Rule-Based Energy Management Strategy for Hybrid Electric Road Train

Franz Joseph D. Libao
Analysis and Testing Division
Metals Industry Research and Development Center
Taguig City, Philippines
franz.libao@mirdc.dost.gov.ph

Robert O. Dizon
Office of the Executive Director
Metals Industry Research and Development Center
Taguig City, Philippines
rodizon@mirdc.dost.gov.ph

***Abstract*— This paper discusses the design and implementation of rule-based energy management strategy for Hybrid Electric Road Train. The Hybrid Electric Road Train is a locally designed and developed mass transportation system envisioned to be an alternative mass transport in the Philippines to help ease traffic in urban cities. As a hybrid vehicle, energy management strategy (EMS) is critical in its operation. A rule-based strategy was used wherein the battery only gives power during a determined power demand from the generator during acceleration or high load conditions. The idea is to balance power availability for the load and the state of charge of the batteries. The proposed EMS was evaluated during the performance testing of the Road Train on actual road conditions, and it was found to be effective in achieving the objective.**

Keywords*— *energy management strategy, hybrid electric vehicle, road train, rule-based, mass transport

I. Introduction

According to a study conducted by Japan International Cooperation Agency (JICA) and National Economic and Development Authority (NEDA), the economic cost of transportation is 3.5 billion pesos a day in Metro Manila alone and it will balloon to 5.4 billion pesos if no measures were done to help address the transport and traffic problems[1]. Coupled with the fast-rising population of the Philippines which was 100.1 million in 2015, there is a great need to have a more efficient and more environmentally friendly transportation system [2].

To help address this problem, the Department of Science and Technology-Metal Industries Research and Development Center (DOST-MIRDC) created the Hybrid Electric Road Train (HERT). The HERT, also known as called Road Train, is an alternative mass transport system that is envisioned to help ease traffic congestion and carry more passengers per trip compared to other local public transport on the road. Its doors are designed wide enough to allow fast loading and unloading of passengers to reduce on-station dwelling time. Its operation is designed similarly to that of regular trains which have designated stops and strict schedules. It is cost-effective, energy-efficient, environment-friendly, and most importantly safe alternative mass transport system designed and built by Filipinos.

The term road train is mainly used in Australia but it also is seen in countries in Europe and the United States where it is a trucking method used in remote areas to move freight efficiently. It has a conventional tractor unit which tows three or more trailers [3][4]. It is only in the Philippines that the idea of the road train is being used to transport people thus increasing the utilization of our roads. Unlike the road train of other countries, the Road Train of the Philippines is a hybrid electric vehicle powered by a diesel generator set and batteries, and an electric motor drives each coach of the Road Train. The HERT is a mass transportation system that utilizes existing roads, thereby, reducing costs and time involving in building additional infrastructures.

The main advantage of a hybrid electric vehicle (HEV) over a conventional vehicle with an internal combustion engine (ICE) is its better fuel economy and lower emissions [5][6]. Compared with fully electric vehicles, a hybrid vehicle has an extended driving range, good power performance, and convenient refuelling [7]. An HEV combines two different power sources to propel the vehicle. One of the challenges in hybrid electric vehicles is how to control the power coming from the two different sources. That is why an energy management strategy (EMS) is a critical component in an HEV. The primary objective of an EMS is to manage energy flow such that fuel consumption and emissions are minimized without affecting the vehicle's performance [8].

There are several energy management strategies for hybrid vehicles available in the literature as of today [9]-[12]. These strategies differ in structural complexity, computation time, type of solution (local, global, real) and a priori knowledge of driving pattern. These EMS can be broadly classified into a rule-based and optimization-based design. Rule-based strategy considers human intelligence, heuristics, or component datasheet and is not dependent on prior knowledge of the driving cycle while the optimization-based approach is based on an analytical or numerical operation that minimizes the cost function [13]. Unlike optimization-based methods, rule-based implementations are low cost, robust, simple, and easy to control but the resultant performance is far from optimum and is not flexible due to pre-defined rules [14]-[16].

The main focus of this study is to design and develop an energy management strategy for the Hybrid Electric Road Train. An overview of the HERT was shortly discussed followed by the proposed design of the EMS, performance testing done, and the discussion of the results.

II. Hybrid Electric Road Train

The HERT is a road vehicle composed of at least three articulated coaches: (1) pilot coach, (2) passenger coach, and (3) power coach. The pilot coach is the first coach, and it contains the driver's cabin where the vehicle is controlled by a driver using a steering wheel and pedals for accelerating and decelerating. Following the pilot coach is the passenger coach wherein both pilot and passenger coaches can carry up to 40 passengers. Additional passenger coaches can be added as necessary to increase passenger throughput. The last coach of the road train is the power coach where the power sources are located.

DOST-MIRDC fabricated two prototypes of the HERT that has five articulated coaches. These prototypes differ only

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in their dimensions and overall capacity. The first Road Train is the bigger of the two which is 40 meters long and can carry up to a total of 240 passengers at a time. The smaller version or the light Road Train, shown in Fig. 1 is only 30 meters long with a total capacity of 160 passengers. The Road Train referred in this paper is the light Road Train.

Fig. 1. The five-coach Hybrid Electric Road Train.

The Road Train is powered by a 150 kW three-phase diesel-generator set and a 24 kW battery bank as its regenerative energy storage system (RESS). A full-bridge rectifier rectifies the 460V AC output of the generator to 621 V DC level. The rectified output is connected to the DC bus where the output of the battery bank is also connected. Connected on the DC bus are the variable frequency drives (VFD) which control the drive motors. A 75 kW inverter-duty motor propels each coach of the road train. The motor is directly coupled to a differential gear which is connected to the rear wheels. The powertrain of the HERT is shown in Fig. 2 while the vehicle parameters are shown in Table I.

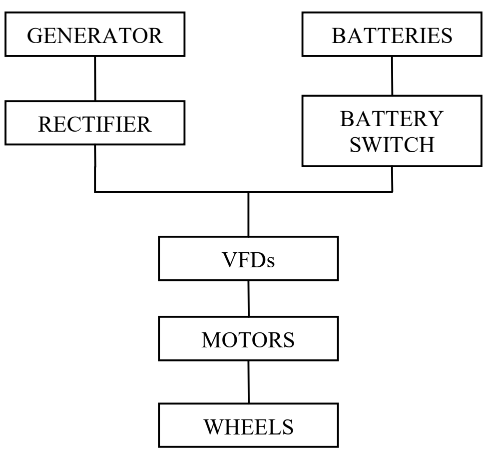

Fig. 2. Powertrain of the Road Train.

TABLE I. HERT VEHICLE PARAMETERS

Generator	240 kW
Battery	131 kW, 624 V
Motor Power per Coach	5 x 75 kW
Total Weight	50,000 kg
Design Speed	50 kph
Turning Radius	25 m

III. ENERGY MANAGEMENT SYSTEM

The proposed energy management strategy for the hybrid electric road train is a rule-based power follower type wherein the real-time power demand on the generator was the primary basis in switching on the power of the batteries. The state of charge (SOC) of the batteries was also considered in defining the rules in such a way that battery limits must not be exceeded while in operation.

The generator is the primary source of power of the propulsion motors and auxiliary loads like air-conditioning units, compressors, and control system. During acceleration, the battery bank is switched on to help the generator in supplying power. The batteries will only give power during high loaded conditions, particularly during acceleration. Like the usual HEV's, Road Train's generator is intentionally downsized compared to the internal combustion engines of a conventional vehicle given the same passenger capacity, so it is imperative that the battery bank provide the needed power boost during its operation.

One of the critical parameters in the operation of the Road Train is the battery switch. It controls when the RESS will supply energy to the load. The switching action is done by a magnetic contactor that is activated by the electronic control unit (ECU). The status of the battery switch is dependent on the power demand of the generator and the voltage of the RESS.

Power meters for the generator and RESS were installed to measure the real-time voltage, current, and kilowatt of the power sources. The power meters are connected to a laptop with a data logger installed in it to log vital information in a CSV file. These power meters were also setup to send a signal to the ECU when the specific limits (P_{upper},P_{lower}, V_{upper}, V_{lower}) were reached. P_{upper} is the upper limit of the generator power demand where the battery switch will be switched on while P_{lower} is the lower limit where the switch will be switched off. V_{upper} is the upper limit of the RESS voltage where the switch must be turned on to avoid overcharging while V_{lower} is the lower limit of the RESS voltage where the switch must be turned off to avoid too much draining.

Table II shows the rule in turning on the battery switch where P_{gen} denotes the generator power and V_{batt} is the voltage of the battery. If the measured kilowatt of the generator is lower than P_{upper}, the battery switch will stay off. If the power demand from the generator reached and exceeded P_{upper}, the battery switch would turn on. Then as the power demand gets lower and eventually lower than P_{lower}, the battery switch will switch off.

TABLE II. BATTERY SWITCH STATUS

	$P_{gen} > P_{upper}$	$P_{lower} > P_{gen} > P_{upper}$	$P_{gen} < P_{lower}$
$V_{batt} > V_{upper}$	ON	ON	ON
$V_{lower} > V_{batt} > V_{upper}$	ON	OFF	OFF
$V_{batt} < V_{lower}$	OFF	OFF	OFF

The SOC of the batteries were also considered to protect and prolong the life of the batteries. If the RESS system voltage reached or exceeded the value of V_{upper}, the battery switch would be on to discharge the batteries. If the RESS voltage gets lower than V_{lower}, the battery switch will be disable to stop the batteries from discharging.

IV. Performance Testing and Results

The Road Train was tested in an identified route inside the premises of the Clark Development Corporation in Pampanga by following the procedure indicated in the Road Train Test Protocol developed in-house. The Road Train underwent functionality and performance testing where acceleration test, deceleration test, and standard tests were performed. Several test runs in no-load, half-load, and full load conditions were done. Fig. 3 shows the actual drive cycle of the testing.

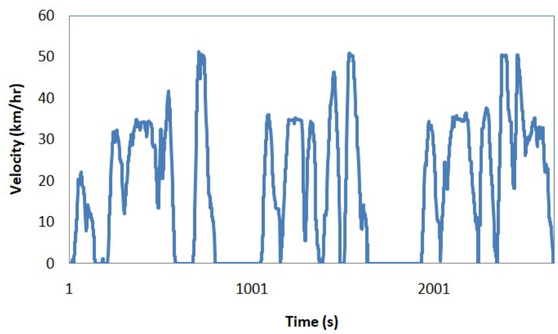

Fig. 3. Actual drive cycle of the Road Train.

A test run was done wherein the generator was the only source of power, and the RESS was never switched on. As expected, since the generator is downsized for its load, low-voltage-during-acceleration faults were experienced by the VFDs. The worst case was that the generator automatically shut down due to overload. Shown in Fig. 4 is the plot of the voltage of the generator during the said test run. We can see from it that there were instances that the voltage significantly dropped due to high loads during acceleration. The faults stopped occurring when the batteries were switched when additional power boost was needed.

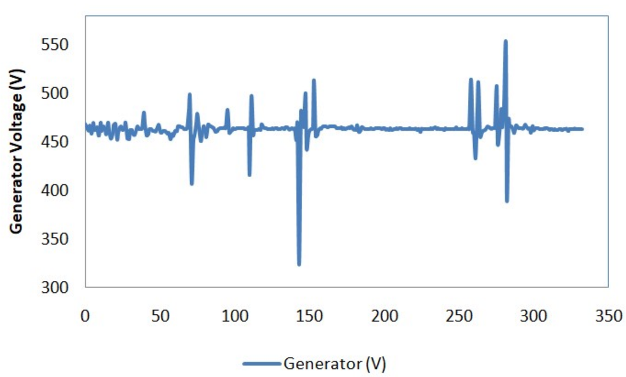

Fig. 4. Generator voltage during test run without the help of batteries.

During the testing, baseline data were gathered to determine the value of the limits. Trial and error were done to see the optimum values of P_{upper} and P_{lower} while the values of V_{upper} and V_{lower} were based on the datasheet of the battery. The most suitable value of P_{upper} determined during the performance testing wherein no faults were encountered is 100 kW while the value of P_{lower} is 50 kW so that the SOC of the batteries would not drop into critical levels. For the battery parameters, V_{upper} was set to be 713 V while V_{lower} was set to be 297 V which are the safe limits of the battery according to its manual.

A delay of 5 seconds was added after the power demand of the Road Train below P_{lower} to ensure that power demand is really low and not just a random event. This is also to avoid the repeated turning on and off of the battery switch which may shorten its lifespan. Fig. 5 shows the flowchart of the EMS after the fine tuning of the parameters.

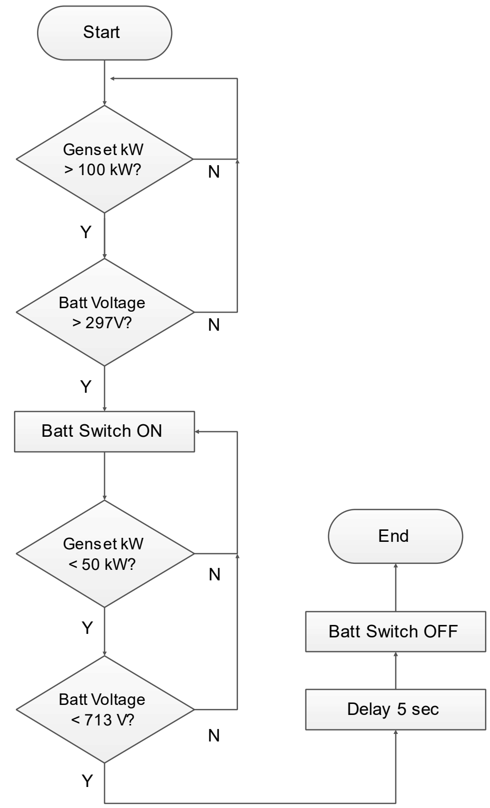

Fig. 5. Flowchart of the EMS.

The Road Train has four driving modes: (1) idle, (2) cruising, (3) accelerating, and (4) decelerating. At idle mode, the generator supplies energy to auxiliary loads like the fan motors, air-conditioning unit, and controls. In this mode also are the batteries being charged by the generator via the onboard charger. In cruising mode, aside from auxiliary loads and charger, the generator is now also giving electrical energy to the propulsion motors. During accelerating mode, the power demand of the drive motors is large enough for the generator to supply alone, so the battery bank is switched on to give additional power to boost the motors. At deceleration mode, there is regenerative energy produced naturally by the motors that is used to charge the batteries.

Fig. 6 shows the plot of the real power of the generator and the RESS as seen by their respective power meters. We can see that as the generator power rose up to 100 kW, the battery power immediately went up since the battery was switched on.

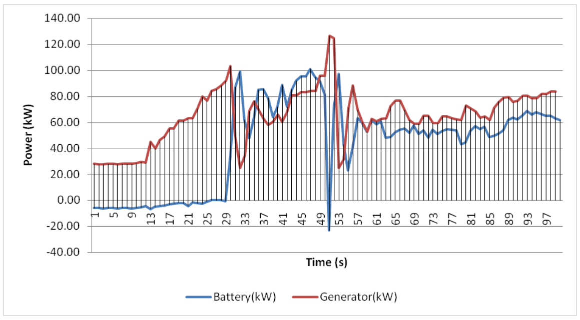

Fig. 6. Power in kW of the generator and batteries during acceleration.

Fig. 7 shows the data gathered during one of the test runs of the Road Train. We can see here that different modes of the driving cycle of the Road Train. It started with idle mode then the Road Train starts accelerating, and when 100 kW generator power demand was hit, the batteries started sharing power. During the regeneration mode, we can see large negative peaks in power of the battery indicating that the batteries are being charged. At the end of the plot, we see that the Road Train is cruising indicated by low generator power and small negative power of the battery due to the charger onboard.

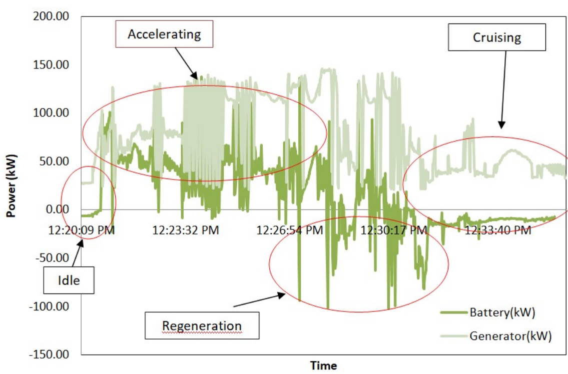

Fig. 7. Plot of data gathered from a test run of the Road Train showing the different driving modes.

V. Conclusion

In this paper, a rule-based energy management strategy was designed and implemented for the Hybrid Electric Road Train, a five-coach articulated road vehicle that was designed and developed locally as an alternative mass transport system in the Philippines. The EMS was tested in actual road condition, and critical parameters were experimented and fine-tuned. The strategy was found to be effective in controlling the power flow from the diesel generator set and the battery bank of the Road Train.

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