuration. In this work a front wheel drive configuration was tested with two dynamometers connected to the outputs of a differential simulating the wheels of an electric vehicle. In a series hybrid test bench, a third dynamometer can be used to simulate an ICE. The simulated engine will be mechanically coupled to the electric generator either directly or through a transmission.

The dynamometers are controlled to run in either speed or torque mode depending upon the test requirements. In either case, they should be able to absorb when the UUT is motoring and drive when the UUT is generating.

An electric drivetrain test bench generally comprises of the following major components: (a) Dynamometer with motoring and regeneration capability (b) Battery emulator or power supply (c) UUT (d) Test cell control and data acquisition system.

II. TEST BENCH COMPONENTS

(a) Dynamometer: An electric drivetrain test bench requires the dynamometer to be able to drive as well as absorb power from the UUT. The dynamometer should be able to operate in all four quadrants of the speed-torque curve of the UUT. The motors typically used in these applications are either PM or induction motors. They can also be coupled with gearboxes to meet the overall speed and torque requirements for the UUT. For the proposed work, two 200kW PM brushless DC motors with gearboxes were used as dynamometers.

(b) Battery Emulator: A power supply is required to operate the electric dynamometers and UUT. It can be an AC supply for an induction motor or a DC supply for a PM brushless and synchronous motors. The battery emulator is a DC power supply which is connected to the grid. It has one or two stages of AC-to-DC conversion and can provide a constant voltage, current, or power. The battery emulator system used for this testing has a maximum capacity of 900V DC, +/-1000A DC and +/-250kW. The emulator was remotely operated as a constant voltage source.

(c) UUT: The UUT is comprised of an inverter with a permanent magnet synchronous motor and a single gear transmission coupled to the motor. The UUT data is proprietary.

(d) Test Cell Control and Data Acquisition System: FEV uses A&D Technology test cell control and data acquisition (DAQ) system known as iTest. It uses a real time controller for data acquisition from the instrumentation in the test cell and to control the dynamometers and the UUT. The data from the thermocouples, speed encoders, torque meters, pressure transducers and flow meters are collected and synchronized to a 100Hz signal bus and sent to the real - time controller from the test cell. The data is used by the controller to execute pre-defined test schedules. The iTest system also communicates with the battery emulator system through CAN.

A high frequency, wide band digital power meter (DPM) is used in the test bench to measure the three phases and DC electrical power to/from the high voltage inverters. iTest communicates with the DPM over Ethernet to import data, set parameters and calibrate the meter. In this proposed work, the DPM was used to measure the three phase power to the UUT motor and DC power to/from the UUT inverter.

A second real-time controller (RTC) is also used for vehicle road-load simulation. The road load algorithms have been developed using a model based approach and can be calibrated during run-time. The controller is also connected to the iTest DAQ system and communicates over a 100Hz communication bus. The controller uses a 4-channel CAN card that is connected to the dynamometers, UUT and coolant pumps.

The electric drivetrain can be controlled in manual mode, pre-selected schedule mode or vehicle simulation mode. For manual and pre-selected schedules, the second RTC receives the torque and speed set-points for the UUT and dynamometer from iTest and sends it out to the devices over a hi-speed CAN bus network. For vehicle simulation, the drivetrain can be commanded to run in pre-defined real-world drive cycles like UDDS, HWFET, etc. or fixed vehicle speed set-points. In the latter scenario, the second RTC receives the vehicle set-points from iTest.

In the proposed work, the dynamometers were controlled in speed mode while the UUT was controlled in torque mode. Speed set-points and rotation direction were simultaneously requested to both dynamometer inverters. The inverter controllers used a closed loop strategy to control the requested speed while maintaining the load from the UUT. The torque request for the test was sent directly to the UUT inverter.

III. TEST BENCH SETUP

There are several different ways to setup a test bench for an electric vehicle drivetrain. Traditionally, each dynamometer and UUT had separate, bi-directional, power supplies that allowed them to use energy from the grid while motoring, and return back to the grid during generation. The proposed design allows the dynamometers and the UUT to utilize the same power supply via a common DC bus. This increases efficiency in several ways. The conversion steps from the inverters to the grid are minimized, less hardware is necessary for those conversions, and the power supply only needs to provide energy to compensate for losses in the test cell setup. This also allows for the possibility of a uni-directional power supply given proper RC filtering on the DC bus.

Figure 1 represents a traditional system with separate DC power supplies for the dynamometer and UUT inverters. During operation power is being fed to or taken from the grid by each machine.

The set-up allows the operation of each inverter at different voltage levels.

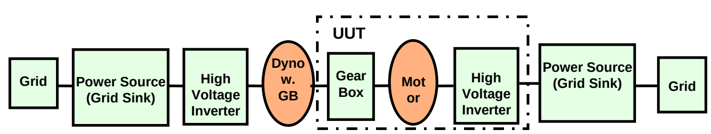

Figure 1: Separate DC Bus System

Figure 2 shows the implementation of a common DC bus. Here the high voltage DC inverters for the dynamometer and the UUT are connected together through the common DC bus. The common DC bus is connected to a single power source. The dynamometer and the UUT motor operate at the same voltage level. However, a DC-DC converter can be introduced before the inverters in order to operate the components at different voltage levels.

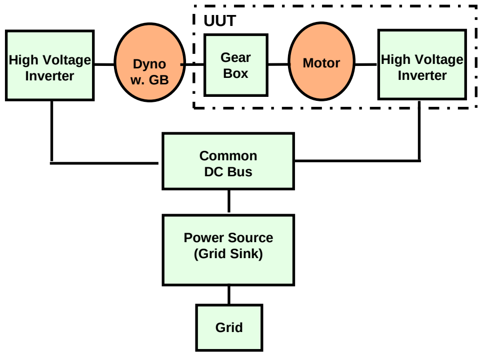

Figure 2: Common DC bus system

The concept is further analyzed for a front wheel electric drivetrain that requires two dynamometers. Figure 3 and figure 4 show the test bench set-up in traditional and the common DC bus systems respectively. The dynamometers used in the test bench are PM brushless DC motors.

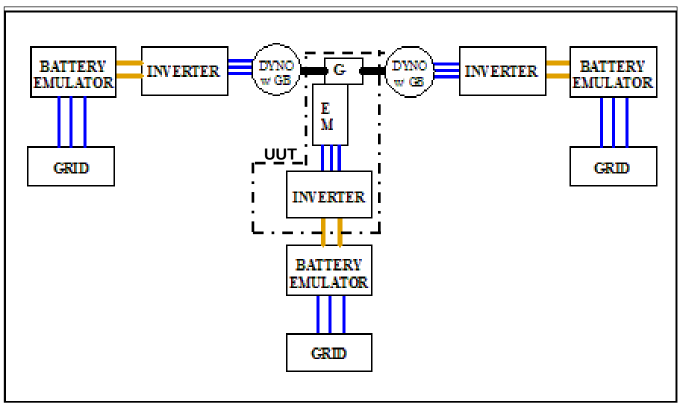

Figure 3: Separate DC Bus FR EPT Drive Test Bench

A. ***Traditional System***: Each battery emulator is connected to the grid on its input side and to the dynamometer inverter on its output. Each dynamometer is coupled to a single ratio gear box. The output of the gear box is connected to the UUT transmission on each side through half-shafts. A separate battery emulator supplies DC power to the UUT inverter during operation. The emulators are connected to the common grid (Figure 3).

B. ***Common DC bus system***: The dynamometers and the UUT DC input sources are connected to a single battery emulator. The battery emulator is connected to the grid on its input side (Figure 4).

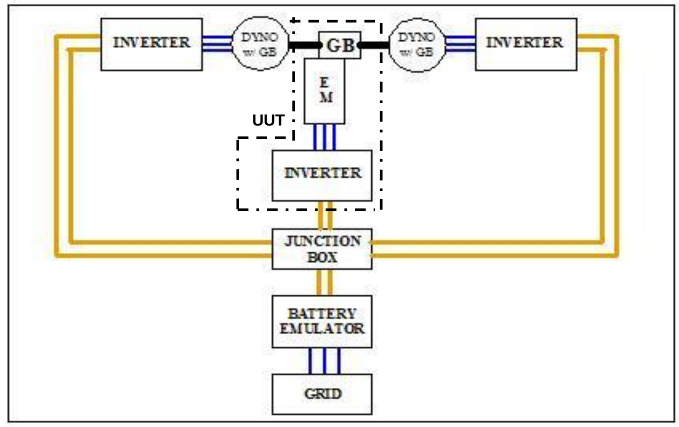

Figure 4: Common DC Bus FR EPT Drive Test Bench

During steady state operation, the UUT and the dynamometers operate in opposite power modes. For example, when the UUT is operating in motoring mode, it is consuming power from the common DC bus. The dynamometers on the other hand are in regeneration mode, and are generating power to the bus. The net power loss in the bus is due to the inefficiency of the entire system. These are mechanical losses in the gear boxes, electrical losses in the inverters, and both types of losses in the motors.

In a traditional system on the other hand, each individual battery emulator system has to meet the full power requirements of each component. The objective of the proposed work is to study in detail the net power loss in the system during steady state operations and understand the benefits of the common DC bus system.

IV. SIMULATION

A simple simulation of the previously described test-cell system was developed on a MATLAB/Simulink platform and is shown in (Figure 5). The system is bounded at the electrical input/output of each motor/inverter pairing. All components that contribute to the overall efficiency are included. Only static speed and torque points have been used for calculations with the current model.

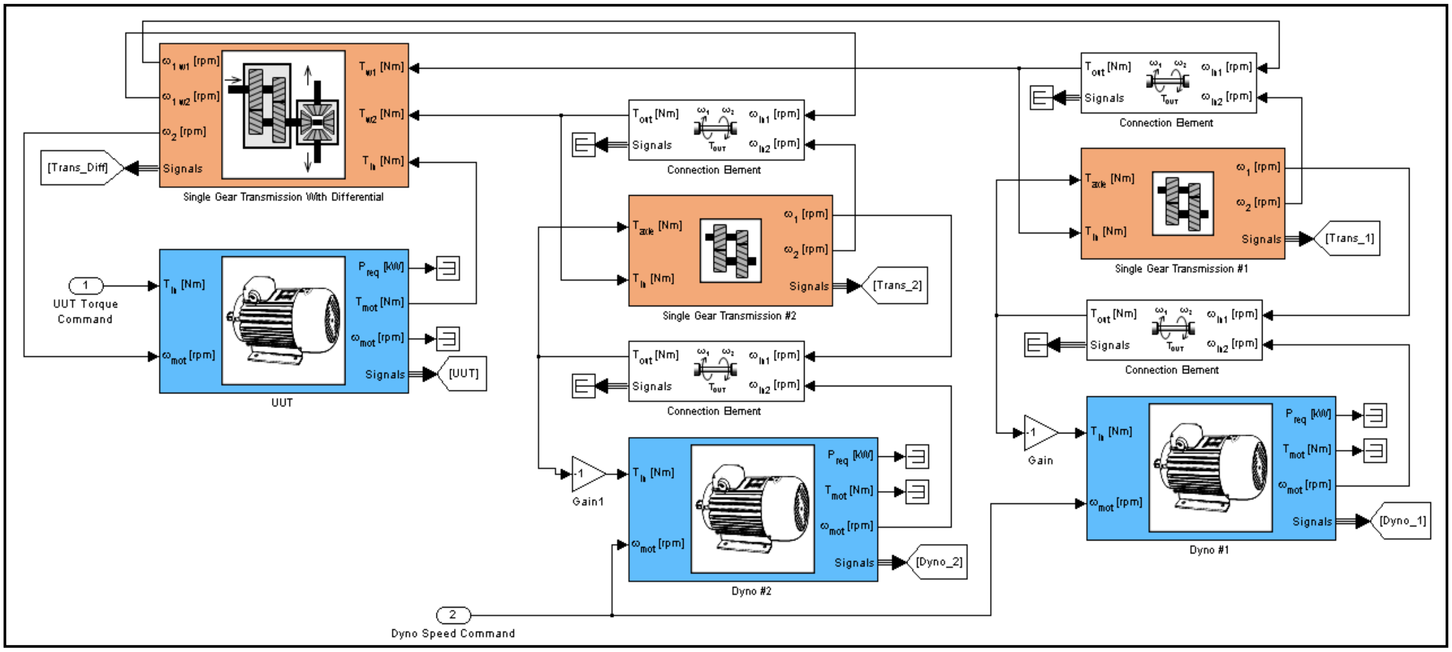

Figure 5 : Test Cell Simulation Block Diagram

The motors are connected via a series of single gear transmissions. The transmission directly coupled to the UUT motor includes a differential to split torque between the two half-shafts.

Transmission equation of motion:

$$\boldsymbol{I \cdot d\omega/dt} = \boldsymbol{T}_t + \boldsymbol{T}_r + \boldsymbol{T}_{res} \qquad \text{(Eqn. 1)}$$

- $\boldsymbol{I}$ - transmission moment of inertia
- $\boldsymbol{d\omega/dt}$ - wheel angular acceleration
- $\boldsymbol{T}_t$ - traction torque (from the UUT side)
- $\boldsymbol{T}_r$ - reaction torque (from the dynamometer side)
- $\boldsymbol{T}_{res}$ - resistance torque

There is an additional resistance torque and inertia calculation for the transmission with the differential. The dynamometers and the UUT models utilize look-up tables based on supplied data. The generation table mirrors the motoring table for the dynamometers and UUT.

Results of the simulation show predicted energy consumption/generation of the entire system. Figure 6 shows the power input/output of the UUT and the two dynamometers in all four quadrants of operation. Speed and torque set points were 1500rpm and 200Nm respectively and they are plotted along with the power calculations. The sign on the speed and torque reflects the different quadrants of operation.

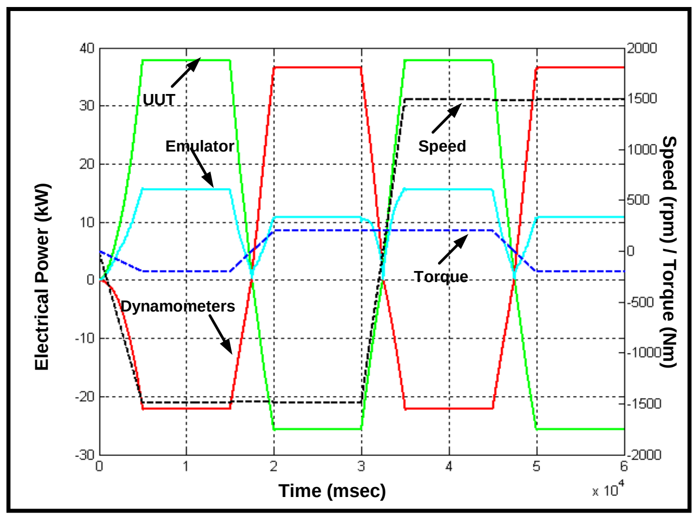

Figure 6: Simulated power requirements of UUT and dynamometers

The simulation data shows that the UUT requires 37.8kW of power, and that the dynamometers generate 22.2kW of power, in quadrants one and three. In quadrants two and four the dynamometers require 36.6kW, and the UUT generates 25.8kW.

In a traditional set up the power input/output of each unit would be handled by separate power supplies and power sinks. Even if each sink could feed back to the grid, the amount of electrical conversions to do so would result in unnecessary waste. The common DC bus implementation allows the generated power to be fed directly into the motoring unit. The light blue line indicates the power required from the emulator to compensate for losses in the system. A common DC bus design will allow for the possibility of a simpler, cheaper power supply to be used instead of a bi-directional battery emulator.

V. TEST RESULTS

The concept of the common DC bus was evaluated in a test bench set-up. The test bench set-up was run through a speed-torque profile in all four quadrants and the power requirements of all the components were studied under steady-state conditions.

Two torque-meters were used to measure the mechanical torque on each half-shaft. Speeds on the half-shafts were calculated from the speed encoders connected to each dynamometer. Mechanical power was calculated from these values. Electrical power to the UUT was calculated from the measured voltage and current using the DPM. Electrical power of the dynamometers was calculated using the voltage and current feedback signals from the dynamometer inverters. The errors on the feedback signals are less than 5%.

Figure 7, shows the electrical power to the UUT, dynamometers (combined) and the battery emulator. The UUT motor reported speed and torque are shown on the second y-axis. The speed and torque set-points during the test were +/-1500rpm and +/-200Nm. The power flow during the four quadrants of operation of the UUT is explained below.

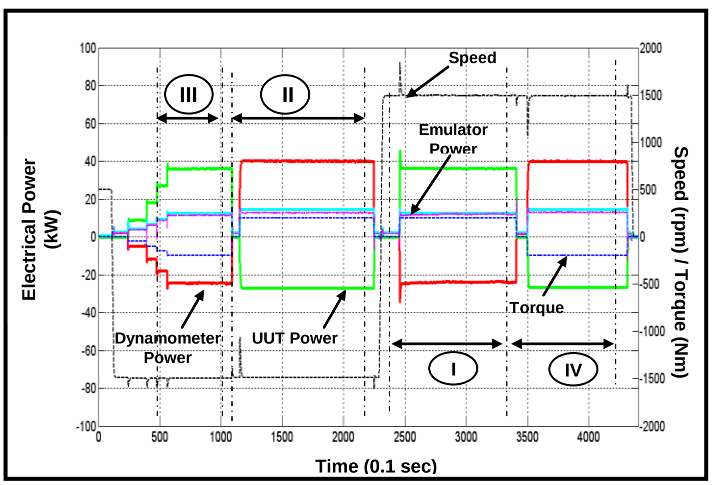

Figure 7: Test Results (Component electrical power in four quadrants)

(I) *Quadrant I*: This quadrant is also known as '**FORWARD MOTORING'**. The speed and torque in this quadrant is positive [5]. The motor was in motoring mode and the dynamometers were in regeneration mode. The electrical power consumed by the UUT in this mode was 35.9kW. Due to the losses in the system, the dynamometers generated only 24.4kW. For this quadrant UUT simulated consumption has 5.3% error and simulated dynamometer generation has 9% error. The battery emulator provided only 12.37kW to the system.

(II) *Quadrant II:* This quadrant is also known as '**REVERSE REGENERATION'**. The speed is negative and the torque is positive in this quadrant [5]. The motor was in regenerative mode while the dynamometers were in motoring mode. The dynamometers consumed 40.2kW of power from the common DC bus. UUT generated 27.4kW of power back to the common DC bus. For this quadrant UUT simulated generation has 5.8% error and simulated dynamometer consumption has 9% error. The battery emulator provided 14.2kW of power to compensate for the losses in the system

(III) *Quadrant III:* This quadrant is also known as '**REVERSE MOTORING'**. The speed and torque in this quadrant is negative [5]. The motor and dynamometers operated in motoring mode and regeneration mode respectively. The electrical power consumed by the UUT in this mode was 35.8kW. The dynamometers generated 24.4kW of power to the common DC bus. For this quadrant UUT simulated consumption has 5.6% error and simulated dynamometer generation has 9% error. The battery emulator provided 12.3kW to compensate for the losses in the system.

(IV) *Quadrant IV:* This quadrant is also known as '**FORWARD REGENERATION'**. The speed is positive and the torque is negative in this quadrant [5]. The motor and dynamometers operated in regeneration and motoring mode respectively. The electrical power generated by the UUT in this mode was 26.79kW and the dynamometers used 39.64kW for motoring. For this quadrant UUT simulated generation has 3.7% error and simulated dynamometer consumption has 7.6% error. The battery emulator provided only 14.3kW of power to the common DC bus to compensate for the losses.

Figure 8 shows the power consumption in '**FORWARD MOTORING**' mode, or quadrant I, of the speed-torque curve.

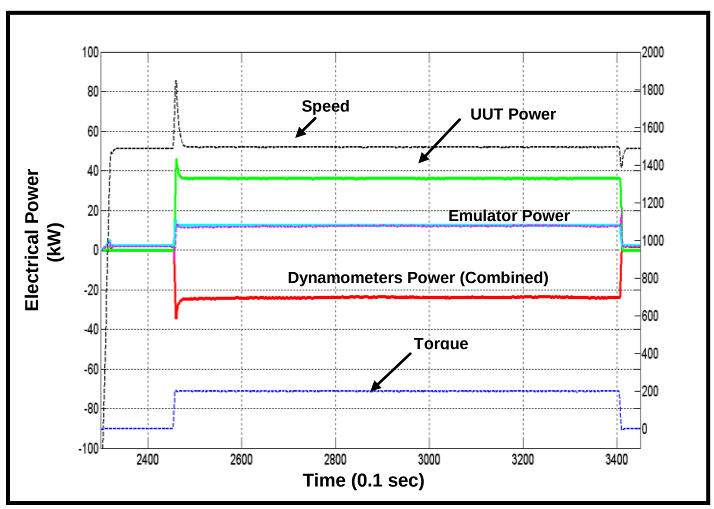

Figure 8: Test Results (Component power losses at 1500rpm, 200Nm)

Figure 9 shows the mechanical and electrical losses in the major components during '**FORWARD MOTORING**', or Quadrant I of the speed-torque curve. The losses represented in Figure 9 are of the UUT and the dynamometers systems. The UUT represents the maximum losses during this mode of 5.5kW followed by dynamometer systems contributing to 7kW. The total power loss of the system is around 12.5kW which is approximately equal to the battery emulator power.

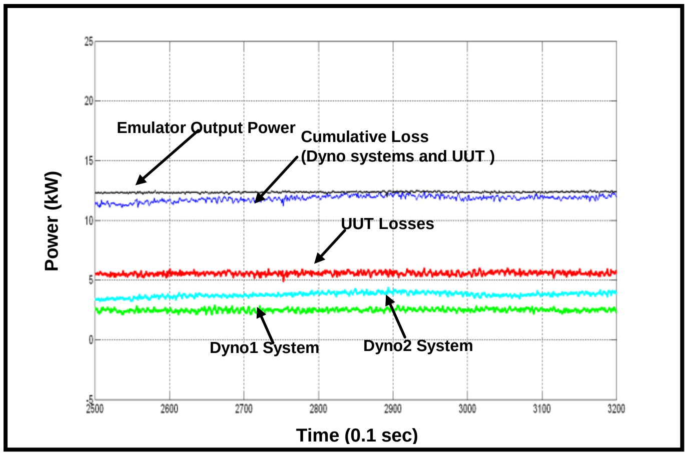

Figure 9: Test Results (Component electrical power at 1500rpm, 200Nm)

Figure 10 shows the power at 6000rpm and 20Nm. Under steady-state conditions, the emulator was providing all the power to the UUT. The dynamometers are generating negligible power to the DC bus due to the system efficiency losses.

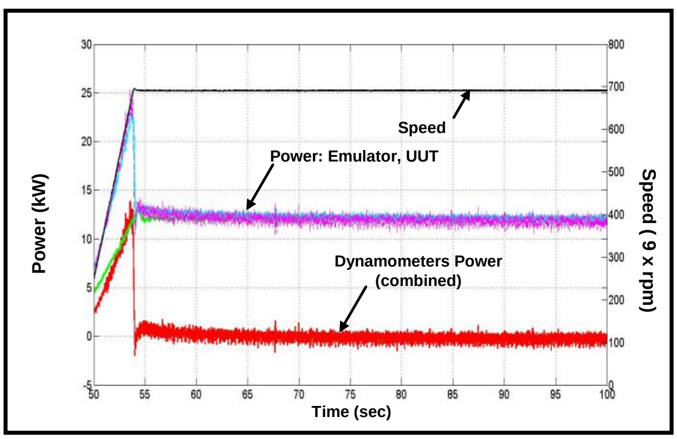

Figure 10: Test Results (Component power output at 6000rpm, 20Nm)

Tables 1 and 2 compares the power output to the grid for a system with multiple emulators' vs. one with a common DC bus during 'FORWARD MOTORING' operation of the drivetrain.

Table 1: Separate DC Bus grid power usage

Traditional: Separate DC Bus System				
Component	**Battery Emulator Output (kW))**	**Emulator Losses (kW)**	**Emulator Input from the Grid (kW)**	**Total Grid Power Consumed (kW)**
Dyno1	-12.48	4.87	-7.61	**27.74** (sum of all the emulator inputs from grid)
Dyno2	-11.90	4.83	-7.07	
UUT	35.9	6.51	42.41	

The emulators for dynamometers 1 and 2 return 7.61kW and 7.07kW of power respectively back to the grid. The emulator for the UUT on the other hand draws 42.41kW of power from the grid. The net power flow from the grid to the emulators under steady-state conditions is 27.74kW. The calculation assumes the emulators are connected directly to the grid.

Table 2: Common DC Bus grid power usage

Proposed: Common DC Bus System				
Component	**Battery Emulator Output (kW))**	**Emulator Losses (kW)**	**Emulator Input from the Grid (kW)**	**Total Grid Power Consumed (kW)**
Dyno 1	12.37	4.87	17.24	**17.24**
Dyno2				
UUT				

With the common DC bus system, one emulator is providing 12.37kW of power to all the drivetrain components and after the losses in the emulator system; the grid is providing 17.24kW of power. The calculation assumes the emulators are connected directly to the grid.

Table 3: Grid power usage in all quadrants

	Grid Power Consumed in a Separate DC Bus (kW)	**Grid Power Consumed in a Common DC Bus (kW)**
Quadrant I	27.74	17.2
Quadrant II	29.53	19.7
Quadrant III	27.61	17.1
Quadrant IV	29.5	19.1

Table 3 shows the grid power usage under steady-state conditions in quadrant I, II, III and IV. In all the quadrants of operation the grid power usage in a common DC bus system is almost 35 - 38% lower than a traditional separate bus system.

VI. FUTURE WORK

The main focus of this paper was to present the concept of a common DC bus system in a test cell application. A very simplified model of the test cell system has been used for analysis. The next project has been planned to include a detailed model of the various components and analyze the behavior of the system during transient conditions. An extension to this project will be to use this analysis as a tool for determining the size of the dynamometers and battery emulator for an electric or hybrid drivetrain test bench.

CONCLUSION

This paper presented the requirements for an electric drivetrain test bench. Different components for the test bench were discussed in details. A test set-up for a front wheel drivetrain was simulated in MATLAB/Simulink and verified with empirical data from the test bench. The test set-up was also validated in all four quadrants of UUT operation.

One of the major goals was to present the concept of 'Smart Green Technology'. The concept was achievable through the common DC bus system. This system used one battery emulator for operating a complete front wheel drivetrain that included two PM brushless dynamometers and a PM synchronous machine. The emulator provided power to compensate for the losses in these different components. The losses in each drive train component were studied and compared with the emulator power output. This concept will work for all types of motors that use a DC voltage source for their inverters. The motors will operate at the common dc bus system voltage. However, a DC-DC converter can be added to operate at different voltage levels. Comparison with a separate bus (traditional) system showed that the common DC bus system required considerable less energy from the grid than a separate DC bus system. This study also opens up the possibility of using a uni-directional power supply with proper filtering.

The common DC bus system that was presented for an electric drivetrain testing configuration minimizes both hardware and cost. Currently, this system has been implemented in several electric drivetrain test cells at FEV. This system is working under both steady state and transient operating conditions. Data analysis under transient conditions will be presented in future works. FEV offers all type of durability and development projects on these test cells and provides them as turn key cells to our customers.

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ABBREVIATIONS

UUT: Unit Under Test

PM: Permanent Magnet

CAN: Control Area Network

UDDS: Urban Dynamometer Driving Schedule

HWFET: Highway Fuel Economy Cycle

DC: Direct Current

AC: Alternating Current

DYNO1: Dynamometer

DYNO2: Dynamometer

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