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System integration of China's first PEMFC locomotive

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Abstract In the face of growing environmental pollution, developing a fuel-cell-driven shunting locomotive is a great challenge in China for environmental protection and energy saving, which combines the environmental advantages of an electric locomotive with the lower infrastructure costs of a diesel-electric locomotive. In this paper, the investigation status and the development trend of the fuel-cell-driven shunting locomotive were introduced. Through innovation of the power system using fuel cells, an experiment prototype of a fuel-cell shunting locomotive was developed, which would reduce the effects on the environment of the existing locomotives. This was the first locomotive to use a proton exchange membrane fuel-cell (PEMFC) power plant in China. From October 2012, we started to test the fuel-cell power plant and further test runs on the test rail-line in Chengdu, Sichuan. The achieved encouraging results can provide fundamental data for the modification of the current individual fuel cell locomotives or further development of the fuel-cell hybrid ones in China.

Keywords Proton exchange membrane fuel cell · Locomotive transportation · Hydrogen storage · Permanent magnet synchronous motor

1 Introduction

Energy consumption plays an important role in our modern civilization and daily life, which is heavily dependent on fossil fuels. The increasing threat of the fast depletion of resources, such as petroleum, coal, and natural gas, forces people to seek renewable energy sources, such as solar, wind, geothermal, and hydroelectric. Among them, as a hydroelectric conversion assembly, fuel cells and fuel-cell power systems hold great promise as a clean technological approach; they meet all requirements for the future sustainable development for their high electrical efficiency, low emissions, and good part-load characteristics. Among the various kinds of fuel cells, proton exchange membrane fuel cells (PEMFCs) have the ordinary operation temperature (below 80 °C), which makes it greatly suitable for many kinds of applications from small portable electronic devices to automotive transport, with the power level ranging from several watts to hundreds of kilowatts [1–4].

With the rapid development of PEMFC technology in automotive industry and the electrification of railway systems as an alternative to diesel-electric locomotion undergoing serious consideration, large research efforts have been underway to develop the PEMFCs for applications in locomotive transportation in recent years. Besides, fuel-cell power for locomotives combines the environmental benefits of a catenary-electric locomotive with the higher overall energy efficiency and lower infrastructure costs of a diesel-electric; that is, fuel-cell locomotives are expected to be slightly more energy efficient than diesel locomotives, and the fuel infrastructure requirements of the former will be homologous to that of the latter. Therefore, they have a large emerging market, and their widespread adoption could lead to a reduced dependence on fossil fuels as well as encourage the development of a favorable hydrogen economy [5–7].

In comparison with the two types of traditional rail-traffic tools—catenary-electric and diesel-electric—the locomotives powered by PEMFC stacks have many great advantages as follows [6–8]:

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- Power is derived from regenerative hydrogen instead of traction electric network which is eventually from fossil fuels, and the by-product of the electrochemical reaction in the PEMFC stacks is just pure water. Thus, the related issues in terms of urban air quality and national energy security affecting the rail industry and transportation sector can be resolved, and the generated heat in the meanwhile can also be used for water heating for the passengers.
- The relatively lower operation temperature of the PEMFC stacks reduces the costs of the heat transfer and precautionary measures in case of the high-temperature failure.
- The operational railway requirements of the PEMFC-powered locomotives are compatible with the existing electric railway and nonelectrified sectors, so the locomotives powered by PEMFC stacks could perform on the existing railway lines.
- Their effects on weather are minimal, which enables it to be capable of coping with emergency situations quickly and efficiently.
- No need for the use of the traditional tractive power supply system could avoid the deleterious consequences from the faults of pantograph-contact line and the traction system, thus improving the reliability in operational safety of the locomotive.

Several countries have made great efforts to the vigorous development of locomotives powered by PEMFC stacks, which shows big potential and extensive application foreground. Among them, several areas or countries, such as North America and Japan have successfully developed several prototype locomotives based on PEMFCs so far.

The world's first fuel-cell locomotive was born in North America for underground mining, in which PEMFC stacks with continuous rated power of 14 kW gross were the prime movers [9]. In 2007, a public–private project partnership composed of Vehicle Projects LLC, BNSF Railway Company, and the U.S. Army Corps of Engineers developed a prototype road-switcher locomotive for commercial and military railway applications in Canada [10]. It was a type of hybrid power locomotive, with 250 kW from its PEMFC power plant, and transient power well in excess of 1 MW; this hybrid locomotive is the heaviest and the most powerful fuel-cell land vehicle yet. Moreover, in 2009, Vehicle Projects and BNSF continued cooperation to develop a fuel-cell-powered shunting locomotive for testing in the USA [11].

Since 2000, East Japan Railway Company and Railway Technical Research Institute continued to make efforts to develop new energy train (NE Train), in order to reduce environmental load of railcar. The first-generation "NE Train" was first delivered from Tokyo Car Corporation in April 2003, configured as the world's first hybrid diesel/battery railcar, which was named KiYa E991-1 [12]. Then, the *NE Train* underwent modifications in 2006 in having the diesel generator replaced with a hydrogen fuel cell, becoming the world's first fuel-cell/battery hybrid railway vehicle, classified KuMoYa E995-1, which was used to power 95-kW traction motors and fitted with lithium-ion batteries with an increased storage capacity (19 kWh) [13, 14]. Table 1 summarizes the configuration of the locomotives mentioned above.

Table 1 Critical parameters of the existing fuel-cell locomotives

Item	LLC and BNSF		NE
Region	North America		Japan
Fuel-cell type	PEMFC		PEMFC
Usage	Mining	Shunting	Experimental railcar
Power level	14/17 kW	250 kW	2 × 95 kW
Hybrid power	No	Yes	Yes
Traction motor	Induced	Induced	Induced
Year	2002	2009	2006

Although there have been several types of fuel-cell locomotives put forward during the last decade, the domestic research and development is still on the threshold stage.

Based on the above, the main motives of this paper and its associated work are to design and develop a novel shunting locomotive powered by individual PEMFC stack, and evaluate the performance of the ultimate locomotive prototype as pilot study. Due to the benefit from the duty cycle and operational conditions of the shunting locomotive the need of the transient response performance is not as high as that of the automobile and other types of locomotives such as passenger or freight locomotives. Thus, under this circumstance, the power supply by individual PEMFC stack is feasible, although the PEMFC power system has inherent response time in the range of several hundred milliseconds to several seconds for large power applications [15–19].

Furthermore, some key factors and challenges that influence the operation and performance of the locomotive, such as temperature and the match between the power subsystem and the tractive subsystem, are also investigated. Some encouraging results have been obtained, which can provide fundamental data for the further research, modification, and optimization of the PEMFC locomotive. The photograph of the experimental shunting locomotive is shown in Fig. 1.

2 Locomotive layout and packaging

The integration of the complete PEMFC locomotive is shown in Fig. 2. The structure of the fuel-cell shunting locomotive consists of mechanical and electrical portions. The mechanical portion is made up of locomotive framework, bogies, traction apparatus, and air-braking subsystem; the electrical portion is composed of PEMFC power plant, high-voltage lithium-ion pack, traction inverter, permanent magnet synchronous motors (PMSMs), system controller, startup resistors array, and other auxiliary electrical system and actuators [20].

The middle machinery compartment houses the PEMFC power plant based on the framework of the traditional diesel locomotive along with the auxiliary cooling subsystem, ventilation subsystem, and traction driving subsystem. The hydrogen storage subsystem is composed of nine carbon-fiber composite tanks each with 128 L available volume, located near the power plant, which can store a total of 23 kg of hydrogen at 35 MPa [21]. The ballard 150 kW FCvelocity$^{\mathrm{TM}}$–HD6 fuel-cell power module supplies power to the 600 V DC traction power bus and the existing locomotive auxiliary electrical system [22].

The locomotive prototype consists of four built-in subsystems: the PEMFC power plant, cooling subsystem, hydrogen storage subsystem, and tractive power supply subsystem. Each of the four subsystems was independently tested, and then tested as an integrated system, before being finally installed in the locomotive.

Fig. 1 Photograph of the experiment shunting locomotive

As seen from Fig. 2, the largest part of the fuel-cell power system is the hydrogen storage subsystem. It consists of nine 35 MPa carbon-fiber/aluminum cylinders that approximately store 23 kg of compressed hydrogen. The nominal maximum operation pressure of each cylinder is 50 MPa. When the impact pressure reaches or exceeds 80 MPa, hydrogen will be discharged to prevent from explosion hazards. Besides, in consideration of the approximate equiponderance between the hydrogen storage system and PEMFC power system, the above layout has minimal effect on the locomotive's center of gravity and symmetry with better power distribution between the two bogies located at the basis of the framework, which will be favorable for the efficient operation of the locomotive.

The PEMFC power plant, two traction inverters, electric cabinet, and cooling subsystem are housed in the remaining half of the machinery compartment. The air-braking subsystem already housed in the locomotive stands aside the hydrogen storage subsystem, which is used for the deceleration and braking of the locomotive. There is a low-power air compressor dedicated for the air pressurization, which is located at the lower left side of the locomotive framework. The air compressor will automatically startup when the operation pressure falls below 400 kPa and shutdown, when the operation pressure reaches 850 kPa in order to provide enough air for braking at low speed.

However, the fuel-cell power plant itself is equipped with air delivery system, which operates at a maximum air

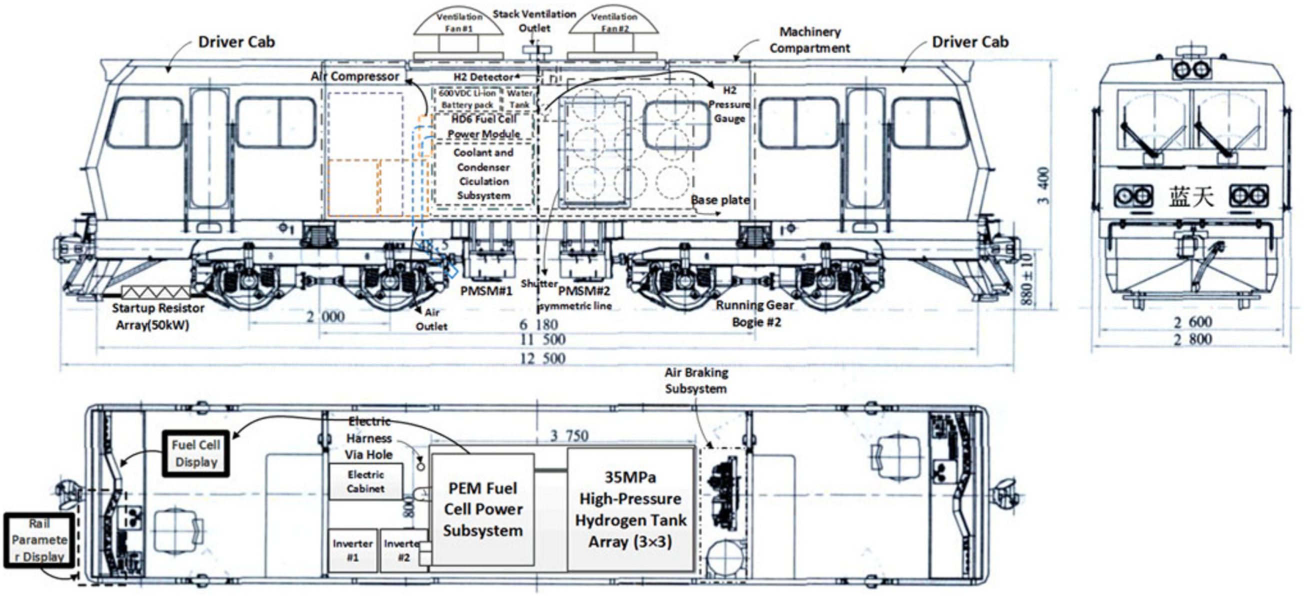

Fig. 2 System layout of the PEMFC locomotive including mechanical and electric portions

pressure of ~1.2 bar (relative pressure), with a maximum mass flow of ~150 g/s. Compared with the high pressure operating fuel cell, this "low-pressure" operation results in lower parasitic losses of gross power (~10 % for a 1.5–1.8 bar air system and near 20 % for higher-pressure air system) [7] and the need to employ just one-stage compression. Besides, in order to make the fuel-cell power system work more efficiently at the start-up stage, a 600 V lithium-ion pack is equipped to provide the startup power, which is located on the HD6 power module.

The generated pure water is exhausted with the residual air and a small fraction of formation heat through the "air outlet" pipe. The formation heat of the PEMFC power module is so large that the cooling subsystem is necessary to reject the redundant heat in order to maintain the optimal operating temperature of the PEMFC stack. The cooling subsystem consists of the primary and secondary radiators which reside in the lower left and lower middle sections of the power plant, respectively. The secondary radiator is applied for heat transfer of the stack condenser that is used to insure that enough process water be made available at all time for air humidification. The primary radiator will suck air and exhaust it through the shutter of the locomotive framework. Under normal conditions, the leaked hydrogen will be exhausted through the ventilation outlet of the PEMFC stack module, and the ventilation fans located on the upper side of the locomotive will assist in precluding confinement of any accidentally leaked hydrogen.

It is worth mentioning that the startup-resistors array (approximately 50 kW) located at the bottom of the locomotive (as shown in Fig. 2) is used to overcome the inherent surge phenomenon of the turbo charger in the air delivery system at low flow rate. The startup resistors array is divided into three groups to match with the power demand of the gear increment (about 15–20 kW/gear for each PMSM with velocity modulation).

3 Results and discussion

3.1 Overview of the test locomotive

The test shunting locomotive in this test module consists of only one locomotive, which is the smallest test unit that is able to individually operate. Also, in order to effectively use the existing locomotive technologies, we make various devices that are standardized, to be compatible with the latest electric locomotive. The locomotive body used is a stainless steel body which is the same as the traditional diesel locomotive that is run on local lines. As for the motors and locomotive controller, the latest PMSM and its driving technologies are used aiming at improving the efficiency and power factor in comparison with induction and wound-rotor synchronous motors [23–25]. Figure 2 shows an overview of the test locomotive, and Table 2 shows the technical specifications of the locomotive.

3.2 Performance test

At the time of this writing, the fuel-cell shunting locomotive has undergone several weeks of operational testing at the test rail-line in Chengdu, Sichuan, China. The locomotive work schedule involves the gear test and running test. The PEMFC locomotive performed all operational testings as a single unit, and thus, the entire work energy was provided solely from the PEMFC locomotive itself. The duty cycle of the running test as shown in Fig. 3 is an acceleration–deceleration duty cycle which simulates and evaluates the load–response performance.

From a functional perspective, the fuel-cell locomotive works well in all respects. The fuel-cell stack module and the associated cooling and fuel subsystems performed without any issue during the duty cycle test. During all work shifts, the power plant was able to provide power to the traction motors and/or provide current to all the auxiliary peripherals. Operation of the fuel-cell power plant was closely monitored, and data for key parameters were logged at a 0.5 s rate during operation. Of particular interest are the response performance of the mean operating power levels and the associated switch control of the startup resistors array. Figure 3 shows the snapshot of the typical acceleration–deceleration duty cycle for the integrated locomotive. The fuel-cell operating power level is dynamically predicted and determined by the system

Table 2 The test fuel-cell shunting locomotive specifications

Item	Value
Model	XQG45-600P
Unloaded mass (t)	45 ± 3 %
Driving mode	DC–AC transmission
Shaft type	B-B
Wheel diameter (mm)	840
Wheel track (mm)	1,435
Minimum bend radius (m)	80
Distance between shafts (mm)	2,000
Distance between bogies' center (mm)	6,180
Physical dimension ($l \times w \times h$, mm)	13,500 × 2,600 × 3,600
Continuous speed (km/h)	21
Maximum operating speed (km/h)	65
Design speed (km/h)	100
Continuous tractive force (kN)	36.5
Startup tractive force (kN)	50
Main motor	PMSMs
Tractive motor power (kW)	2 × 120
Brake type	Air brake + holding brake

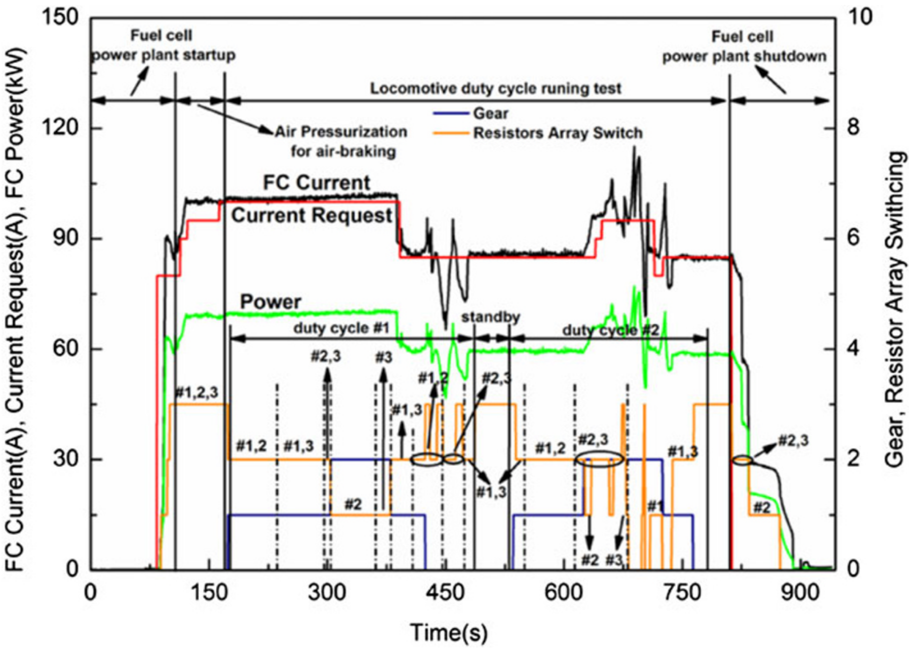

Fig. 3 Sample of the locomotive operation curve during a duty cycle of reciprocating running in the test rail-line in Chengdu, Sichuan, China, the maximum power requirement of which was 80 kW corresponding to gear 2

controller which determines the power set-point based on the current demand, tractive characteristics of the traction motors, and states of the startup resistors array.

As seen from Fig. 3, the sample locomotive integration test consisted of two duty cycles, each with independent acceleration–deceleration procedure. Each time when the locomotive starts up, the air pressurization for air-braking is necessarily carried out at first, so that there is sufficient compressed air for braking at low speed ($\leq$20 km/h). After the preparation as mentioned above, the integration test could be carried out subsequently. As the test rail-line is just about 1 km, it could not test all the gears switching. Besides, as the speed modulation parameters of the two inverters are not optimal, when the locomotive decelerates, in particular in duty cycle #2, the real-time current drawn is fluctuant with the effect of energy braking, thus resulting in the fluctuating power consumption. The situation that there is some slope in the test rail-line makes the power fluctuation in the return acceleration–deceleration procedure–duty cycle #2 more serious.

Furthermore, the startup-resistors-array-switching subroutine is customized in order to keep the temperature rise of each resistor within reasonable limit, and minimize the heat-transfer power consumption. The progress of the startup resistors switching is also shown in Fig. 3.

4 Conclusion

In this paper, the first PEMFC shunting locomotive developed in China that combines the environmental advantages of an electric locomotive with the lower infrastructure costs of a diesel-electric locomotive was introduced. Moreover, the performance of the fuel-cell power plant and the integrated locomotive were experimentally investigated in a test rail-line in Chengdu, Sichuan, China. Depending on the primary PEMFC power source and relatively environmental high-voltage lithium-ion batteries pack for the startup power source, it can a totally zero-emissions vehicle, that is, with zero carbon in the energy duty cycle. Through the proper system design and development of the PEMFC shunting locomotive, utilization of hydrogen fuel cell in the rail environment with the characteristics of relatively simple duty cycle condition has proven technically feasible. After several weeks of operational testing, the achieved encouraging results can provide fundamental data for further modification or development of the fuel cell or even fuel-cell hybrid locomotives in China.

The body of the locomotive in particular for the fuel-cell power plant underwent a large number of detailed adjustments using important technological know-how learned during the course of running test, and thus we arrived at designing the current system and locomotive prototype. However, from a technical perspective, there are still many important issues that need to be modified or improved, such as follows:

- Substitution of the turbotype compressor with double flight screw-type compressor because of its lower noise level and little surge, although the cost of the former is lower.
- Although the turbo charger with the substitutive double flight screw-type compressor having low boost pressure

ratio is suitable for these locomotive applications and quieter material has been utilized in the framework construction of the locomotive, the air outlet is still necessary for optimal noise abatement.

- With the double flight screw-type compressor in place, the startup resistors array can be canceled, the control logic will be simplified, and the available power will be maximized.
- The parameters of the traction inverters for PMSMs driving need to be further debugged, in order to achieve more efficient PMSMs and the better matching between the fuel-cell power plant and the tractive motors.
- The condenser circulation system could be further improved to dynamically control the temperature of the condenser, as it is directly related to the humidification of the air entering the stack as mentioned above.

In light of the above, we will make further efforts and work on resolving the above issues to achieve the viability for the practical use of an ecofriendly PEMFC shunting locomotive.

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