A3/B3 Colloquium 2023
PS No. Description – PS1/B3

Paper No: 108

Study on Zero Emission Hydrogen-powered Backup Generator for Substations

Prem RANJAN[1*], Timothy HUGHES, Ibrahim IDDRISSU,
Sean COLEMAN, Theo ELMER[2]

[1]Deeside Centre for Innovation, National Grid plc,
Kelsterton Road, Connah's Quay, CH5 4BP, UK

[2]GeoPura Ltd., Wysall, Nottinghamshire, NG12 5QT, UK
***prem.ranjan@nationalgrid.com**

SUMMARY

Powering substations, home and business sites with backup diesel generators contribute to the emission of greenhouse and toxic gases including CO_2, NOx and particulates leading to restricted usage. Currently, National Grid uses diesel generators and batteries to provide backup power to a substation to supply LVAC loads enabling it to continue to perform its crucial role in the electricity transmission system in the event of primary power loss. These backup diesel generators if replaced by alternatives with a low carbon footprint, can avoid harmful environmental emissions. This work investigates the feasibility of using a Hydrogen Power Unit (HPU) as a zero-emission alternative. HPU (400 V_{AC}, 250 kVA, 216 kWh battery) converts hydrogen to electrical power via a fuel cell system - a zero emission process, only by-products are water and heat. HPU is tested with varying loads and durations in 10-weeks trial, including 1-week test for efficiency and reliability. HPU responds well to the large changes in demand as well as to load rejection and the power output is within the tolerances specified by standards. Electrical tests and emission savings calculations suggest that the HPU integrated with hydrogen management on substations can be a viable alternative zero-emission backup generator.

KEYWORDS

Substations, zero emission, hydrogen energy, backup generator

1 Introduction

Backup power plays an important role in uninterrupted power supply to the work sites. This is true in case of home – residents use uninterruptible power supply (UPS) for the installed electrical equipment. For large workplace with higher demand, backup generators are used for continuous supply of power. This is very important for the critical sites, e.g. hospitals, live-filming locations, construction sites etc. For National Grid Electricity Transmission (NGET), low voltage AC (LVAC) power is required to power the loads at substations which are critical operation sites. The load comprises of cooling fans, pumps, and lighting etc. Continuous power to these loads is crucial to enable the safe operation of substations and subsequently the electricity transmission system.

The LVAC supply board, needed for normal site operation, which powers the essential and non-essential services at substation is connected to the local distribution network operator (DNO) 11 kV network through a 11 kV_{AC} / 415 V_{AC} transformer. A backup generator (415 V_{AC}) is connected to the LVAC board as shown in Figure 1 which powers the connected load in case of power loss from the DNO. NGET uses more than 300 diesel generators across the substations in UK to provide the backup power in case of primary power loss from DNOs. It is expected that the connected diesel generators provide power to the essential and non-essential loads until the supply restoration. Technical Specification (TS) of NGET mandates to store 72 or 168 hours of fuel to run the generators on full load. This is important when the paper discusses about the alternatives to diesel fuel operated generators later.

Figure 1: Schematic of connection to LVAC board at Deeside Centre for Innovation; connections are at the back of the board at indicated arrows, DNO incomer indicates the 415 V_{AC} connection through the step-down transformer

These diesel generators are known to emit different greenhouse and toxic gases. The emissions include carbon dioxide (CO_2), nitrous oxides (NO_x), carbon monoxide (CO) and particulate matters (PM). These emissions are detrimental to environment which prohibits the usage of diesel generators at different sites. There are different alternatives which are more sustainable in long run are explored by different researchers/organizations [1-3]. Alternatives can be basically divided into three groups as (A) Alternative to diesel fuel with low carbon emission, (B) Fuel cell technology and (C) Energy storage.

Group A consists of different liquid fuels which can be a replacement of diesel in the existing generator fleet or different gas fuels which can be combusted in new generators or renovated existing generators. Liquid fuels include the hydrotreated vegetable oil (HVO), biodiesel, synthetic diesel which are candidates with lower emissions compared to the traditional diesel ones. Gas fuel concept includes using natural gas, propane, biomethane, ammonia and hydrogen. These gases can be combusted or used in different process such as fuel cells. Group B comprises of generating electricity using fuel cells.

Fuel cells can provide the heat and electricity if there is a supply of fuel [4] but can't store energy. These are sustainable and provide very low to zero emissions compared to the combustion engines like diesel. There are different types of fuel cells [5], proton exchange membrane (PEM) or polymer electrolyte membrane fuel cell provides high power density and one of the mostly used. PEM fuel cell works on the principle of exothermic reaction between protons (H^+), electrons (e^-) and oxygen to form water.

Unlike fuel cell, group C consists of devices storing energy. Here one can store energy and use as per the requirement at any instant of time. Most common energy storage device used at a substation is batteries. This is a good solution for the lower load sites where the low energy is required for shorter span. For large power requirement with 72 to 168 hours energy storage, maintaining batteries bank is cumbersome but it is good for short time power supply. The tested HPU uses this and have a battery bank to supply the sudden increase in load. It is based on PEM fuel cell (group B) utilizing hydrogen as a fuel (group A) with battery bank (group C), making it a combination of all the three groups of alternatives to diesel generator.

The most important aspect of a backup supply is the reliability against different kind of loads. At the substation, in case of blackout – how quickly a backup can bring the power and in case of power restoration – how efficiently it can reject the power being generated. The load types may vary viz. inductive in case of fans/motors, constant load in case of normal operation. These scenarios were created in the present work and the HPU was tested for 10 weeks [6] at Deeside Centre for Innovation (DCI) [7]. Other than electrical performance tests, discussion on safety with hydrogen usage, different challenges and prospective mitigation with substation integration are discussed in the present work.

2 Experimental setup

The testing of HPU was performed in test area 5 of DCI as shown in Figure 1. The HPU is rated for 100 kW continuous load and 250 kW peak load for 45 minutes (for details one can visit [8]). This difference of 150 kW is delivered by 216 kWh battery bank arranged on the floor of HPU. Complete HPU weighs ~16 tonnes with dimension of 7.2 m x 2.5 m x 5.2 m (length x breadth x maximum height) and is fit into a shipping container. The HPU was delivered as one unit with installation of complete unit with auxiliaries taking about 20 working hours including the initial safety checks. HPU was connected to the distribution board to connect the electrical loads. There were two loads connected to distribution board. First one is the 300 kW pure resistive load bank where the load can be controlled in steps of 1 kW with the help of handheld controller. The minimum load was few kW (<6 kW) for the cooling fans connected to the load bank. Second port of distribution bank was connected to the 'backup generator' port of LVAC board as shown in Figure 1. The LVAC board provides connection to all the site loads which can be varied using the switches across the site, e.g. cooling fans (4 fans – each of 1 kW, 3.1 A) and motors (2 Pumps – each of 3.5 kW, 7.2 A) of 132 kV / 400 kV can be switched ON/OFF to provide different loads.

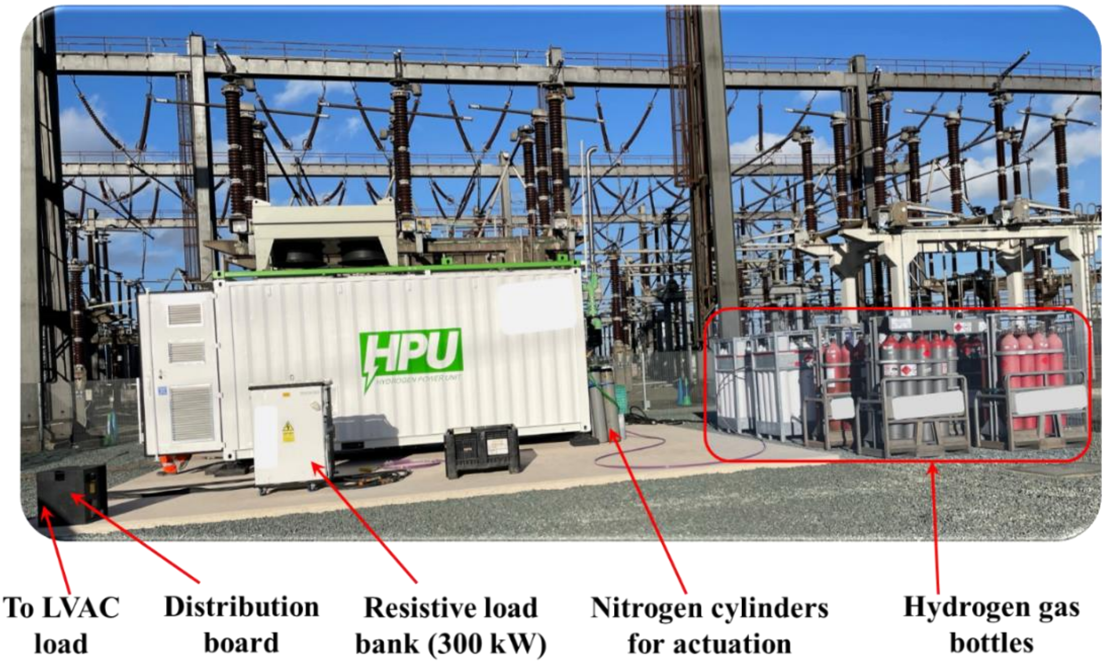

Figure 2: Picture of test setup; LVAC load indicates the connection to LVAC board through distribution board

Hydrogen gas with a purity of 99.999% was used as fuel to combine with oxygen from air in the fuel cells. The flow of gases was controlled using the pneumatic actuators. Nitrogen gas cylinders shown in Figure 1 were used for actuation of the gas flow. The hydrogen gas was supplied as stored in manifolded cylinder pallets (MCPs) as shown in Figure 2 as well as in tube trailers from different suppliers. A hazard zone with horizontal distances 5 and 8 m was defined for safety of site and personnel as per BCGA CODE OF PRACTICE CP 33 [9].

The electrical performance tests were carried out to ensure that the HPU can (a) Respond to variable inductive loads, (b) Meet dynamic response requirements, (c) Provide reliable response at constant loads and (d) Be reliable for load >100 kW. (a) and (b) were achieved with varying load level through load bank and site loads including black start and complete load rejection with load profiles for 8, 24, 72 and 168 hours. (c) was carried out using the load bank with levels at 25, 50 and 75 kW for continuous 6 hours. (d) was integrated in (a) and (b) with HPU running on 250 kW for few minutes. Table 1 shows the tests carried out in the present work with test days.

To determine the acceptable performance three parameters were analysed, after measurement using Fluke 1770 3-phase power quality analyser, viz. (i) Power output, (ii) Frequency deviation in AC voltage output and (iii) Total harmonic distortion. Voltage and frequency deviations are compared against the requirements set in IEC 62040-3. THD was compared as per the requirements of Uninterruptible Power Systems (UPS) – IEC 62040-3 [10] and Engineering Recommendation G5, Issue 5 2020 – Harmonic voltage distortion and the connection of harmonic sources and/or resonant plant to transmission systems and distribution networks in the United Kingdom [11]. TS of NG recommends having a measurement of voltage, frequency and related parameters every 15 minutes. In the present work, test data was recorded each second.

Table 1: Description of the test regimes used in the present work with duration of the tests; 'Both' in load column indicates that HPU was connected to both LVAC board and load bank

Test day	Duration (hours)	Load	**Description of load connected and stepping**
1	8	Load bank	40 → ~2.5kW, 125 kW for ~15 minutes. 40 kW, stepped up 3 times to 65 kW for 15 minutes. Full capacity peak load of 250 kW was introduced for 5 minutes.
2	1	LVAC board	Formalise HPU transfer to LVAC supply. HPU to provide DCI office for 1 hr. Switch LVAC supply back to grid after test.
3	8	LVAC board	8hr LVAC supply test (DCI office + SGT cooling system). Switch LVAC supply back to grid after test
4	6	Load bank	HPU reliability test at 25% of rating – run HPU at 25 kW for 6 hrs
5	6	Load bank	HPU reliability test at 50% of rating – run HPU at 50 kW for 6 hrs
6	6	Load bank	HPU reliability test at 75% of rating – run HPU at 75 kW for 6 hrs
7	8	Load bank	Reliability test – repeat test of day 1 for
8	6	Both	HPU reliability and dynamic response test with significant and fast increase and drops in the load. Part of the test was to turn the fans and pumps on and off, as well as the NG office with load bank stepping on and off (25 and 50 kW).
9	6	Load bank	HPU dynamic response test with significant and fast increase and drops in the load – with load bank stepping from 0 to 50 kW, 0 to 100 kW and 0 to 150 kW.
10	22	Both	HPU dynamic response test with site loads and additional load bank – HPU to supply power to the site load of ~30 kW with increments of the requirement from load bank, from 20 kW to 40 kW to 60 kW.
12	8	Both	HPU dynamic response test with site loads and additional load bank – HPU to supply power to the NG office with load stepping of the load bank, from 0 to 100 kW down to 75 kW to 25 kW.
13-14	48	LVAC board	HPU reliability in response to NG loads – To assess the reliability of the HPU in response to DCI site loads over two days.
15	24	Both	HPU reliability against to site loads with an additional 50 kW from load bank.
16-22	168	LVAC board	7-days LVAC test to check the HPU reliability.

3 Results and discussion

3.1 Response of HPU against dynamic loads

Figure 3 shows the power output of HPU measured for the Day 7 – 8 hours test. Test duration of 8 hours was taken from the TS of NGET where the test for 8 hours is recommended prior to installation of the new diesel generators. The test regime was defined to fulfil the TS requirements as well as to understand the response of HPU with changing loads. Here, only load bank was connected, the measurements of instant power, load in handheld control of load bank and the power shown in digital meter of HPU was matching. This gave the confidence of carrying out the tests further.

The load was varied from zero to 40 kW and then back to zero kW. Similarly, the load level was varied as shown in Figure 3. The HPU was run at 250 kW for 5 minutes. Zoomed version of load stepping up from 40 kW to 250 kW is shown in right of Figure 3. The HPU follows the load. One can see an impulse peak at the instant of stepping up of load. This was due to resistive load bank used which uses a heater bank. The load is applied instantly then it goes down in few tens of seconds as seen in Figure 3 (249.2 kW at 27906 s). This is due to the fact that the heating elements get warm and go to higher temperature as resistance of elements changes. In short, HPU was able to follow the electric loads instantly and good with dynamic load including the peak load of 250 kW.

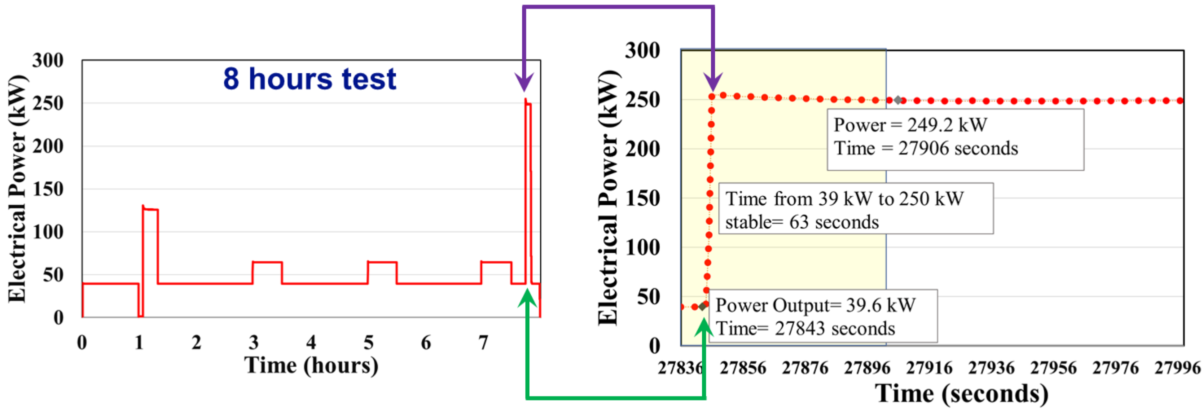

Figure 3: Electric power output of HPU for day 7 – 8 hours test, figure on the right is zoomed version of load stepping from 40 kW to 250 kW

3.2 Quality of HPU voltage output

Figure 4(a) shows the frequency of voltage output of HPU measured for the Day 7 – 8 hours test. The frequency was about 50 Hz and not considerable deviation (average of 0.029 Hz) was observed for the test duration. The frequency deviation for all the tests were calculated as shown in Table 2 and a maximum average deviation of 0.029 Hz was observed which is well within the limit of 0.5 Hz. Figure 4(b) shows the %THD of voltage output of HPU measured for the Day 7 – 8 hours test. Maximum THD observed was 2.08% for Day 7 test. Calculations carried out for all the tests suggest the maximum THD is 3.09% which is well within the limit of 12%. In short, the voltage output was well within the limit specified by IEC 62040-3 in terms of frequency deviation and %THD.

3.3 Overall summary from the tests

Table 2 shows the summary of the results for tests listed in Table 1. Different tests are matched with the objective of the corresponding tests and the criteria to be checked against. Tests were designed in such a way that all aspects of electrical performance be evaluated and HPU output (frequency deviation and %THD) was following the load and well within the tolerances specified by the standards as discussed in sections 3.1 and 3.2. Tests for Days 4, 5 and 6 show that the HPU output is consistent for the constant loads. Tests carried out for Days 13-22 with continuous 24, 48 and 168 hours of operation indicates the long term reliability of HPU power output.

Theoretical calculations for emission savings were carried out for different tests, using factors from the UK Government GHG Conversion Factors for Company Reporting 2022, considering the case of power production from diesel generator. The column 'Energy generated' shows the energy in kWh used for the corresponding tests. Day 15 – 24 hours test was carried out to understand the energy consumed in a day for a 400 kV substation with corresponding hydrogen usage. The internal discussion suggests that the typical load for substations with 3 SGTs is about 70-80 kW. DCI is a 400 kV substation but reconfigured with one SGT and non-operational, hence low load in the range of 25-40 kW. To emulate the higher load, constant load of 50 kW through load bank was provided in addition to DCI site load. For a day operation with consumption of 1815 kWh, 102 kg of hydrogen is required. If translates to ~300 and ~700 kg of hydrogen requirement for 3 and 7 days correspondingly, which poses a challenge for space at substation as discussed in next section. Emission savings for all the tests are listed in Table 2 in terms of CO_2, CO, NO_x and PM. For a day operation with data for Day 15 test, ~1800 kg of CO_2 emission can be saved if HPU is used which is a zero emission alternative.

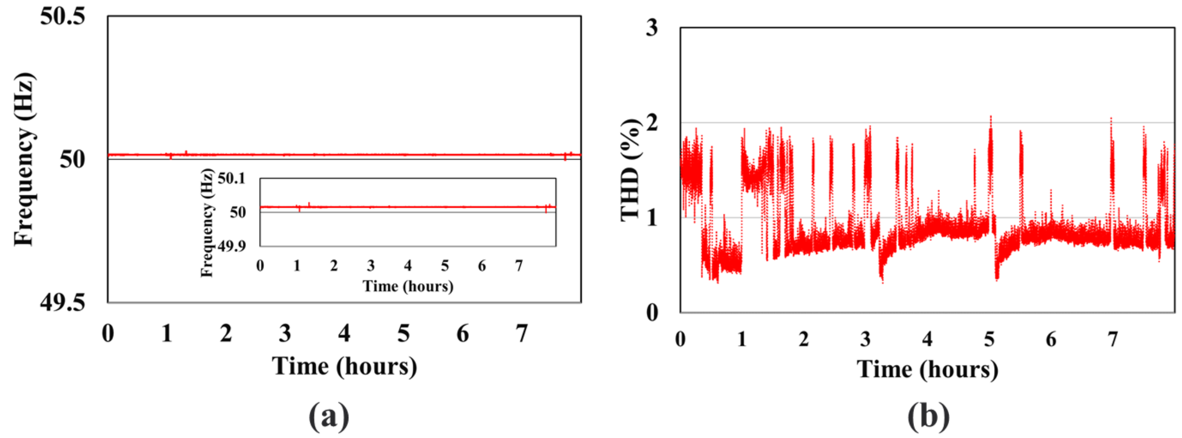

Figure 4: (a) Frequency and (b) average %THD of the output voltage waveforms of HPU for day 1 – 8 hours test

Table 2: Test criteria matched with different tests corresponding frequency deviation and %THD

Test Criteria		**Day**														
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**13-14**	**15**	**16-22**	
Response to Inductive Loads			●	●					●		●	●	●	●	●	
Dynamic response of HPU			●					●	●	●	●	●			●	
Reliability at constant loads					●	●	●									
Reliability with overload >100 kW		●						●		●						
HPU Performance																
Frequency deviation (Hz)	Limit	0.5														
	Measured	0.029	0.020	0.018	0.019	0.019	0.019	0.029	0.024	0.026	0.024	0.020	0.023	0.022	0.022	
THD (%)	Limit	12														
	Measured	2.22	2.14	2.25	2.18	2.26	2.26	2.08	2.19	2.25	2.13	2.09	3.09	2.01	2.41	
Emission Savings																**Total**
Energy Generated (kWh)		397.5	8.5	166.8	163.5	309.6	459.7	395	153	30.9	379.6	398	1272	1815	5630	**11579**
Hydrogen Usage (kg)		22.4	0.5	9.4	9.2	17.5	25.9	22.3	8.6	1.7	21.4	22.4	71.7	102.3	317.3	**652.6**
CO_2 savings (kg)		387.6	8.3	162.6	159.4	301.9	448.2	385.2	149.3	30.2	370.1	388	1241	1770	5489	**11290**
NOx Savings (kg)		5.2	0.1	2.3	2.2	4.2	6.2	5.4	2.1	0.4	5.2	5.4	17.3	24.6	76.4	**157**
CO Savings (kg)		2.9	0.06	1.2	1.2	2.3	3.4	2.9	1.1	0.2	2.8	3	9.5	13.5	42	**86.06**
PM Savings (kg)		0.2	0.004	0.09	0.09	0.16	0.24	0.21	0.08	0.02	0.2	0.21	0.67	0.96	2.97	**6.104**

4 Challenges with HPU for usage at substations

4.1 Health, safety, cost and hazard implications

Flammability of hydrogen poses a challenge for safe storage of hydrogen at substations. CP 33 dictates the hazard distance of 5 and 8 m for bulk storage of hydrogen. Prior to tests, local hazard zones were defined as per Dangerous Substances and Explosive Atmospheres Regulations (DSEAR) 2002 (SI 2002

No.2776). Nomograms by Kashkarov and Molkov [12, 13] suggests different hazard distances based on the hydrogen container volume and pressure. The recommendations from standards and literature as well as the arcing environment of substation need to be considered for safe hydrogen management. 72 and 168 hours of fuel storage at full load continuous operation of 100 kW need ~400 and ~950 kg. It can be supplied in multiple MCPs or 2-4 tube trailers depending on the size. It poses a challenge for storage of gaseous compressed hydrogen. Some other alternatives need to be evaluated such as having liquid hydrogen and an evaporator to feed gaseous hydrogen to the fuel cell. The cost of per kWh produced can be calculated using LDGE (litre diesel generator equivalent), where 1 LDGE hydrogen produces about 2.75 kWh of electricity (the same as 1 litre of diesel in a 250 kW diesel generator) and efficiency of generators (fuel cell in case of HPU).

4.2 Footprint, maintenance and lifecycle cost

The HPU, as described in section 2 is fit into a standard shipping container with ancillaries attached. A standard site footprint of 9.5 m x 16 m is required (from local DSEAR assessment) for the HPU and a tube trailer (which may have gaseous hydrogen as fuel for 3 days on full load). This space is quite demanding as some substations are quite compact and may not have enough space to accommodate the HPU. A survey need to be carried for suitable substations for initial phase of installation and trial. Table 3 compares the maintenance schedule of diesel generator with that of HPU. The life of HPU is limited by that of fuel cell use which is about 10 years and needs replacement whereas diesel generator is expected to be operation for few decades. These factors need to be considered in calculating the lifecycle cost (ongoing for the tested HPU) before installation in bulk.

Table 3: Maintenance schedule for diesel generator and HPU

Maintenance schedule	**Diesel generator**	**HPU**	
		Fuel Cell	Entire HPU
Major service - intervals	1 year or 600 hours	3 months	6 months
Major service - expected unit downtime	1 day	None, unit can supply power via batteries	1 day, unit can supply power via batteries
Minor service - intervals	250 hours	Monthly	Bi-weekly (optional)
Minor service - expected unit downtime	0.5 day	20 minutes; check of oil levels & filters	None

4.3 Other challenges

Different solutions available in the market needs to be considered to have a comparison before large deployment, e.g. hydrogen, methanol (combustion) engines are readily available. There are solutions with multiple hydrogen fuel cells which can take higher load (suitable of large substation with high load demand), e.g. HPU with 10 fuel cells of 100 kW each provide continuous power of 1 MW. HPU is operated with Human-Machine Interface (HMI) and cybersecurity concern need to be resolved before bringing to the substation network.

5 Conclusions

The 10-weeks trial at National Grid DCI concluded that the HPU is able to:

- Respond suitably to variable inductive loads
- Meet dynamic response requirements including 250 kW peak load
- Provide reliable response at constant loads

The HPU conforms with the IEC 62040-3 standard for acceptable harmonic distortion, frequency and voltage deviations. The HPU can be considered as a viable, zero emission replacement for a diesel generator subject to overcoming the identified challenges in section 4 especially with footprint and safety from the flammable hydrogen. Footprint includes that of the HPU as well as that of hydrogen container required to store the mandated fuel supply.

Acknowledgements

The authors would like to thank internal stakeholders especially Andrew Ridley, Simas Stankus and Joe Duckers from National Grid for the fruitful discussion and trial installation. The authors would like to thank Omar Ramadan and Dina Arzina from GeoPura for support with analysis of data collected during the trial.

6 Bibliography

[1] National Grid, 'National Grid call out to industry to find low-carbon alternatives to back up diesel generators', https://www.nationalgrid.com/national-grid-call-out-industry-find-low-carbon-alternatives-back-diesel-generators, accessed on 31 March 2023.

[2] Innovate UK, 'iX Challenge: Low Carbon Alternatives to Standby Generators in Electrical Substations - Innovate UK KTN (ktn-uk.org)', https://iuk.ktn-uk.org/opportunities/ix-challenge-low-carbon-alternatives-to-standby-generators-in-electrical-substations/, accessed on 31 March 2023.

[3] EPRI Technical Update, 'Low-Carbon Backup Generator Technology', 3002020505, March 2021.

[4] Department of Energy, 'Fuel Cells', https://www.energy.gov/eere/fuelcells/fuel-cells, accessed on 31 March 2023.

[5] Department of Energy, 'Types of Fuel Cells', https://www.energy.gov/eere/fuelcells/types-fuel-cells, accessed on 31 March 2023.

[6] National Grid, 'National Grid goes carbon-free with hydrogen-powered substation trial', https://www.nationalgrid.com/national-grid-goes-carbon-free-hydrogen-powered-substation-trial#, accessed on 31 March 2023.

[7] National Grid, 'Deeside Centre for Innovation', https://www.nationalgrid.com/electricity-transmission/engineering-and-consultancy-solutions-ecs/deeside-centre-for-innovation, accessed on 31 March 2023.

[8] GeoPura, 'Hydrogen Power Unit', https://www.geopura.com/our-technology/products/, accessed on 31 March 2023.

[9] British Compressed Gas Association: CODE OF PRACTICE CP 33, 'The Bulk Storage of Gaseous Hydrogen at Users' Premises', Revision 1: 2012.

[10] 'Uninterruptible Power Systems (UPS) – Part 3: Method of specifying the performance and test requirements' IEC 62040-3:2021.

[11] 'Engineering Recommendation G5', Energy Networks Association, Issue 5, 2020.

[12] S. Kashkarov, Z. Li, V. Molkov, 'Blast wave from a hydrogen tank rupture in a fire in the open: Hazard distance nomograms', International Journal of Hydrogen Energy, Volume 45, Issue 3, 2020, Pages 2429-2446, https://doi.org/10.1016/j.ijhydene.2019.11.084.

[13] S. Kashkarov, Z. Li, V. Molkov, 'Blast wave from a hydrogen tank rupture in a fire in the open: Hazard distance nomograms, International Journal of Hydrogen Energy', Volume 45, Issue 3, 2020, Pages 2429-2446, https://doi.org/10.1016/j.ijhydene.2019.11.084.