FINAL REPORT

NETWORK-H2

CALL 2 - OPEN

PROJECT DETAILS

Grant number

NH2-007

Award holding organisation

Organisation	University of Birmingham University of Liverpool

Title of research project

Development of a smart hybrid system with advanced hydrogen refuelling logistics for railway applications

Investigators

Role	Name	Organisation
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Final Project Report

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I. Introduction

The world has committed to move towards a low-carbon economy [1]. The primary measure to achieve that is through electrifying more the transport sector by encouraging the electrification of railway lines along with the adoption of road electric vehicles (EVs) since the transportation sector is the major emitter of greenhouse gas (GHG) and the level of release of harmful gases nearly unchanged at level of 1990s [2]. Fuel hydrogen cells (FHC) have been presented as great candidate to replace other powertrain technologies in the electrification of the rail transportation. They offer reduced or zero emission options for rail transportation in various applications currently powered with diesel engines or liquefied natural gas (LNG) powered trains [3]. However, the traction demands of the railway network are characterized by their rapid variations depending on the trains' operational conditions and timetables. Consequently, FHC cannot respond appropriately to such tractions' fast load transients due to their slow internal electrochemical and thermodynamic responses. Alternatively, they can be integrated with energy storage device with fast dynamics such as Li-ion battery cells (LiBC) to form a hybrid power source for traction systems. Accordingly, this project proposes a development of a new smart integrated power source of FHC and LiBC to supply dual three-phase machines for driving the trains in railway networks. Moreover, it presents novel and transformative approaches towards establish a Hydrogen (H_2) refuelling system for such railways' vehicles which are supplied by the integrated power source of FHC and LiBC.

II. Work Plan

The project work plan is illustrated in Table 1, in which the project is established and developed through these three successive work packages:

- WP2 Requirements elicitation
  Systems engineering is used to develop a process for requirements capture given the university of Birmingham's excellent industrial links with the railway and hydrogen sectors. Accordingly, a number of railway case studies are investigated, and the best railway line is nominated through selection criteria for the implementation of the new smart drive traction system. This work package is discussed in Section III of this report.
- WP3 HIL development and validation for the new drive traction system
  Hardware-in-the loop (HIL) procedure is implemented for the new drive traction system where the models for the proposed new drive system are developed in the Typhoon HIL404 equipment. Section IV demonstrates this work package.
- WP4 Concept design for H_2 refuelling station and operation optimization
  The concept design for hydrogen (H_2) refuelling station will be a desktop study, where the outputs are provided in Section V to articulate the overall design of a H_2 refuelling system. Furthermore, Section VI presents an operation optimization analysis to reduce the overall hydrogen consumption with the same journey time spent using Particle Swarm Optimisation approach.

On the other hand, WP1 is for the project management, which is delivered by the project principal investigator and the co-investigators. Finally, WP5 which involves engagement activities with the Network-H2 for the hydrogen transportation as well as a new journal paper, based on the research outcomes, will be submitted to Hydrogen Fuelled Transportation, Forthcoming Special Issues, International Journal of Hydrogen Energy.

Table I Project Work Plan

WP / Task	M1	M2	M3	M4	M5	M6
WP1 Project management	■	■	■	■	■	■
WP2 Requirements elicitation	■	■				
WP3 HIL development and validation for the new drive traction system		■	■	■	■	
WP4 Concept design for H_2 refuelling station and operation optimization		■	■	■	■	
WP5: Engagement and dissemination	■	■	■	■	■	■

III. Requirements’ elicitation and Line selection

This phase of the project consists of the following stages:

- Route Suggestion
  At first, routes are suggested. These will depend on the type of train that is proposed; certain types will be more appropriate for slower branch lines, whereas others might be more suitable for faster main line use. In this case, given the limited acceleration capabilities of the train, branch line routes are preferred.
- Operational Assessment
  The operational considerations around the route are investigated, including frequency of services, expected operating hours, alternative routes which rolling stock is expected to cover, etc.
- Data Gathering
  Data must be gathered on both route and train in order to feed into the simulation phase.
- Simulation
  A modified version of the University of Birmingham’s Single Train Simulator was used; this models the fuel cell stack and battery as two basic power sources, using basic physical modelling of efficiency.
- Selection
  The decision between the routes is achieved by using a weighted scoring system (from 1 to 5), based on rating the routes against:
  - Hydrogen consumption (HC), where the lower consumption is better and it is the most important factor, i.e. it has the largest weight.
  - Operational factors (OF), where the fewer complex operations are better
  - Number of units required (NU), where the more units are better and it is the least important factor, i.e. it has the lowest weight.

  Therefore, the weighted scoring formula becomes as follows:

$$Overall\ Score = 3HC + 2OF + NU \tag{1}$$

The following routes are suggested in this project

- The St Ives branch is a 6.7 km long branch line in the southwest of the UK and is operated by a single unit or pair of units, assumed to be making approximately 24 round trips per day, in addition to a short empty stock or passenger move from the depot at Penzance [4]. Trains call at 3 stations between the terminals.
- The Heart of Wales line is a longer (but still low speed) route between Llanelli in Wales and Craven Arms in England. Trains call at 28 stations between the terminals, and the line may be operated with a pair of units.
- The Wherry lines are a small network of rural lines in the east of the UK, extending from Norwich to various seaside towns in East Anglia. In this case, the lines to Sheringham (via Cromer, a total of 8 intermediate stops) and Great Yarmouth (via Acle, a total of 4 intermediate stops) were simulated
- The Falmouth branch is an 18.8 km long branch line in the southwest of the UK, running from the mainline at Truro to Falmouth Docks, via 4 intermediate stations. There are, according to the timetable [5], two units required.
- The Newquay branch is a 33.3 km long branch line in the southwest of the UK, running from the mainline at Par via 5 intermediate stations. The timetable [5] suggests that only one unit is required.

In each case, one round trip was simulated. The scores for these routes were compared, as given in Table 2, and the highest score, based on the criteria listed above, was by the St Ives branch. Therefore, this branch is the chosen route.

Table 2 routes scores on the selection criteria

Route	**Score**
St Ives Branch	24
Heart of Wales Line	20
Wherry Lines	17
Falmouth Branch	20
Newquay Branch	21
Best	**St Ives Branch**

Several alternative scenarios were compiled in order to test the validity of this approach, including the following:

- Giving each of the criteria equal weighting.
- Giving stronger priority to operational considerations.
- Giving stronger priority to the number of units.

While in some of these scenarios, the Wherry Lines appeared to be a better choice, the St Ives branch performs well in most of the analyses, as well as in the original analysis. Therefore, the St Ives branch is considered henceforth.

IV. HIL development and validation

A new traction drive system design is demonstrated in this section for hybrid FHC and LiBC in order to meet both decarbonisation criteria and user expectations. Proposed traction scheme is shown in Fig.1 where each windings sets are fed from individual energy sources via three phase voltage source inverters. The modularity of the system increases, and size along with the cost of the traction module decrease by removal of DC/DC converters. The values for the utilized system parameters are given in Appendix A

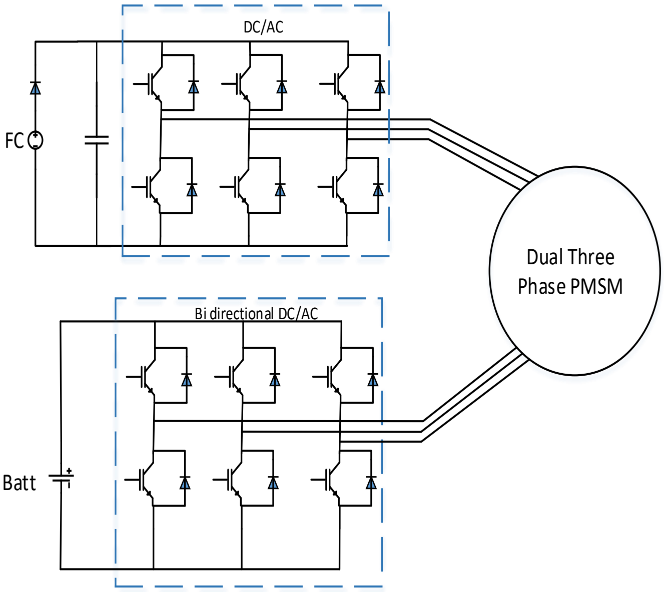

Fig. 1 The new hybrid traction drive unit

The dynamic analysis of the dual three phases permanent magnet synchronous motor (DTPMSM) has been investigated in [6] to provide smooth torque transition, higher torque density, fault tolerant operation and acts as a voltage regulator to have a smooth voltage on behalf of DC-link which existed in traditional traction system. Additionally, a power sharing algorithm has been implemented to distribute the power demand over the two power sources based on the state of charge (SOC) of the (LiBC) as well as the train operational mode. A single train simulator (STS) is used to find the average power requirement of the train. Thus, the FHC is designed for such average power and the LiBC is accordingly designed for the peak power demand and energy recuperation. Furthermore, the proposed system has two constrains to protect the LiBC overcharging (by limit its SOC to be $\leq$ 80%) as well as to protect the LiBC depletion (by limit its SOC to be $\geq$ 20%). Consequently, these two constrains are defining the activation/deactivation of the charging/discharging modes of the LiBC in which during the charging mode, the FHC is solely providing the power to drive the train as well as charge the LiBC, while in discharging mode both FHC and LiBC are both supplying the train based on its power demand. The new hybrid traction unit is implemented for train line of the St. Erth -St. Ives branch. The proposed power sharing algorithm is explained as follows:

1. During the train acceleration, both FHC and LiBC are directed to supply power to the train based on its demand. However, if train demand is less than the FHC power, the rest of the FHC power is then used to charge the LiBC.
    i. If SOC of the LiBC becomes 20% or less, the FHC will provide its maximum power to charge the LiBC and drive the train (but with lower speed).
    ii. If SOC of the LiBC becomes 80% or more, the FHC will only drive the train and not charge the LiBC.
2. When the train is cruising, there is not much power demand required from the train, so the FHC is used to drive the train and charge the LiBC if its SOC < 80%.
3. Finally, during the deceleration/braking mode of the train, the regenerative braking power will charge the LiBC given that its SOC < 80%.

The new hybrid traction system along with its proposed power sharing algorithm is implemented in HIL environment using Typhoon HIL 404 platform for the selected train line of the St. Erth -St. Ives branch. The real-time simulation results are presented in Fig. 2. The driving cycle of the specific route is illustrated in Fig.2-a) where train starts from St. Erth to St. Ives and back to the St. Erth again. The electromechanical torque (T_{el}) is following the resistance torque (T_r) as shown in Fig.2-b) which are depending on gradient of the track as illustrated in Fig.2-i) respectively. Fig. 2-c) shows the quadrant current (i_{q1}) of the first winding of the DTPMSM which is fed from FHC. Similarly for Fig. 2-d) which represents the quadrant current (i_{q2}) of the second winding which is supplied by LiBC. From these two figures it is shown that both i_{q1} and i_{q2} are following their reference values i_{qref1} and i_{qref2} respectively based on the proposed power sharing algorithm. The total i_{qref} (i_{qref1}+i_{qref2}) is illustrated in Fig.2-e).

The FHC current is supplied based on the i_{q1} as illustrated in Fig.2-h). Besides, the LiBC current and SOC, (Fig.2-k, and f respectively) are depending on i_{q2} according to the acceleration and deceleration operational mode of the train. At last, the whole driving cycle is covered in 13.4 km within 24 minutes as given in Fig. 2-g.

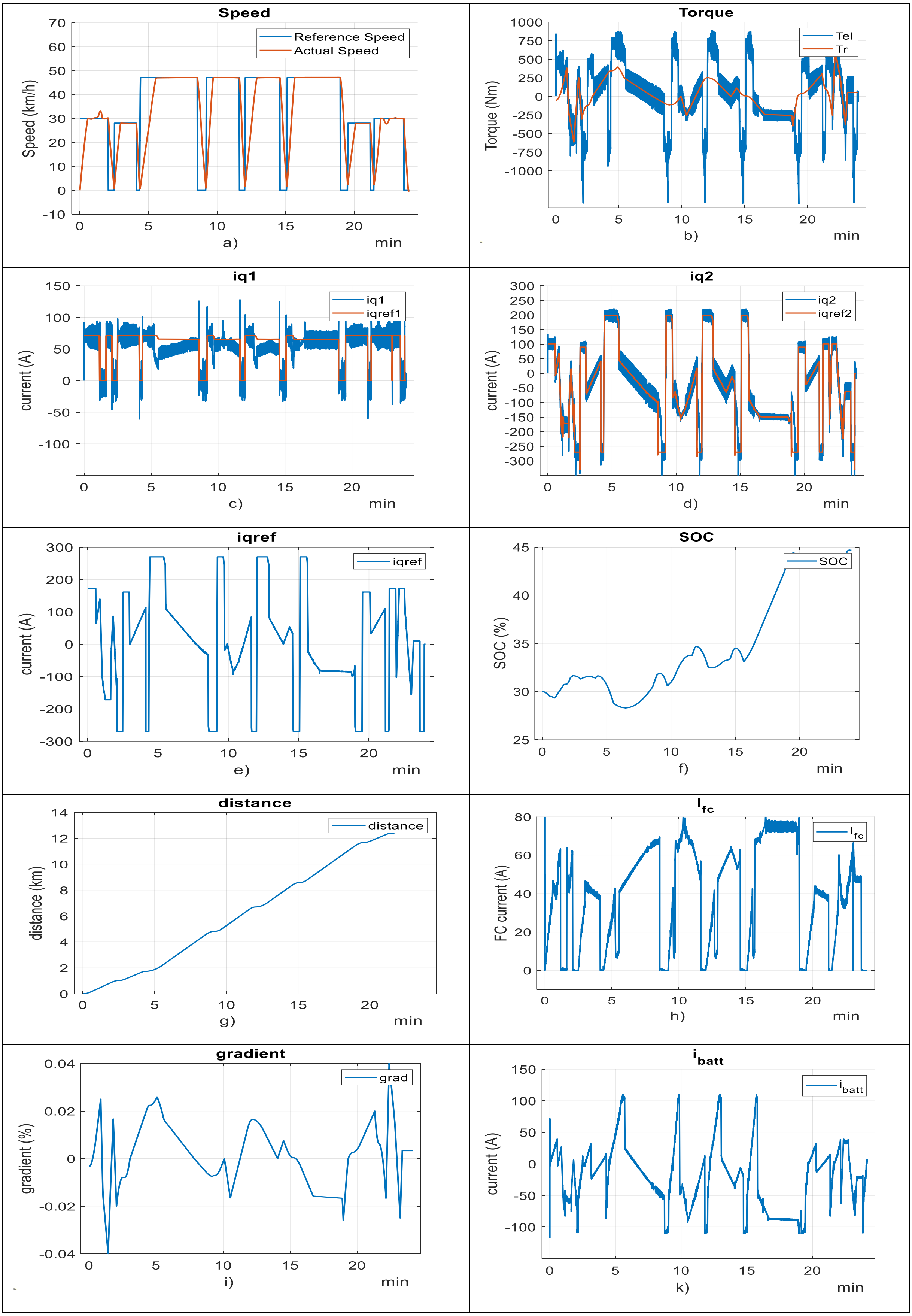

Fig. 2 the Simulation Model Outputs for the Selected Route

V. Concept design for H_2 refuelling station

The methodology used in this part of the project includes the following principal stages:

- Site selection
  This follows a similar pattern to that used in section II., giving several plausible sites, and evaluating them against several criteria using a weighted scoring system, before coming to a final selection.
- Equipment requirements
  This section considers the specification of equipment to be fitted to the site and discusses some of the key aspects.

Regarding the site, the suggested sites were rated against the following criteria:

- Land area available, where the more area is better since it allows more hydrogen to be stored and it is the most important factor.
- Empty Coaching Stock moves requirement, where the shorter distance is better as the train travels to the depot, it runs the risk of disrupting more trains and using up more hydrogen.
- Other rolling stock requirement, where the less stocks are better as fewer mistakes are likely to be made if there is a single type of rolling stock required.

The suggested sites for a hydrogen train depot in the selected train line of the St. Erth -St. Ives branch, Fig. 3, are as follows:

- St Erth, Fig.4-a), at the mainline end of the branch. This has a patch of available ground which might be suitable.
- St Ives, Fig.4-b), at the other end of the branch. No large available sites were found at this location.
- Penzance, Fig.4-c). This location is not situated on the branch, but the mainline to the south does lead to it. In this case the obvious solution is to make use of part of the existing train depot.

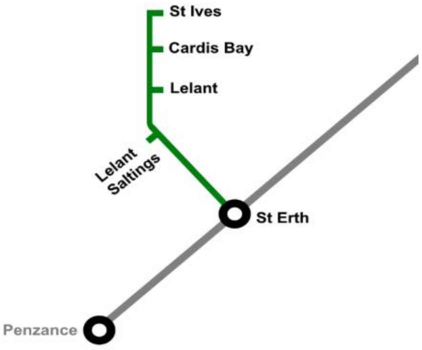

Fig. 3 St. Erth -St. Ives branch

(a) (b) (c)

Fig. 4 suggested sites for a hydrogen train depot

As a result of the analysis, the St Erth site was identified as the most suitable. In order to test the selection approach, the following alternative scenarios were explored:

- Lower importance of land (e.g. the equipment takes up less space than anticipated; therefore the importance of land is lower).
- Other rolling stock desirable (e.g. an operator might find it desirable to have all their rolling stock maintained in the same location).
- Equal weighting of factors.
- Equal weighting of factors, with other rolling stock preferable.

In this case, the choice is between the St Erth and Penzance sites, as depending on the analysis, either solution could be considered preferable; ultimately this decision would have to be taken by the operator.

With respect to the equipment requirements, the first issue for any depot is whether hydrogen should be delivered or produced on site. Although, there are locations where delivery of hydrogen might be organised (for example the trial area in [7], with the required production sites and reasonable delivery mechanisms, these are extremely limited in the UK, especially in the southwest where the St Ives branch is located. Therefore (and considering the high purity of hydrogen required, and the desirability of low or zero emission production) it is recommended to produce hydrogen on-site using water electrolysis.

Since hydrogen is not a very energy dense fuel compared to diesel [8], it must be compressed to make the on-train storage small enough to be practical; therefore, another choice to be made is refuelling methods, for which there are two basic options:

- “Decant” filling; that is, boosting the pressure in the refueller to greater than that in the train; this results in a fast fill but requires a large amount of compression effort before filling.
- “Compression” filling; that is, compressing hydrogen directly into the train

In either case, a compressor must be selected; there are several options for this [9-10]. Besides, high pressure storage is required for the decant method and the size of this must be ascertained; this is achieved by looking at existing equipment.

Dispensing equipment is then analysed, showing the various options for fuelling times. Since hydrogen is being transferred (the maximum automotive rate is 3.6 kg/min according to [11]), a chiller unit would be required in certain methods to avoid high temperatures. Suitable units are already available [12-13]. However, experience on the HydroFLEX project [14] suggests that true refuelling rates decrease as the pressure difference decreases, so this may have to be monitored.

Accordingly, based on the aforementioned discussions, the concept layout design for H_2 refuelling station is developed as shown in Fig.5, consulting also work performed on hydrogen-powered buses [15-16], and for traditional railway depots [17-18]. The proposed layout consists of six successive stages as follows:

1- Production stage using the water electrolysis units
2- Then, Compressor unit to store the produced H_2 at high pressure for fast refuelling procedure.
3- The high pressurized H_2 will be then stored in stage 3
4- Chilling and dispensing processes are required as mentioned before, since during refuelling the H_2 into the train its temperature rises with its high pressure.
5- Serving stage is used for other maintenance purposes or replacement of any consumables.
6- Finally, stabling or parking the train if it is not at use.

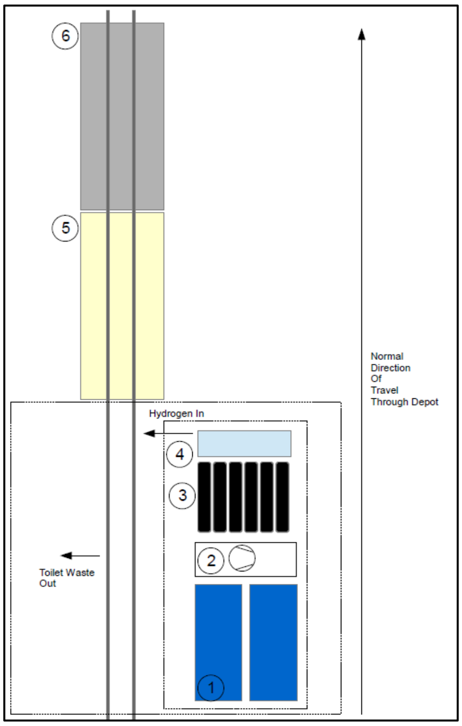

Fig.5 Schematic of proposed layout for H_2 refuelling station at St Erth.

VI. Optimization Analysis

This section provides the optimisation analysis for the hydrogen fuel cell train. This optimisation aims to reduce the overall hydrogen consumption with the same journey time spent. The validation considers the hydrogen consumption and the actual journey time which are evaluated through a dynamic train simulator. An optimisation algorithm called Particle Swarm Optimisation (PSO) is employed in this project. This optimisation can generate new variables to find the optimal solution. The optimization objective function includes the hydrogen consumption in kilograms ($Weight_{hydrogen}$) and the actual journey time difference. Hydrogen consumption is used in two parts, one is consumed by fuel cells during train operation, and another is for compensating the battery energy consumption. In some scenarios, the battery discharges more energy than they charge by regenerative braking, so the fuel cell needs to consume additional hydrogen to charge the battery to its start state after it stops. The optimization objective function is as follows, where W is the importance of the time factor:

$$f = Weight_{hydrogen} + W \times (Time_{actual} - Time_{target}) \tag{2}$$

The optimisation algorithm through the PSO is illustrated in Fig. 6, in which the variables are updated according to the group history best value variables and its individual best value variables. The variables are usually updated to optimal variables by the guild of group best variables and individual best variables.

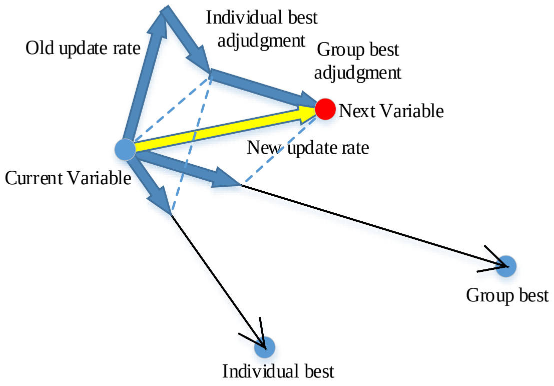

Fig. 6 PSO variables updating

To control trains' performance smartly, the speed profile is optimised. Each of the speed profiles between adjacent stations is independent. Besides, the speed profile includes not only maximum speed but also the coasting speed. The test route is from St. Erth to the St. Ives branch. There are five stations in total located on this route. The total length of the route is 6.7 km and 13.4 km if considering returning. The train's maximum speed is 80 km/h, whereas the line speed limit is 48 km/h. In this case, the benchmark train operation curve is shown in the top of Fig. 7. After considering the energy-saving probability, the accepted maximum speed top limit is increased from 48 km/h to 60 km/h. Besides, the coasting stage is applied to train operation. After the optimisation, the optimal variables are shown in Table 3. Additionally, the smart controlling train performance curve is shown in the bottom of Fig 7. The coasting speed equals the maximum speed if no coasting is required between two stations.

Table 3 Optimised speed profile

Start station	St Erth	Lelant Saltings	Lelant	Cardis Bay	St Ives	Cardis Bay	Lelant	Lelant Saltings
End station	Lelant Saltings	Lelant	Cardis Bay	St Ives	Cardis Bay	Lelant	Lelant Saltings	St Erth
Maximum speed	54.3	38.7	54.3	46.8	54.3	54.3	45.8	54.3
Coasting speed	46.8	38.7	41.5	46.8	25.6	54.3	33.2	36.4

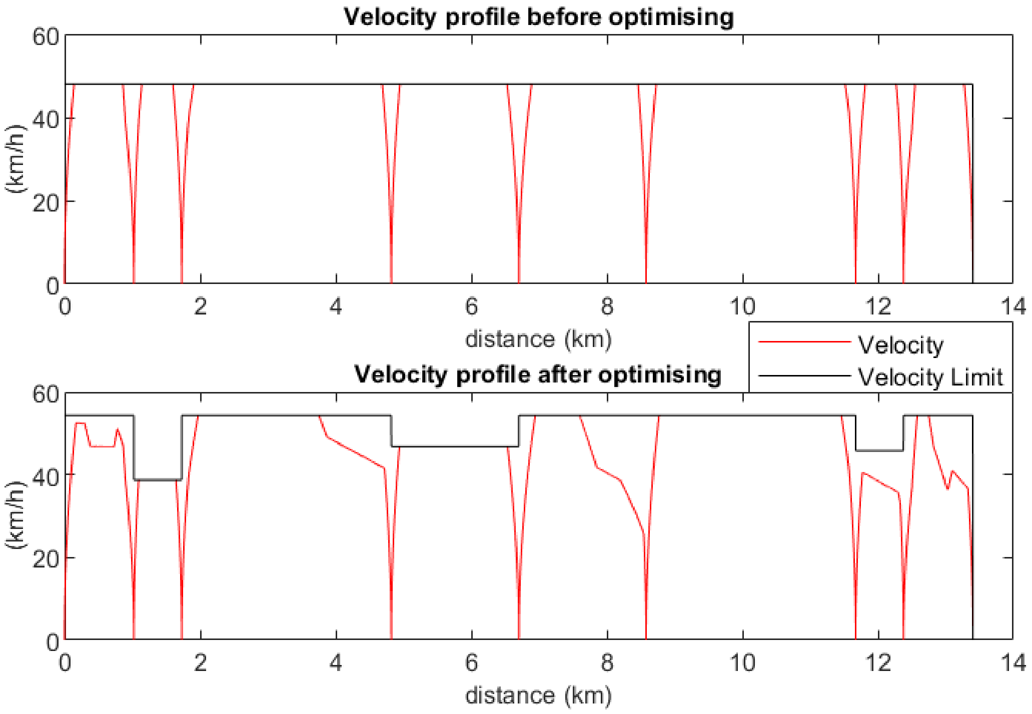

Fig. 7 Train performance plot before and after optimising

From the view of hydrogen consumption each day, the overall hydrogen consumption is reduced by 9.6%, from 55kg to 49.7 kg, by optimising the speed profile. Table 4 shows the hydrogen energy consumption between any two adjacent stations. Almost all the hydrogen fuel cell energy consumption is reduced, but it raised a little bit from Cardis Bay to Lelant by 14.9%. Moreover, the table shows that more hydrogen is needed to recharge the battery after the train stop. The battery's total capacity is 260 kWh, and the additional battery energy cost in battery side is 2 kWh, which is less than 1% of the total battery capacity. Hence, the battery SOC change is still acceptable.

Table 4 Energy usage of each return

Start station	End station	Hydrogen energy cost	
		Before optimising	After optimising
St Erth	Lelant Saltings	5.37	3.94 (-26.7%)
Lelant Saltings	Lelant	3.66	2.77 (-24.5%)
Lelant	Cardis Bay	24.91	23.36 (-6.2%)
Cardis Bay	St Ives	3.78	3.67 (-3.0%)
St Ives	Cardis Bay	15.95	12.54 (-21.4%)
Cardis Bay	Lelant	4.94	5.68 (14.9%)
Lelant	Lelant Saltings	4.32	2.93 (-32.2%)
Lelant Saltings	St Erth	10.02	6.97 (-30.4%)
Total (kWh)		72.96	61.85 (-15.2%)
Battery charging by a fuel cell (kWh)		4.02	7.76 (+92.9%)
Overall energy consumption (kWh)		76.98	69.61 (-9.6%)
Total hydrogen weight (kg)		2.29	2.07 (-9.6%)

VII. Conclusions and Future work

This project develops a new smart hybrid power source of FHC and LiBC to supply dual three-phase machines for driving the trains in light railway networks. Firstly, a number of railway case studies are chosen to implement the proposed smart drive traction system. For each case study, the train and route data are introduced to single train simulator. Accordingly, the most suitable railway line is then nominated through selection criteria for the implementation of the new smart drive traction system in HIL platform. After that, an analysis is carried out to select the site location for the proposed hydrogen refuelling station, Then, the equipment for the refuelling station is then discussed and investigated. Finally, optimization analysis is carried out to reduce the overall hydrogen consumption with the same journey time spent using PSO approach.

With respect to the new developed hybrid traction system, the removal of DC/DC converter and integration of DTPMSM is added up the control complexity for independently fed power supply. Nevertheless, it includes more advantages as the new configuration is going to be more compact and promising to implement catenary free FHC and LiBC powered hybrid trains compare to the traditional ones. Moreover, the torque density of the traction motor is higher, and size of the power converter unit reduces by the involvement of the new traction scheme.

As a next step, T-type neutral point clamped (NPC) converter unit would be considered to replace the voltage source inverters. As a result, the feature of fault tolerant of the machine is achieved. This enables to disconnect the faulted part of the traction system which might be the DC power supply or faulted winding by using converter switches.

On the other hand, for the H_2 refuelling station, the anticipated location for the station site at St Erth is the preferable one, based on the selection criteria of land area, necessary ECS moves, and other rolling stock requirements. Furthermore, the production of the hydrogen on site is also the desirable approach, ideally using a containerised solution. Besides, the decant method of refuelling is more appropriate for this context and only one train will need to use the refueller; thus low pressure “buffer” storage is considered unnecessary. For future work, number of processes have to be carried out in order to determine the exact arrangements necessary for designing the H_2 refuelling station. Processes such as rolling stock design, specifically the positions and type of connections for hydrogen fuelling and toilet waste removal, as well as a study of each of the components of the system, and selection of the optimal candidates.

Lastly for the implemented optimization case study, the hydrogen consumption has obviously reduced after applying the optimal speed profile. The maximum speed during the whole trip is changed from 48 km/h to 54.3 km/h. However, between the station of Lelant and Lelant Saltings, the maximum speed is reduced no matter which direction the train is operating. Although there is one hydrogen energy consumption increased, and it needs additional hydrogen to charge the battery, the total required hydrogen weight is reduced. With the reduction of hydrogen requirement, the train can install fewer hydrogen tanks compared with the benchmark design. Especially for the low energy density like hydrogen, the volume saving would be more obvious than other fuel trains, such as diesel trains. Therefore, the saved space can be designed for other functional facilities, such as passenger seats and luggage racks.

VIII. Appendix

The Table below provides the values for the system parameters for the HIL development and validation.

Motor Rated Speed (RPM)	1500
Train Maximum Allowed Speed (km/h)	48
Rated Torque (Nm)	750
Rated Power of Fuel Cell (kW)	30
Rated Power of Battery (kW)	90
Nominal Voltage (V)	359
Nominal Current (V)	191
Stator Phase Resistance (Ω)	0.0088
Ld and Lq Inductances (H)	0.005175
Md and Mq Inductances (H)	0.002691
Motor Moment of Inertia ($kg.m^2$)	150.135
FC / Average Power of Train (kW)	20
Train mass-m (tone)	150
Gear ratio -G	6
Wheel radius-r (m)	0.5
Length of the branch line (km)	6.7

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