Multi Fuel Cell Module Architecture Investigation: Key of High Efficiency in Heavy-Duty Electric Transportation

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This article is on the subject of Multi Fuel Cell (MFC) power module system in heavy-duty electric transportation. MFC system is promising to increase system power level, redundancy, lifetime and reduce costs. In particular, the number of fuel cell module can affect system fluidic and electrical architectures significantly. Furthermore, system complexity and performance can also be influenced. Different MFC system electric architectures can lead to system global efficiency varying a lot which is closely related to fuel economy. Meanwhile, optimization strategy can also be used to help assign power demand among fuel cell modules more efficiently, then help reduce power loss and hydrogen consumption of the system. Hence, this article aims to make an investigation of MFC system architecture development in heavy-duty electric transportation and find the most suitable architecture from the view of efficiency and fuel economy based on quantitative analysis.

Introduction

Nowadays, reducing dependence on fossil fuels and declining CO_2 emissions becomes more urgent than ever. Depending on statistical information, transport pollutions have a major impact on greenhouse gases emissions throughout the world. Available data indicate that in the year of 2019, the domain of transportation leaded to 8222Mt CO_2 emissions and accounted for 24.3% of total annual emission worldwide [1].

Hydrogen is an energy storage medium with a high calorific value, and which can be produced from diverse energy resources. Hydrogen energy-based transport electrification is a practical solution to reduce CO_2 emissions caused by the gasoline and diesel-based conventional transportation [2]. Proton Exchange Membrane Fuel Cell (PEMFC) is essential to convert chemical energy from hydrogen to electricity and the only by-products are water and heat.

In the passenger vehicle domain, fuel cell electric vehicles (FCEVs) are well developed and already achieving commercialization era. Due to space constraints and power requirements, fuel cell systems based on a single fuel cell stack are more suitable for passenger vehicle. For other transportation means such as medium/heavy-duty truck, bus, rail transport and marine applications, the power requirements are in the level of several hundreds of kilowatts. In order to consider fuel cell system in these high-power applications, the most direct approach is to use a single fuel cell stack which can satisfy the power requirement. However, in this case, the cost of research and development will increase since the requirement varies from one application to another. Multi Fuel Cell (MFC) power module systems, which are an integration of specific electrical, fluidic and thermal architectures, have proven to be a hopeful solution [3][4]. The total power of MFC system is the sum of each power module. Hence, MFC system can reach high power level easily. Modular configurations make them flexible to satisfy power demands for various applications. Furthermore, when the application field is changed, the requirement for FC system will change. As MFC system is an integration of multiple same sub-FC systems, it can be re-constructed conveniently. Thus, the research period can be decreased while the manufacturing cost can be reduced. MFC system features the advantage that can operate in degraded mode; thus, system reliability is increased [3][5][6]. By cooperating with energy storage systems such as battery packs or supercapacitors, MFC systems enable improving the energy distribution strategy among the different sources [7]. FCs can be controlled to work in high efficiency range and the power variation rate can also be limited. Hence, the fuel cell system efficiency can be improved and the fuel cell durability can be extended [8].

In this paper, firstly the applications of MFC systems in various transportations are investigated. Then, both similarities and differences of MFC system based powertrain for different heavy duty transportations are discussed. As MFC system construction influences system efficiency strongly, four different MFC architectures are compared from the view of system electrical efficiency. In order to verify the effectiveness of the proposed strategy for MFC power allocation, hydrogen consumption of Heavy-Duty Fuel Cell Electric Truck (HD-FCET) is estimated based on simulation with the driving cycle U.S. Environment Protection Agency Heavy-Duty Urban Dynamometer Driving Schedule (EPA HDUDDS).

Table.1 *MFC system applications in heavy duty transportation*

Domain	Product Information			Fuel Cell System			H2 Storage		Energy Storage	
	Model	Manufac.	Range	OEM	Power	Archi.	Pressure	Capacity	Type	Capacity
Rail	Coradia iLINT Train	Alstom [9]	800 km	Hydrogenics	2*198 kW	Parallel	350bar	180 kg	Li-Ion Battery	111 kWh
	LF-LRV Tramway	CRRC [7]	No info.	Ballard	2*150 kW	Parallel	No info.	No info.	Li-ion Battery	50 Ah
									Supercapacitor	30 F
	Locomotive	PESA [10]	No info.	Ballard	2*85 kW	No info.	No info.	175 kg	No info.	No info.
Truck	Xcient Fuel Cell	Hyundai [11]	400 km	Hyundai	2*95 kW	Parallel	350bar	32 kg	Battery pack	73.2 kWh
	Garbage truck	Hyundai [11]	600 km	Hyundai	2*95 kW	Parallel	350bar	25 kg	Battery pack	24.2 kWh
	Class-8 HD truck	Toyota-Kenworth [12]	480 km	Toyota	2*130 kW	Parallel	700bar	No info.	Battery pack	12 kWh
Bus	No info.	Hyundai [11]	745 km	Hyundai	2*95 kW	Parallel	350bar	33 kg	Battery pack	78 kWh
Maritime	Sea-going vessel	MARANDA (project) [13]	No info.	PowerCell	2*85 kW	Parallel	300bar	80 kg	Battery pack	No info.

Fuel cell systems in heavy-duty electric transportation

Compared with passenger cars, heavy-duty vehicles have larger space and have greater advantages from the installation of MFC systems. With regarding to larger installation space for the hydrogen storage system, more hydrogen cylinders can be installed; then, the total mass of fuel can be increased and the driving range can be extended.

The applications of MFC systems in heavy-duty transportation fields are comparatively listed in Table 1 and include rail [7][9][10], heavy-duty trucks [11][12], marine [13], and urban buses [11][12]. It can be seen from Table 1 that in different applications, the high weight and long range of the vehicles lead to the fact that the fuel cell system and the energy storage system need to have high power and high capacity, respectively. In most applications, the fuel cell system is built in a parallel architecture with MFC high-power modules. The main advantage of parallel architecture is that system redundancy can be improved significantly.

The medium pressure of 350 bar is selected by many manufacturers as shown in Table 1. Unlike in passenger FCEVs, lower hydrogen storage pressure can be used as there is more space available for heavy-duty applications. Hence, it is possible to use more hydrogen cylinders to guarantee the total quantity of required fuel. High storage pressure, for example at 700 bar, can also be used, as in the fuel cell truck of Toyota-Kenworth [12]. In this way, more fuel can be carried and help to extend the driving range of the vehicle. A set of cylinders are installed in parallel and then connected to the fuel inlet of fuel cell stack through pressure reducing valves.

Energy storage systems generally use high-voltage battery packs, and the capacity of the batteries varies according to the power demand. It should be noted that in some applications with frequent start and stop cycles, such as intercity trams, a supercapacitor system is also integrated into the energy storage system to meet the needs of high dynamic operation [7].

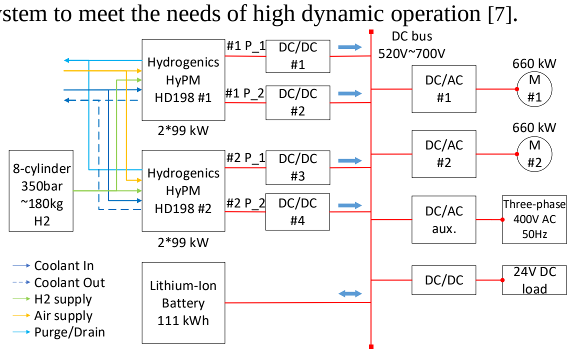


Figure 1 *Alstom HyRail powertrain architecture [9].*

Powertrain comparison of fuel cell system based high-power transportation

The powertrain of fuel cell-based transportation usually includes the following subsystems: fuel storage system, fuel cell system, energy storage system, power conditioning unit, motor controller and driving motor. As an example, the powertrain architecture of Alstom fuel cell train Coradia iLINT is presented in Figure 1.

High-power fuel cell module is the key element of MFC system. Manufacturers have proposed different solutions for the realization of a high-power fuel cell module such as FCvelocity HD6 (150kW) of Ballard and HyPM HD198 (200kW) of Hydrogenics. Toyota applies its new generation fuel cell system, which can deliver high output as 128 kW with a volumetric power density of 5.4kW/L, in the heavy-duty truck and bus [12]. Hyundai also equips its heavy-duty transportation products with high power fuel cell system of the FCEV Hyundai Nexo [11].

According to the literatures and examples of commercial application, the similarities of powertrains based on MFC systems can be found as follows:

- *Power converter:* the fuel cell module electrical outputs are connected with DC/DC power converters to change the fuel cell output characteristics and to meet the DC bus voltage requirement. Sometimes the DC bus voltage is high, for example 750 V in the CRRC fuel cell tramway. Thanks to the high-power module already high output voltage, non-isolated converter can be used while the power losses can be limited.
- *Fluidic architecture:* only parallel constructed fluidic architectures have been found throughout the literature in commercial heavy-duty transportations. The parallel architecture is simple and easy to control. The system complexity is reduced and the system redundancy is increased. Although there are other fluidic architectures such as series and cascade ones, the system and the control requirements are more complex.
- *MFC system:* in the existing heavy-duty transportation applications, two sets of high-power fuel cell modules are usually used in parallel. This is done in order to do a compromise between the cost, the redundancy and the reliability of MFC system. In this way, the system efficiency can be improved by operating each fuel cell module in a high efficiency zone.

For heavy-duty transportation, differences of MFC-based powertrain also exist as follows:

- *Hydrogen storage system:* the hydrogen that needs to be stored on-board is related to the driving range. For the hydrogen storage system, the advantages and disadvantages of liquid hydrogen system and compressed gaseous hydrogen system are studied in [14]. Although liquid hydrogen owns high storage density, compressed gaseous hydrogen storage system is still used in most commercial heavy-duty transportations. For the fuel cell train of Alstom, the driving range is over 800 km and its MFC system has a nominal power of 400 kW. The on-board hydrogen storage system can store 180 kg hydrogen under 350 bar. The hydrogen consumption of Hyundai fuel cell truck is around 8 kg per 100 km. For the fuel cell truck of Toyota, 12.5 kg hydrogen is required per 100 km. The difference is that the capacity of the high voltage battery pack installed in Hyundai fuel cell truck is higher than that of the product of Toyota. In the Toyota fuel cell truck, the hydrogen is stored under 700 bar. Hence, although the hydrogen can be stored under medium pressure benefiting from more space in the heavy-duty transportation applications, high pressure hydrogen storage can still help increase the quantity of hydrogen carried on board.
- *Energy storage system:* the energy storage system is usually based on high-voltage battery packs. In some applications, for example, the fuel cell tramway of CRRC, the energy storage system consists of two Li-ion batteries (40 Ah) and two supercapacitor banks (45 F) [7]. Compared with a battery, supercapacitors have better transient performance and are more suitable for missions with frequent starts and stops. The energy storage device can be directly connected to the DC bus or through a bi-directional DC/DC converter. Although the use of a bi-directional DC/DC converter increases the complexity of system, the DC bus voltage can be better controlled and the energy can be distributed more flexibly.

Comparison and optimization of MFC system efficiency

As presented in Table 2, the specifications of HD-FCET based on MFC system are given here for a quantitative analysis.

Table 2 *Vehicle main specifications for simulation study.*

Vehicle	
Type	Cargo (Chassis Cab)
Dimensions	Length: 9,745 mm Width: 2,515 mm Height: 3,730 mm
Weight	19,000 kg
Powertrain	
Fuel cell stack	4 sets; HyPM^{TM} HD 30; 33kW rated electrical power; 0 to 500 A_{DC}; 60 to 120 V_{DC};
Battery	3 sets; 300V 90 Ah Ni-MH battery

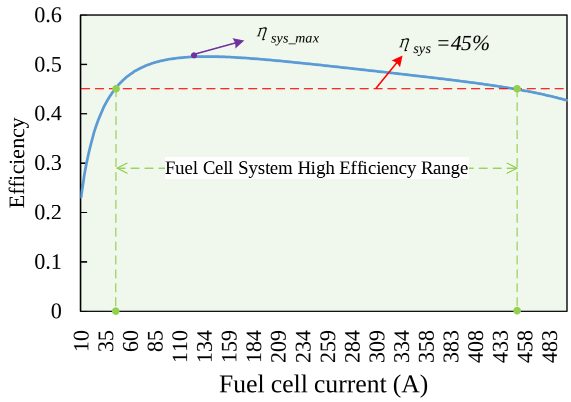


Figure 2 *Relationship between FC operating point and system efficiency.*

In Figure 2, the system efficiency curve of FC HyPM^{TM} HD 30 is presented. Obviously, the system efficiency changes when the FC current varies. Hence, the operating point strongly influences system performance. The high efficiency range is defined as the FC current locates between 35A and 460A. The FC should operate in the high efficiency range in order to improve overall performance.

The efficiency of MFC is also strongly influenced by the connection modes at the output sides of both fuel cell power modules and power converters. The connection modes can be classified as series architecture, parallel architecture and hybrid architecture. In this study, four power modules are used to construct the MFC system and to meet the basic power requirement of HD-FCET. Four different MFC electrical architectures are shown in Figure 3.

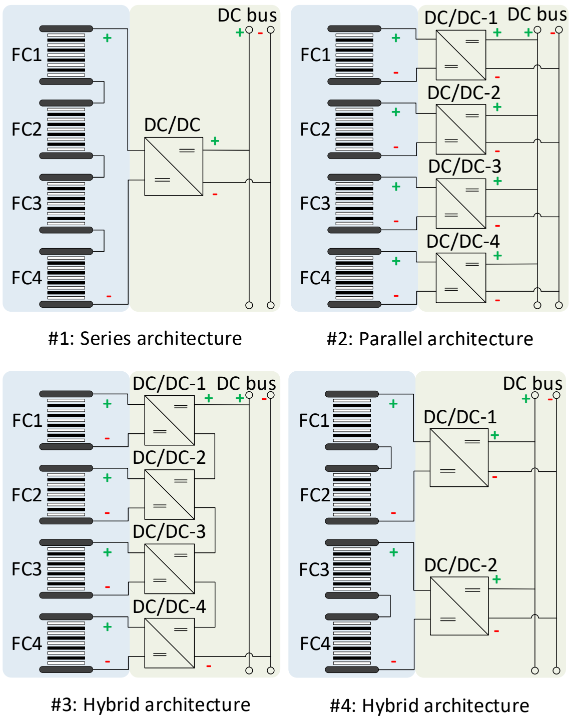


Figure 3 *MFC electrical architecture: series, parallel and hybrid.*

Architecture #1 (series) and #2 (parallel) are two basic configurations. In architecture #1, four power modules are connected in series at the output side in order to increase the output voltage of the fuel cell system. A single DC/DC boost converter is used as the interface between MFC system and DC bus. Due to the increased input voltage, high voltage gain ratio is not necessary and non-isolated power converters can be employed. Although architecture #1 owns simple configuration and easy to be controlled, the redundancy of system and the flexibility of energy management are reduced. For architecture #2, each fuel cell power module is connected to the DC bus through its own power converter. The configuration is a purely parallel structure. The advantage of the specific architecture is that the system redundancy and the flexibility of energy distribution are the highest. However, the system complexity is increased. And due to the low input voltage of each power converter, a high voltage gain ratio is required. Hybrid electrical architectures are derived from these two basic architectures as shown in #3 and #4. The hybrid architectures vary in fuel cell power module connecting format, number of power converters and power converter connecting modes. In architecture #3, four converters are connected in series at the output sides to reduce voltage gain ratio of each converter compared with architecture #2. In #4, the quantity of power converter decreases to two. Each two fuel cell stacks are constructed in series as a group and connected to a converter. The two converters are connected in parallel at the output side of architectures #4. The decrease of converter number helps reduce the complexity of electrical structures and the quantity of passive components. The converter voltage gain ratios are also reduced. Furthermore, architecture #4 also takes advantage of series- and parallel- architectures with flexible power distribution.

Furthermore, a suitable energy management strategy can also improve the global efficiency and the fuel economy of the MFC system. The objective is to control the operating point of each fuel cell module in order to improve the MFC system efficiency and fuel economy, and reduce degradation of the fuel cell stacks. Equi-distribution [7] and Daisy chain [3] are two traditional power distribution strategies for MFC system. The Energy Management Strategy (EMS) of heavy-duty transportation based on MFC and ESS can be dived into two steps: the first step is to distribute power demand between the MFC system and the ESS, while the second step is to manage power efficiently among MFC system. At first, the strategy focuses on assigning peak power demand to the ESS and also limits the degradation of energy storage devices. After that, it aims to operate fuel cell power modules in high efficiency ranges, and hence, to improve the efficiency and fuel economy of the MFC system.

Other researchers also proposed different methods to distribute power demand more efficiently in MFC systems. Xu et al. [15] and Yu et al. [16] optimized MFC system fuel economy based on statistical data of fuel cell efficiency for passenger car and tramway applications, separately. Marx et al. [17] utilized state-machines to decide whether to start or stop an additional fuel cell to meet power demand. Combined with Daisy chain, the MFC system efficiency was improved and the fuel cell start/stop frequency was reduced. Alvaro [18] proposed an adaptive state-machine based strategy which helped not only improve MFC system fuel economy but also reduce fuel cell degradation. Khalatbarisoltani et al. [19] proposed a real time power allocation strategy based decentralized convex optimization in MFC system and less computational time is required compared with other algorithms.

The efficiencies of different MFC architectures are needed to be calculated for the comparison and optimization. Eq. (1) is used to calculate the efficiencies of MFC architectures #1~#4.

$$\eta_{MFC} = \frac{P_{FC1} + P_{FC2} + P_{FC3} + P_{FC4}}{\frac{P_{FC1}}{\eta_{FCS1}} + \frac{P_{FC2}}{\eta_{FCS2}} + \frac{P_{FC3}}{\eta_{FCS3}} + \frac{P_{FC4}}{\eta_{FCS4}}} \quad (1)$$

In Eq. (1), η_{MFC} represents MFC global efficiency; P_{FC1}~P_{FC4} stand for the fuel cell net power; η_{FCS1} ~η_{FCS4} represent FC system efficiency. The electrical efficiency curves of four architectures are obtained as in Figure 4.

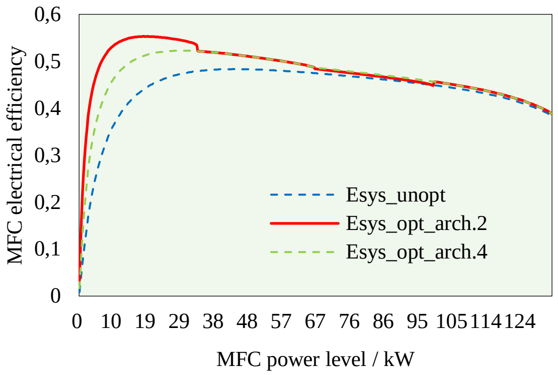
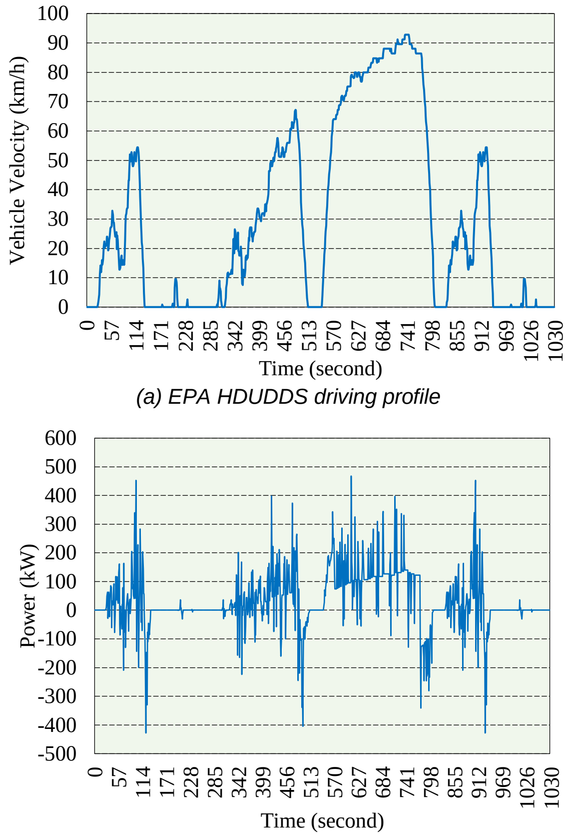


Figure 4 *MFC system electrical efficiency curves: unoptimized (blue dotted curve), optimized of architecture #2 (red curve) and #4 (green dotted curve).*

Here, MFC system efficiency is optimized from the view of system power loss. The optimization strategy is a combination of equi-distribution and Daisy chain. The number of operating fuel cell module is decided according to the power demand, and the power modules start or stop as Daisy chain. For example, two power modules will start to work if power demand is in the range of (2*P_{FCN}, 3*P_{FCN}). P_{FCN} represents the nominal power of fuel cell module. Then, power demand will be allocated to the operating power module(s) equally. This hybrid strategy firstly takes advantage of Daisy chain and requires operating as few fuel cell power modules as possible. Then, as power demand is distributed equally among the operating fuel cell modules, the difference of degradation of each fuel cell can be decreased. Furthermore, fuel cell modules are controlled to work in high efficiency range. Hence, the efficiency of the MFC system is improved. For the MFC architectures in Figure 2, only #2 and #4 can be optimized because the output sides of power converters in the other two architectures are in series.

The blue dotted curve represents the electrical efficiencies of all four architectures based on equi-distribution. In this case, power demand is averagely assigned to four fuel cell power modules in each architecture and the efficiencies are the same. The green dotted curve stands for the electrical efficiencies of architecture #4 with optimization. The operating conditions are optimized as two stages. Combined with the optimization strategy, architecture #2 obtains the highest efficiency especially in the low power range as the red curve in Figure 3. The reason is that when power demand decreases below P_{FCN}, only one power module operates to meet power demand. Therefore, power loss caused by the auxiliary system is also reduced. As a result, the system efficiency of MFC architecture #2 is further improved compared to others.

Furthermore, in order to analyse the effectiveness of the proposed EMS strategy deeply, hydrogen consumption of HD-FCET which is based on MFC architecture #2 is also estimated by simulation. The driving cycle of EPA HDUDDS is selected for the comparative analysis as [20][20]. The vehicle velocity and power demand are presented in Figure 5.



(a) EPA HDUDDS driving profile

(b) Total power demand

Figure 5 *EPA HDUDDS driving cycle and power demand of FCET.*

EPA HDUDDS driving cycle lasts for 1030 s and the maximum driving speed is 94 km/h. EPA HDUDDS owns features as high dynamic and frequent start-stop. Another characteristic is that high power demand exists which is over 400kW. Hence, MFC system is really essential to cooperate with ESS to meet the power demand. The proposed MFC allocation strategy is compared with equi-distribution and Daisy chain. The global EMS is presented in Figure 6.

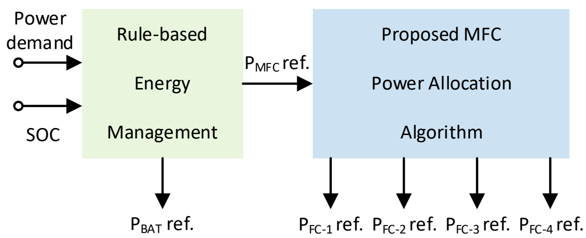


Figure 6 *A global EMS for MFC based powertrain.*

To be emphasized here, the purpose is to quantitatively compare the proposed MFC power allocation method with the other two approaches, thus, the Rule-based Energy Management strategy (REMS) are the same. The simulations results of battery pack power and SOC variations are presented in Figure 7. In the positive power demand range, battery pack supplies the dynamic power and helps control the variation rate of MFC system output power. In the negative zone, the regenerative energy is recycled by battery pack as much as possible. The initial SOC of battery pack is 0.8 while the SOC is around 0.9 at the end. The REMS helps control the battery pack's SOC to avoid over-charge or over-discharge.

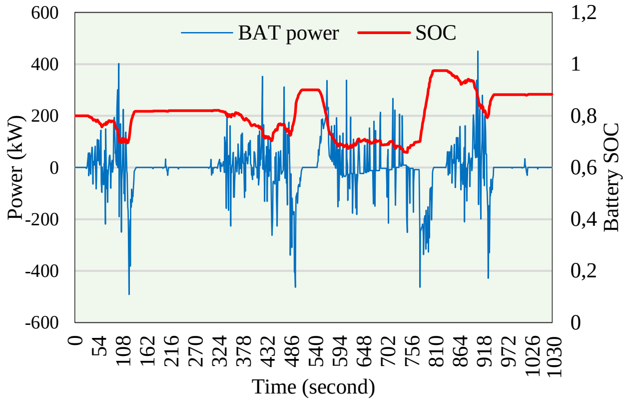
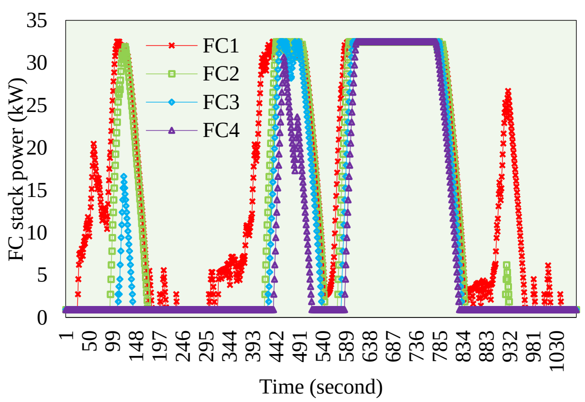
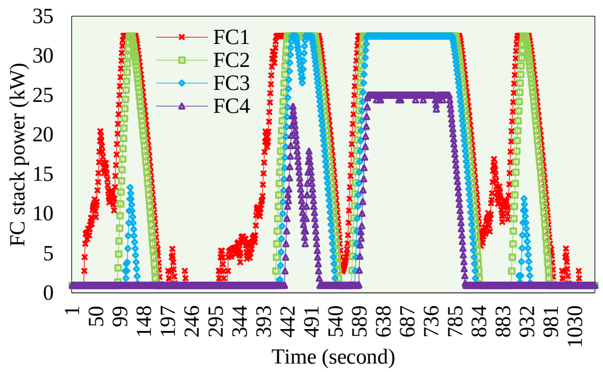


Figure 7 *Battery pack power and SOC variations based on rule-based EMS.*

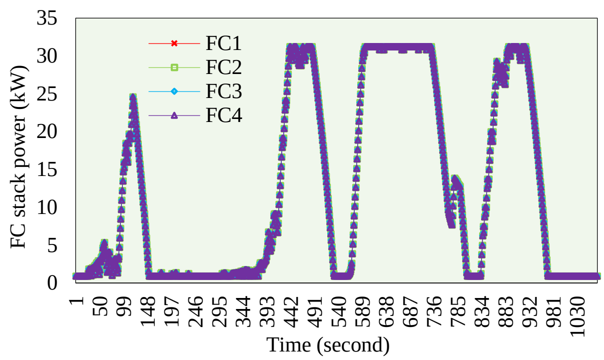
The results of MFC power allocation based on the proposed method, Daisy chain and equi-distribution are presented in Figure 8, separately. Power demand is assigned to FCs equally by equi-distribution as shown in Figure 8. (c). As analysed previously, MFC system efficiency is low based on this strategy. Daisy chain and the proposed method can improve the problem. However, there is still difference between the two strategies. Based on Daisy chain, when the power demand is higher than the nominal power of single FC stack, there is always FC(s) operating at the nominal power which is not belong to the high efficiency range. Therefore, MFC system efficiency is reduced. The proposed strategy assign power demand to MFC system and control the FCs operating in the high efficiency range.



(a) The proposed algorithm



(b) Daisy chain



(c) Equi-distribution

Figure 8 *MFC power allocation results based on different strategies.*

For the economy concern, the hydrogen consumptions are calculated and compared in Figure 9. MFC system based on the proposed power allocation strategy achieves the lowest hydrogen consumption while equi-distribution based one has the highest. Compared with equi-distribution and Daisy chain, the hydrogen consumption is reduced by 11.6% and 8.2% respectively based on the proposed strategy. In Daisy chain, although the hydrogen consumption of FC_4 is reduced, other threes consume more hydrogen, thus the total consumption is increased.

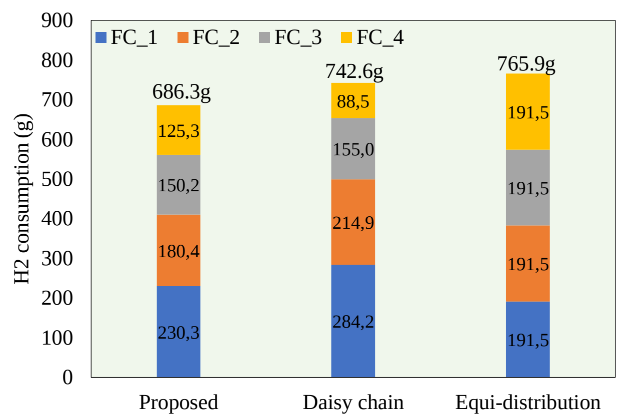


Figure 9 *Comparison of hydrogen consumption of MFC system based on different power allocation algorithms.*

Conclusion

This paper proposed a quantitative analysis of different MFC architectures versus the global efficiency and hydrogen economy in heavy-duty electric transportation. Since power demand reaches several hundred kilowatts in heavy-duty transportation, MFC architecture has proven to be a promising solution to meet power demand easily and efficiently. According to the investigation, MFC system based on parallel fluidic architecture and electrical architecture helps achieve higher net power. The proposed optimization strategy, which is a mix of equi-distribution and Daisy chain, is used to assign power demand among MFC system more efficiently. The efficiency is improved significantly especially in low power range and can help to improve fuel economy. Moreover, MFC system is also promising to be applied in stationary applications such as backup power system of datacenter to realize decarbonization. Further research should be performed on EMS development with consideration of fuel cell degradation impact for MFC system applications.

References

[1] IEA, 2022, "Data and statistics: Explore energy data by category, indicator, country or region." IEA. [Online]. Available: https://www.iea.org/data-and-statistics/data-browser?country=WORLD&fuel=CO2%20emissions&indicator=CO2BySector.

[2] Çabukoglu, E., Georges, G., Küng, L., Pareschi, G., & Boulouchos, K. (2019). Fuel cell electric vehicles: An option to decarbonize heavy-duty transport? Results from a Swiss case-study. *Transportation Research Part D: Transport and Environment*, 70, 35-48. DOI: 10.1016/j.trd.2019.03.004.

[3] N. Marx, L. Boulon, F. Gustin, D. Hissel, K. Agbossou, "A review of multi-stack and modular fuel cell systems: Interests, application areas and on-going research activities", *International Journal of Hydrogen Energy*, vol. 39, no. 23, pp. 12101-12111, 2014. Doi: org/10.1016/j.ijhydene.2014.05.187.

[4] Soltani, A. K., Kandidayeni, M., Boulon, L., & St-Pierre, D. L. (2019). Modular energy systems in vehicular applications. *Energy Procedia*, 162, 14-23. DOI: 10.1016/j.egypro.2019.04.003.

[5] J. Solano, D. Hissel, M. C. Pera, "Fail-safe power for hybrid electric vehicles: Implementing a self-sustained global energy management system", *IEEE Vehicular Technology Magazine*, vol. 13, no. 2, pp. 34-39, 2018. Doi: 10.1109/MVT.2017.2776670.

[6] Marx, N., Cárdenas, D. C. T., Boulon, L., Gustin, F., & Hissel, D. (2016). Degraded mode operation of multi-stack fuel cell systems. *IET Electrical Systems in Transportation*, 6(1), 3-11. DOI: 10.1049/iet-est.2015.0012.

[7] Han, Y., Li, Q., Wang, T., Chen, W., & Ma, L. (2017). Multisource coordination energy management strategy based on SOC consensus for a PEMFC–battery–supercapacitor hybrid tramway. *IEEE Transactions on Vehicular Technology*, 67(1), 296-305. DOI: 10.1109/TVT.2017.2747135.

[8] Rudolf, T., Schürmann, T., Schwab, S., & Hohmann, S. (2021). Toward Holistic Energy Management Strategies for Fuel Cell Hybrid Electric Vehicles in Heavy-Duty Applications. *Proceedings of the IEEE*, 109(6), 1094-1114. DOI: 10.1109/JPROC.2021.3055136.

[9] Walters M., Sehr A., Dirkes S. (2021) Fuel Cell Systems for Rail Applications: Development Trends and Challenges. In: *Liebl J. (eds) Der Antrieb von morgen 2020. Proceedings. Springer Vieweg*, Wiesbaden. DOI: 10.1007/978-3-658-35294-3_17.

[10] PESA Bydgoszcz SA, 2022, "Railway premiere of the year – PESA presented the hydrogen locomotive at TRAKO.", PESA. [Online]. Available: https://pesa.pl/en/railway-premiere-of-the-year-pesa-presented-the-hydrogen-locomotive-at-trako/.

[11] FuelCellWorks, 2021, "Hyundai Commercial FCEVs: From Garbage Trucks To Tractor-Trailers", FuelCellWorks. [Online]. Available: https://fuelcellsworks.com/news/hyundai-commercial-fcevs-from-garbage-trucks-to-tractor-trailers/.

[12] Toyota Motor Corporation, 2021, "Toyota Moves Closer to Production with Next Generation Fuel Cell Electric Technology for Zero-Emissions Heavy Duty Trucks", Toyota Motor Corporation, [Online]. Available: https://global.toyota/en/newsroom/corporate/34464066.html.

[13] A. Pohjoranta, J. Ihonen, F. Tommola, U. Hannesen, M. Kajava, F. Turcer, J. Pajala. "A fuel cell power unit and hydrogen storage for the research vessel Aranda", In 8th Transport Research Arena, TRA 2020-Conference cancelled. Helsinki, Finland. 2020. [Online]. Available: https://cris.vtt.fi/ws/portalfiles/portal/33907180/MARANDA_TRA2020_HydrogenFuelCellPowerSystemForAranda_CLEAN_2019_10_18.pdf.

[14] Wang, Q., Li, J., Bu, Y., Xu, L., Ding, Y., Hu, Z., Liu, R., Xu, Y., Qin, Z. (2020). Technical assessment and feasibility validation of liquid hydrogen storage and supply system for heavy-duty fuel cell truck. In *2020 4th CAA International Conference on Vehicular Control and Intelligence (CVCI)* (pp. 555-560). IEEE. DOI: 10.1109/CVCI51460.2020.9338639.

[15] Han, X., Li, F., Zhang, T., Zhang, T., & Song, K. (2017). Economic energy management strategy design and simulation for a dual-stack fuel cell electric vehicle. *International Journal of Hydrogen Energy*, 42(16), 11584-11595. DOI: 10.1016/j.ijhydene.2017.01.085.

[16] Yan, Y., Li, Q., Chen, W., Huang, W., Liu, J., & Liu, J. (2020). Online Control & Power Coordination Method for Multi-stack Fuel Cells System Based on Optimal Power Allocation. *IEEE Transactions on Industrial Electronics (Early Access)*. DOI: 10.1109/TIE.2020.3016240.

[17] Marx, N., Hissel, D., Gustin, F., Boulon, L., & Agbossou, K. (2017). On the sizing and energy management of an hybrid multistack fuel cell–Battery system for automotive applications. *International Journal of Hydrogen Energy*, 42(2), 1518-1526. DOI: 10.1016/j.ijhydene.2016.06.111.

[18] Fernandez, A. M., Kandidayeni, M., Boulon, L., & Chaoui, H. (2019). An adaptive state machine based energy management strategy for a multi-stack fuel cell hybrid electric vehicle. *IEEE Transactions on Vehicular Technology*, 69(1), 220-234. DOI: 10.1109/TVT.2019.2950558.

[19] Khalatbarisoltani, A., Kandidayeni, M., Boulon, L., & Hu, X. (2020). Power allocation strategy based on decentralized convex optimization in modular fuel cell systems for vehicular applications. *IEEE Transactions on Vehicular Technology*, 69(12), 14563-14574. DOI: 10.1109/TVT.2020.3028089.

[20] Kammuang-Lue, N., & Boonjun, J. (2021). Energy consumption of battery electric bus simulated from international driving cycles compared to real-world driving cycle in Chiang Mai. *Energy Reports*, 7, 344-349. DOI: 10.1016/j.egyr.2021.07.016.

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Short bio (75 - 100 words) per author