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Abstract

Hydrogen could become an important energy carrier, in particular used as an input to fuel cell electric vehicles. Alkaline electrolysers are an attractive technology to produce carbon-free hydrogen from renewable generated electricity. Large-scale alkaline electrolysers used in future hydrogen-filling stations could also be utilised to improve the frequency stability of the electricity power system. The electrolyser load can be controlled to respond to power system frequency variations, and in the case of a sudden loss of generation, these electrolysers could rapidly decrease their load on the system to maintain the power balance. In this study, the potential of alkaline electrolysers to dynamically stabilise the frequency of the power system is assessed. A model of steam turbine generation unit has been developed in MATLAB SIMULINK environment, and a scenario in which there is a sudden loss of generation in the system is examined. It is demonstrated that alkaline electrolysers could prevent unacceptable frequency drop, i.e. below the statutory limit, following by an abrupt loss of generation, even with no spinning reserve on the system. In this article for the first time, the ramping rate of an alkaline electrolyser is shown through experimental data.

Keywords

Demand side management, alkaline electrolyser, frequency control, grid stability

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Introduction

Hydrogen has the potential to become a significant fuel in the future. It can be used to power fuel cells to generate electricity, in particular for transportation. Fuel cell electric vehicles are attractive for transportation because they produce no significant greenhouse emissions provided the hydrogen is produced from a renewable source. Electrolysis is a simple and attractive way to produce this hydrogen. There are three types of electrolysers in common use:

- alkaline electrolysers;
- proton exchange membrane electrolysers;
- solid oxide electrolysis cells.

Alkaline electrolysers are more popular than the other two types because they are the most developed ones and have the lowest capital costs.[1] Hydrogen could be produced sustainably by electrolysis if the electricity used for this process comes from renewable resources.

If hydrogen is produced in a vehicle filling station, then it does not need to be shipped in tankers or through pipelines, thereby eliminating the cost of transportation or hydrogen transmission infrastructure. Electrolysers could be used to consume the excess wind or solar energy in an electric power system, and they can also provide load levelling. The response of electrolysers to fluctuations in wind or solar power or consumer demand can help to improve the performance and stability of the electricity system especially in the case where the penetration of wind power is very high.[1]

Frequency stability and control is an important issue for electricity power systems. Frequency should remain within a specified range at all times. In the UK, National Grid is responsible for management of the transmission network in a secure way. It is also responsible for balancing generation with load demand in real time.

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The National Grid has the following steady-state operational and statutory limits for the frequency of the electrical network:

- statutory steady-state limits of ±0.5 Hz (i.e. 49.5–50.5 Hz);
- operational limits of ±0.2 Hz (i.e. 49.8–50.2 Hz).[2]

Active power control is closely related to frequency control. Sudden loss of generation in the power system will result in a deviation from the nominal frequency. This frequency deviation is a result of the mismatch between the generated power and load. With excess generation in the system, the frequency will rise, and if there is a lack of generation, then the frequency will fall reflecting the amount of mismatch between generation and load. The rate of change of frequency will also be determined by the effective inertia of the power system. It is impractical for generators to perfectly match their output to the amount of demand at every moment, so there is always some deviation from the nominal frequency in the system.[3]

Due to the difficulty of forecasting, the exact demand from consumers, there must be enough spinning reserve available in the system to supply additional power when required. In addition, when there is a sudden loss of generation, it takes some seconds for the spinning reserve to become fully available, and slower backup generation might take up to 30 min to become available. If a generation loss which is bigger than the infrequent infeed loss risk happens, then a national low frequency demand disconnection scheme will automatically disconnect loads from the system to prevent a total or partial shutdown of the electrical power system.[2]

To reduce the amount, and consequently the cost of spinning reserve on the system, control strategies can be used to vary key loads; this is known as demand side management (DSM). Suitable control of loads can be used in place of part of spinning reserve to control the frequency of the system.

Power system operators must spend a significant amount of money to purchase frequency response services. DSM is able to help maintain the system frequency to a useful extent. In particular, alkaline electrolysers have characteristics that allow them to be used as DSM tools. This will be of increasing importance with high penetrations of time variable and intermittent renewable generation. In addition, when there is a loss of generation, such electrolysers can rapidly reduce their load on the power system, thus providing immediate reserve supporting the restoration of the frequency.

There are a number of projects implemented around the world related to stabilisation of the power system frequency using electrolysers. Recently, the Hydrogenics Corporation announced successful completion of a trial project with Ontario's Independent Electricity System Operator (IESO) demonstrating the grid stabilisation capability of its electrolysers. During the trial period, the load from a Hydrogenics HySTAT^{TM} electrolyser provided frequency regulation to the IESO system by responding to power regulation signals provided by the IESO on a second-by-second basis.[4]

Literature review

There are many published papers related to the hydrogen economy, electrolysers, DSMs and frequency control using dynamic demand. Key literature is reviewed briefly below.

Technologies related to hydrogen production are reviewed in Holladay et al.[1] The current state of technology for hydrogen production by water electrolysis is examined in Zeng and Zhang.[5] This article also identifies areas where research and development effort is needed in order to improve the technology.

An electronic device that emulates the electric power generated by wind farms has been used to test an alkaline electrolyser under variable wind power conditions.[6] An advanced alkaline electrolyser has been tested in Hug et al.[7] for various constant and intermittent operational modes, and a simulation model has been developed which calculates thermal behaviour, cell voltage, gas purities and efficiencies for any given power or current profile. In Brossard et al.,[8] the behaviour of a 3 kW (250 A) electrolyser has been examined under constant and variable load operation.

In Zhou and Francois,[9] control oriented modelling of an electrolyser is implemented. Their model is capable of characterising the relations between the electrolyser's physical parameters and can be used to design a control system to ensure efficient and reliable operation of the electrolyser. A mathematical wind turbine model and also a dynamic electrolyser model are developed and validated in Pino et al.[10] The transient response of an electrolyser employed in a residential scale renewable-regenerative system has been explored experimentally in Bergen et al.[11]

In Short et al.,[3] the impact of dynamically controlled consumer loads (e.g. fridges) on the frequency stability of an electrical grid was investigated. In Hamidi et al.,[12] the value of wind generation without dynamically controlled demand is quantified. The results of this article show the benefits of responsive demand on the operational and environmental characteristics of an electrical power system.

In Miland et al.,[13] a new generation of load controllers which enable stand-alone power systems to use one or many standard grid connected wind turbines were modelled, and a hydrogen subsystem, which can work in parallel with the distributed intelligent load controller, was implemented. In Vachirasricirikul et al.,[14] an electrolyser is utilised to absorb the power fluctuations on the electrical power system, and a robust controller of the electrolyser and micro-turbine for frequency stabilisation was designed.

Li et al.[15] focuses on the stability of micro-grid operation and discusses the control techniques for combining a micro-turbine with the fuel cell and electrolyser hybrid system to expand the micro-grid system's ability to improve power quality issues resulting from frequency fluctuations.

Methodology

A change in the active power demand or generation in the power system will drive a change in frequency of the entire electrical system. A speed governor provides primary speed control ability to each generator unit, and central control system allocates generation as supplementary control. The relationship between the frequency change in the grid and the overall load change in the system is as follows

$$\Delta P_e = \Delta P_L + D\Delta\omega_r \tag{1}$$

The damping constant (D), which represents the impact of frequency sensitive loads, is expressed as percent change in load for 1% change in the frequency, and it has typical values of 1% or 2%.[16]

If there is a load change in an electrical system, then all of the generators with speed governing connected to the system will change their output generation to recover the frequency of the system. The governor is responsible for maintaining the frequency at its nominal value by changing the position of the valve of the turbine. There may be many such generators operating in an electrical system, so the change in demand must be shared properly among the generators.[16] Droop (R) in a turbine controller determines steady-state speed versus load characteristic of the generating unit. It is expressed by the following equation

$$R\ \% = \frac{\Delta f\%}{\Delta P_G\%} \times 100 \tag{2}$$

When there is a loss of generation in the system or when there is a sudden increase in the load demand, the rotational inertia of all the generators and rotational loads in the system lose energy to provide the power deficit, so their speed will decrease, and therefore the frequency of the system will decrease. In steady-state condition, the frequency of the system will fall to a level that the power deficit is met by released demand of the frequency sensitive loads (represented by D constant) and the increased generation which is a result of the governor response. In actual power systems, a secondary response will start to return the frequency to its nominal value within around 10 min.

In the case that there are more than one generator operating and all of them have droop governor characteristics, then the system will have a common frequency, and all of the generators in the system share the load change. When there is a load increase in the system, the droop characteristic causes a steady-state deviation from the nominal frequency. The relationship between the load and the frequency could be changed by adjusting the load reference set point, which in effect moves the speed droop characteristic up or down.

The output of each generating unit at each frequency can only be changed by a change to its load reference set point. The collective performance of all of the generators in an electrical system will determine the frequency of the grid. It is shown in Kundur[16] that if there are many generators in a system, then for the analysis of the system frequency, these generators may be represented by one single generator that has an inertia constant equal to the sum of the inertia constants of the individual generators. The frequency characteristic of the electrical grid also depends on the combined effect of the droops of all generator speed governors. An equivalent droop (R) can be found for the combined effect of all the individual generators.

A block diagram of a generator based on a steam turbine with reheat is shown in Figure 1. This can be used for the analysis of frequency deviation following a sudden mismatch between the generation and the demand. This block diagram comprises a speed governor, turbine, model of rotor inertia and load. For simplicity, as is conventional, it has been assumed that the boiler pressure is constant.[16]

Typical values for this model are taken from Kundur[16] as

$$R = 0.05;\ T_G = 0.2\,\text{s};\ F_{HP} = 0.3;$$
$$T_{RH} = 7.0\,\text{s};\ T_{CH} = 0.3\,\text{s};\ M = 10\,\text{s};$$
$$D = 1;\ K_I = 0.2$$

Instead of a sudden increase in the demand of system, we could have an equivalent sudden drop in generation from other units in the system; this will have the same effect on the frequency of the system.

Due to the governor droop characteristic, if a system has only primary speed control action, then a change in the system load would cause a steady-state deviation from the nominal frequency. If the frequency of the system is to be restored to its nominal value, supplementary control action must be used to adjust the load reference set point. Automatic generation control system can restore the frequency using an integral controller to change the load reference set point. This integral controller, which is shown in Figure 1 as supplementary control, ensures zero frequency error under steady-state conditions. The primary speed control acts much faster than the supplementary generation control. The gain, K_I, (0.2) in this figure is determined so that the controller

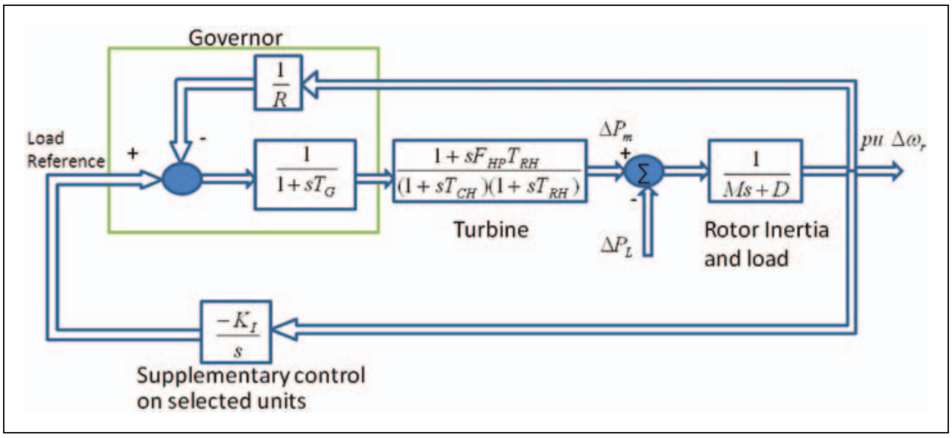

Figure 1. The block diagram of a typical reheat steam turbine, governor, rotor inertia and load.

returns the frequency of the system to its nominal value within 10 min after a step change in load, provided that there is sufficient reserve available on the system. The ability of the system to restore the frequency to its nominal value has some limitation. The amount of spinning reserve is limited in each electrical grid, and this limits the maximum generation power which can be achieved quickly.

In actual electrical power systems, the generators have complex dynamics, and their models differ from each other. To construct an accurate model of a grid for the frequency analysis purposes, many different generator models may need to be considered.[3] In this study, all of the generators are considered to be of the same steam turbine type and are considered to have governor control action for speed control. In this study, the spinning reserve which is provided with the governor controlled generator is equal to the aggregated amount of spinning reserve available from all of the steam turbine generators on the system.

It has been assumed that during the simulation period the loads from non-electrolysis plant in the electrical power system do not change. The electrolysers are intended to produce hydrogen for future hydrogen-filling stations. The hydrogen produced by electrolysis plants would be stored at the filling stations. The storage of hydrogen would be required to accommodate the expected time variations of hydrogen demand for vehicle filling, but it can also be used to allow the electrolysers to act as controllable loads. The electrolysers will then not be constrained to operate at a fixed constant load at all times. This also assumes that the variable load operation of the electrolyser does not result in any significant degradation of its performance or the lifetime of electrodes or other key components.

A MATLAB SIMULINK model was developed based on the model in Figure 1 to represent the frequency of the electrical system using electrolysers as dynamic demand. A single generator which has the aggregated characteristics of all of governor controlled generators is modelled. This generator is responsible for delivery of all power to the system and maintaining the frequency within operational limits. If there is sufficient spinning reserve, then this unit must increase its output power when a frequency drop occurs. In this case, the governor controller will change the output of steam turbine, in order to stabilise the system frequency.[16]

The aggregated effect of a number of electrolysers which are used as dynamic demand control (DDC) is considered in this study. It is assumed that 24 electrolysers with a nominal load of 2 MW each are operating in the electrical power system. The aggregate nominal power of all the generators in the system is assumed to be 320 MW.

Standby load of the electrolysers is assumed to be equal to 1.5 kW, and the minimum load of the electrolysers is assumed to be about 20% of their nominal load. These values are taken from the atmospheric alkaline electrolysers designed by NEL Hydrogen Company.

It is also assumed that every electrolysis plant on the grid has a controlled rectifier which is able to supply the electrolyser up to the acceptable load limit of the electrolyser. There is a communication system between the controller of each large-scale electrolyser and the grid control centre so that the operating point of the electrolysers can be changed easily in response to a command signal from the control centre.

In this study, the response of the generators to a sudden loss of generation of 0.15 per unit (pu) is investigated. This means that the input of ΔP_L has a step change of 0.15 in the beginning of the simulation. For this study, the aggregated load of electrolysers (48 MW) is set to be equal to the amount of generation loss in the system. Two scenarios are considered, as follows.

1. The generators are provided with enough spinning reserve, and the electrolysers are not used as dynamically controlled loads to control the frequency of the grid.

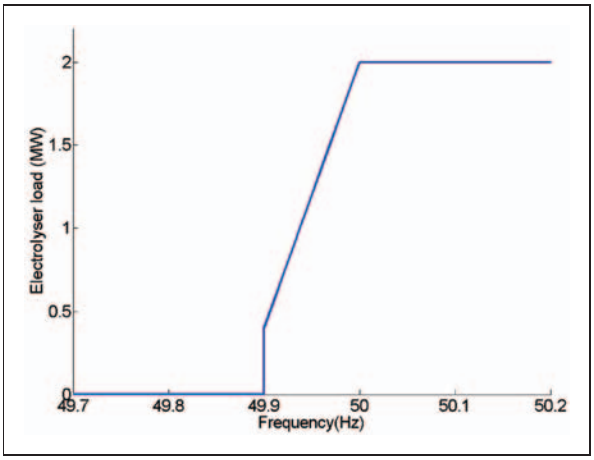

Figure 2. Load of each electrolyser with respect to the frequency of the grid (electrolyser control strategy).

2. There is no spinning reserve provided on the system, and electrolysers are utilised to control the frequency of the grid following a loss of generation.

Before the generation loss event, the total amount of load in the system, which is made of electrolyser loads and conventional system loads, is equal to the amount of generation, and the frequency of the system is assumed to be 50 Hz, which is the nominal frequency of the UK electrical grid. The strategy which is used to control the electrolyser is explained below.

The electrolyser loads must be changed with respect to the frequency deviation in the system to provide demand response. For system frequencies between 49.9 and 50 Hz, the electrolysers are controlled to load the system by

$$P_{N.EL} - \frac{(P_{N.EL} - P_{\min.EL}) \times (50 - f)}{0.1} \quad (3)$$

If the frequency drops below 49.9 Hz, then the electrolysers go into standby condition. Figure 2 shows the resulting relationship between the electrolyser load and the frequency.

The frequency of 49.9 Hz is chosen because the operational frequency limit in the UK is 49.8 Hz, and under these conditions the electrolysers should consume the minimum allowable power, but we know that it takes some time for the system to sense this frequency drop and react to the situation, so the value of 49.9 Hz is selected to provide some safety margin.

If electrolysers reduce their loads, then ΔP_L will decrease, and this means that the amount of mismatch between generation and demand will decrease. It was assumed that if electrolysers go into standby condition, then they will remain in that condition until the backup generation becomes available.

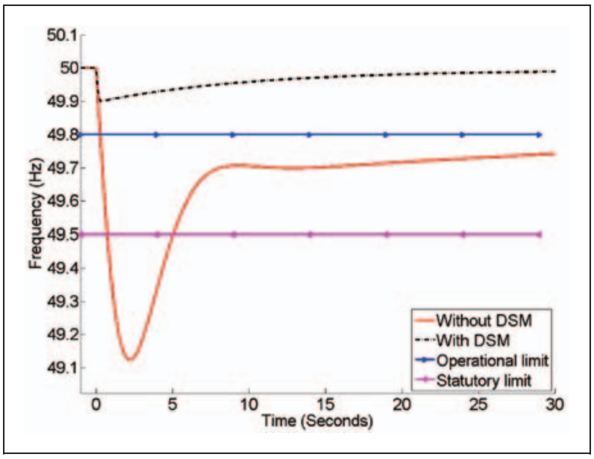

Figure 3. The frequency of the grid with or without DDC in the first 30 s from the generation loss.
DSM: demand side management.

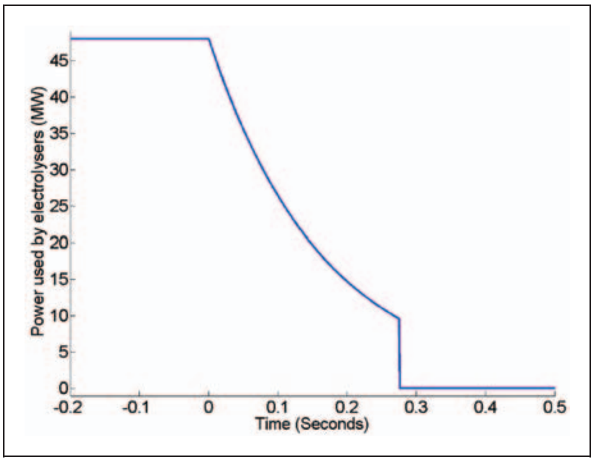

Figure 4. The load of electrolysers during the first 0.5 s from generation loss.

Discussion and result analysis

Figure 3 compares the primary system responses for the two scenarios. The resolution of the SIMULINK file for this short time analysis is 1 ms.

Immediately following the loss of generation event, the frequency decreases as energy is extracted from the aggregate rotor inertia and other frequency sensitive loads in the system. The frequency of the system without DDC drops very sharply below statutory limit, and it takes more than 50 s for the system frequency to recover. On the other hand, in the system with electrolysers as dynamic demand, the frequency drop is much reduced, and it remains above the operational limit at all times.

Figure 4 shows the aggregate load of electrolysers in the first 0.5 s following the loss event. To assist the

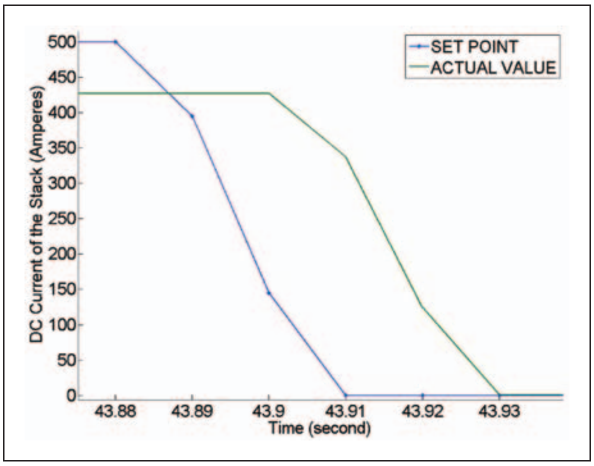

Figure 5. The set point and actual currents of the electrolyser tested in Porsgrunn hydrogen-filling station.

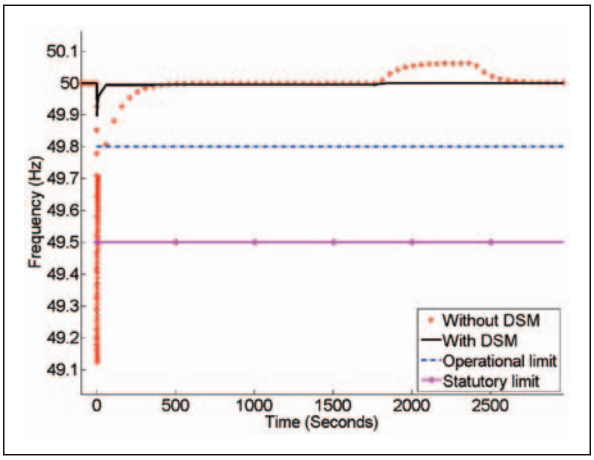

Figure 6. The frequency of the grid with or without DDC. DSM: demand side management.

system in frequency stabilisation, the electrolysers must be able to reduce their load in a very short time; 280 ms. This capability is confirmed by recent experiments undertaken in collaboration with the NEL Hydrogen Company at the Porsgrunn Research Park in Norway. It was found that a pressurised alkaline electrolyser[17] could respond quickly to a command signal and could reduce its current from 427 A to standby current of 0 A in about 50 ms.

Figure 5 shows that the current set point was changed to 0 A at 43.88 s, and the actual current of the electrolyser reached 0 A (standby condition) at 43.93 s.

According NEL Hydrogen, their electrolysers with nominal load of 24 kW offer a maximum load change of ±18,480 kW/min, so if the load of each electrolyser in the system is 2 MW, then by scaling up the above ramping value, the maximum load change of each 2 MW electrolysis load will be ±25.7 MW/s.

Such alkaline electrolyser systems can thus offer the required degree of flexible control to allow them to be used to compensate for sudden imbalances in a power system.

In actual power systems, secondary response will start to return the frequency to its nominal value within around 10 min. However, after 10 min the frequency of the system with dynamically controlled electrolysers does not return exactly to the nominal frequency of 50 Hz because the electrolysers require some power during standby operation, but this deviation is very small (0.0003 Hz).

About 30 min after the loss of generation, backup generation is connected to the system resulting in a linear increase from zero within 10 min until it compensates for the power deficit caused by the generation loss.

During this time for the system with DDC, the electrolysers linearly increase their load until they reach their maximum demand, and the system is fully recovered from the generation loss. To make sure that the frequency of the system with DSM does not drop significantly when electrolysers go into operational mode from standby, the controllers of the electrolysers take them into operational mode 2 min after the backup generation starts adding power to the system. The 2 min time delay is selected to make sure that the generators can compensate 20% of the loss which is equal to the minimum aggregate electrolyser load.

Figure 6 shows the response of system in the first 3000 s (50 min) following the loss of generation. The resolution of the SIMULINK file for this longer analysis is 0.1 s.

When backup generation is added to the system, the frequency of the system without DSM overshoots, exceeding 50 Hz, but the frequency of the system which has dynamically controlled electrolysers does not do this. Instead, it increases linearly until the frequency reaches its nominal value. When backup generation is added to the system, the power which is coming from the spinning reserve in the system with no DSM will be reduced, and the spinning reserve contribution will become zero after the backup generation fully compensates for the loss of generation.

Figure 7 shows the electrolyser load during the first 3000 s following loss of generation. It is obvious that because of the significant generation loss, the electrolysers had to go to standby condition almost immediately. After 32 min from the start of simulation, the electrolysers start to increase load because the backup generation is able to compensate the system for the loss of generation.

The system with DSM should result in reduced carbon dioxide emissions from electric power plants as a consequence of the reduced need for spinning reserve.

As long as there is enough hydrogen stored to meet the demand at each filling station, there would not be any cost or risk for the electrolyser operators to participate in this sort of dynamic demand scheme, and even there could be some financial benefits for the

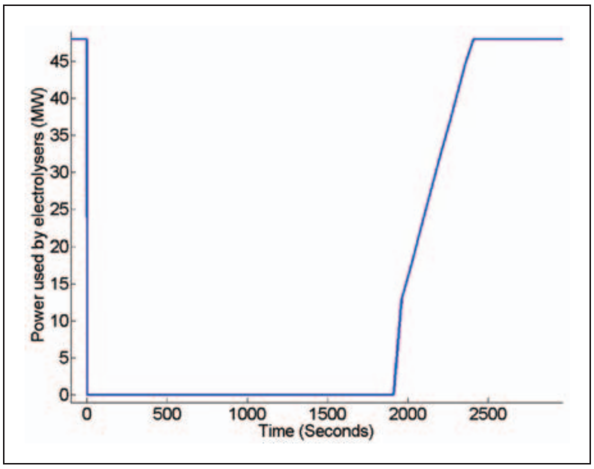

Figure 7. The load of electrolysers during the first 3000 s from the time that there is a generation loss.

electrolyser operators by providing frequency response.

The model in this article is based on a simple model of one generation unit, and it has not been verified yet by real data from a real system. The real dynamic of the UK electricity network is much more complicated than the simple case considered in this article.

The maximum electricity demand in the UK is around 55 GW,[18] so by scaling up the system in this article to the UK electricity network, the aggregate demand from the electrolysers would be around 9.7 GW. This makes electrolysers more attractive than other sorts of DSM, e.g. heat pumps or refrigerators, which have very limited availability and cannot help in the decarbonisation of the transportation sector. Considering the current commercial technology and 73%[19] efficiency of electrolysers, this aggregate load will produce 4354 tons of hydrogen every day which can provide more than 30% of the UK road transport energy requirement,[20] assuming the hydrogen will be used in fuel cell vehicles with the efficiency of 60%.[21]

The penetration of different energy resources in the future energy network is not exactly known, but the UK Department of Energy and Climate change has published '2050 Pathways Analysis' report,[22] which predicts six different scenarios for the UK electricity network in 2050. Its alpha pathway considers the total decarbonisation of the UK electricity generation system by utilising nuclear power plants, non-thermal renewable generators and combustion generators with carbon capture and storage systems. In that case, there would be no carbon dioxide emissions as a result of hydrogen production by electrolysers.

As wind power penetration increases, controlling the frequency of the grid will become increasingly difficult because of high variations in the wind generated power, and also because wind turbines do not contribute naturally to system inertia but displace conventional generation thereby reducing the total power system inertia. Because electrolyser controllers can react much more quickly than the thermal plant governors, it is expected that the use of electrolysers as dynamic loads would help to smooth the frequency variation of systems with a high wind penetration. Currently, the annual cost of providing spinning reserve and demand response for frequency regulation in the UK is around £260 m, and it is predicted that in 2020, this amount will increase to £550 m because of the problem of uncertainty in wind forecasting.[23] This highlights the potential financial benefits of the utilisation of electrolysers as dynamic loads to stabilise the frequency of the UK power system in future. Qualifying the impact of DDC on such systems will be considered in future work.

Conclusion

A MATLAB SIMULINK model has been developed to investigate the impact of alkaline electrolysers as dynamically controlled loads for stabilisation of system frequency in the case of a sudden loss of generation. Such electrolysers could help maintain the network frequency within operational limits by reducing their load as a function of the frequency deviation. On the other hand, the system without dynamically controlled electrolyser could not keep its frequency within operational or statutory limits after the significant generation loss of 0.15 pu. The electrolysers providing dynamic response must be capable of changing their load in a very short time, e.g. less than 200 ms. There are also some electrolysers available in the market which can provide such fast response. This article has evidenced the ramping rate of a pressurised alkaline electrolyser through experimental data for the first time.

Electrolysers can produce clean fuel for future transportation needs and at the same time be used as dynamic load to stabilise the system frequency. Such electrolysers can provide long term energy storage and provide load control on a short term basis.

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Appendix

Notation

D	load damping constant
f	power system frequency (Hz)
F_{HP}	fraction of total turbine power generated by high pressure stage
K_I	integral control gain
M	inertia constant (s)
$P_{\min.EL}$	minimum load of each electrolyser to work properly in normal hydrogen production mode (W)
$P_{N.EL}$	nominal load of each electrolyser (W)
R	speed droop characteristic
T_{CH}	time constant of main inlet volumes and steam chest (s)
T_G	governor time constant (s)
T_{RH}	time constant of reheater (s)
$\Delta f\%$	percentage of the frequency change in the system

ΔP_e	total load change in the system in pu
$\Delta P_G\%$	percentage of the power output change of the generator
ΔP_L	change in load as a result of the change in non-frequency sensitive load in pu
ΔP_m	total mechanical power change in the system in pu
$\Delta \omega_r$	change in the rotor speed in pu