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A flywheel energy storage system for an isolated micro-grid

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ABSTRACT: *The paper presents an investigation into the effects of integrating a Magnetically Loaded Composite (sMLC) flywheel to an isolated micro-grid. The Fair Isle is a small island located in northern Scotland, and supplied from two wind turbines and two diesel generators. The model of the micro-grid is developed and run on a real-time simulator with the physical MLC flywheel as a Hardware-In-the-Loop (HIL). Furthermore, a time-domain model of the MLC flywheel system is developed and its predictions are compared to measurements.*

I. INTRODUCTION

Isolated micro-grids, which include islands and remote communities, are generally characterised by high electricity generation costs and exhibit stability problems. High generation costs can be alleviated by maximising the usage of renewable sources, such as wind, solar and hydro powers, albeit at the expense of an increase in frequency and voltage fluctuations due to the varying environmental conditions. The introduction of short-term energy storage systems, such as flywheels, can improve the stability of a micro-grid and maximise the penetration of the renewable energy sources.For grid stabilisation applications, a high cycle life is normally required, typically 15 million cycles over a 20 year life span. The cycle life of battery systems is typically in the order of <10,000 cycles and therefore, would require frequent replacements, hence offsetting the potentially lower initial capital cost advantage . The cycle life of capacitor energy storage systems is significantly higher at approximately 1 million cycles. However, the life cycle of Magnetically Loaded Composite (MLC) flywheel systems is of the order of 10 million cycles, and combined with excellent power density and a wide temperature operating range, the MLC flywheel system is very suitable for frequency and voltage stabilisation applications.

The paper presents an investigation into the effects of integrating an MLC flywheel to an isolated micro-grid. The Fair Isle is a small island located in northern Scotland, it has around 80 residents living in 30 houses supplied from an isolated micro-grid, which consists of a heating network and a service network, which can be connected by two inductioncouplers, and supplied from two Wind Turbines (WT), rated at 60kW and 100KW, and two 32kW Diesel Generators (DG), as shown in Figure 1. The model of the micro- grid is developed and run on a real-time simulator connected to the physical MLC flywheel through a programmable power supply in a HIL set-up. The inputs to the model are power profiles measured on five selected nodes on the micro-grid, and sampled at 1 second intervals. Furthermore, a time-domain model of the flywheel is developed and experimentally validated.

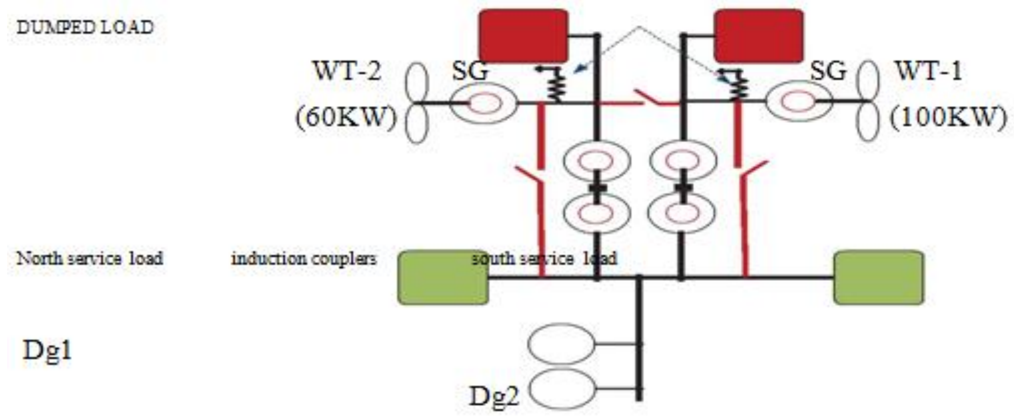


Figure1: Fair ISLE power system

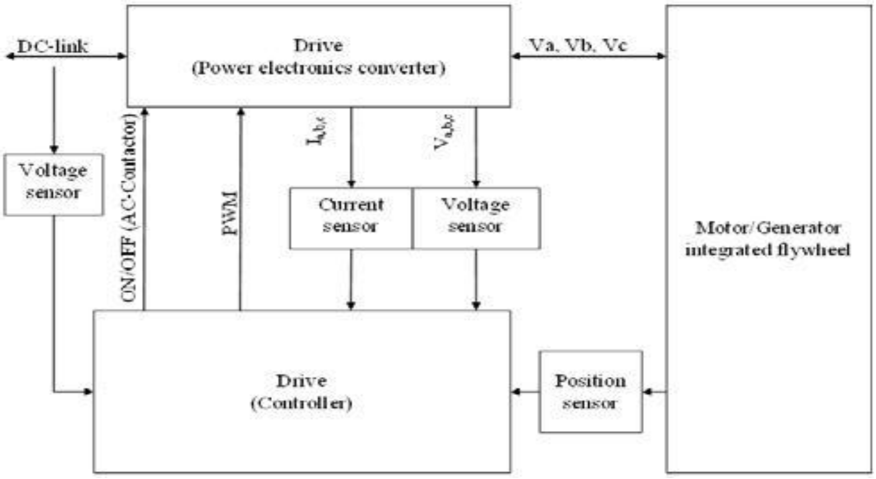
Time-domain modelling of the MLC flywheel system:-A high-fidelity time-domain model of the MLC200 flywheel system, whose parameters are given in Table 1, has been developed and validated. The model includes the integrated permanent magnet motor/generator, the 3-phase power electronic converter and the low level controller for the power electronic switches and the high level controller for the flywheel Simulink and reproduces the behaviour of the flywheel system in its operating range.

Table 1 Parameters of the MLC200 Flywheel

Parameter	
Energy	14.3 MJ (4.0 kWh)
Power	200kW
Minimum speed	30,000rpm
Maximum speed	36,000rpm
Nominal dc-link voltage	700V

The functional schematic of the MLC200 flywheel system is shown in figure 2. The power electronic converter has been modelled using Simulink powerSystems toolbox and consists of a standard 3-phase converter, which provides the interface between the DC-link and the integrated permanent magnet motor/generator of the flywheel.

(a) MLC200 Flywheel



(b) Functional diagram

Figure 2: MLC200 flywheel system

The power demand of the flywheel is determined by the dc-link voltage level, as shown in Figure 3. Therefore, the controller monitors the DC link voltage and the speed of the flywheel, and generates the PWM signals for the IGBTs of the power electronic converter, in order for the flywheel to generate or absorb the required power. The controller aims to keep the DC- link level in the recovery region, adjustable between 570V and 900V.The controller has been modelled as a state machine using Simulink State-flow toolbox and was designed to reproduce the behaviour of the flywheel under various load conditions, i.e. various states of charge and DC-link voltages.

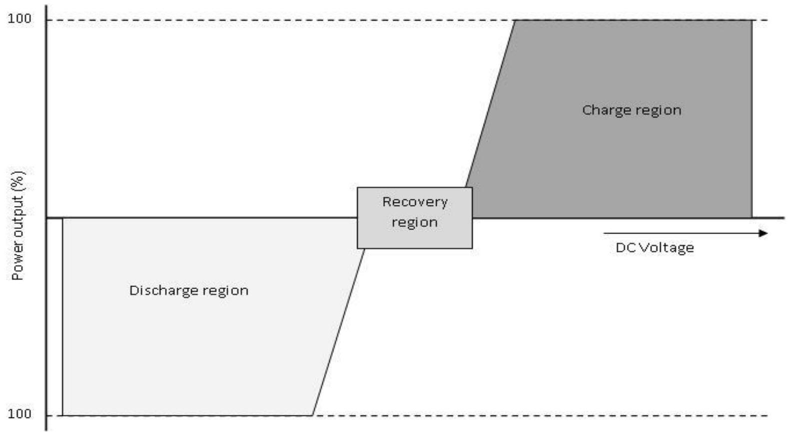
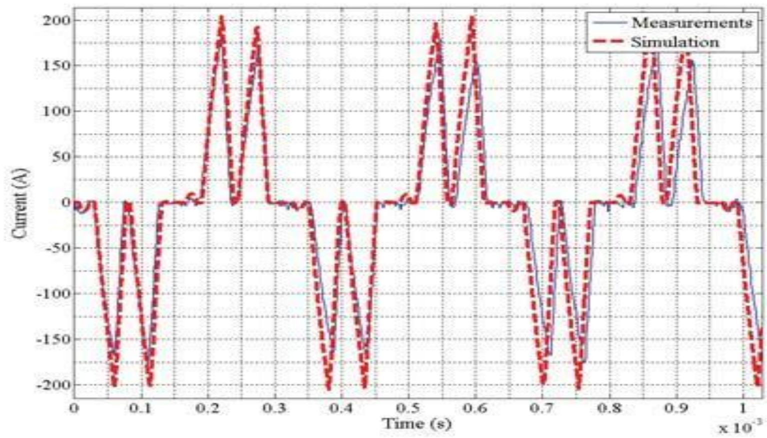


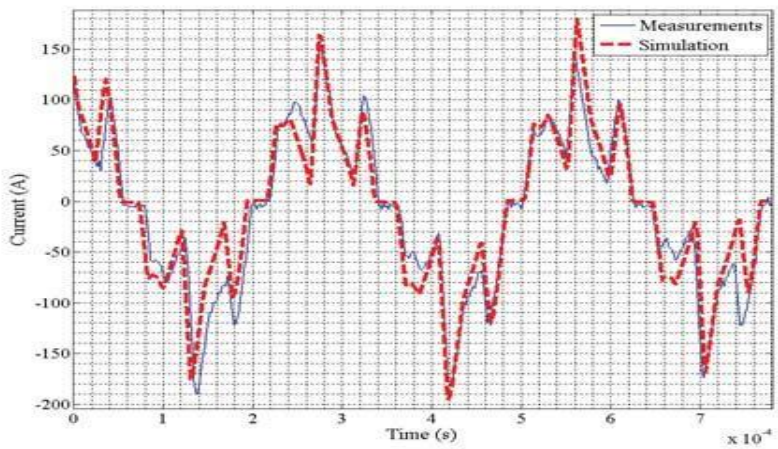
Figure 3: MLC200 power profile

II. EXPERIMENTAL VALIDATION

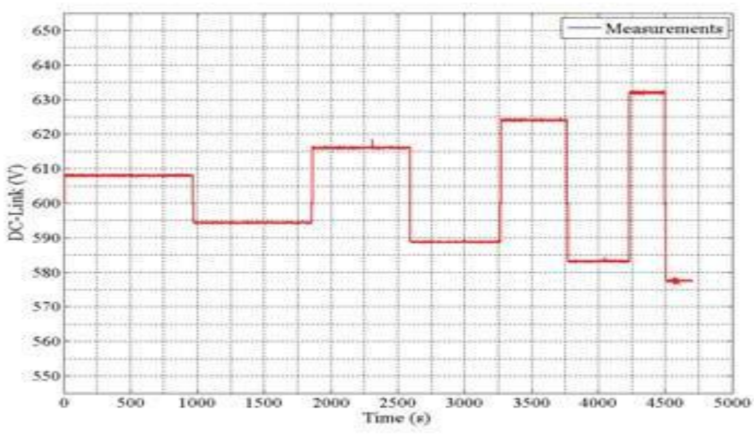
The MLC200 flywheel has been tested under different conditions, and the results have been compared to the predictions from the time-domain model, Figure 4 compares measured and predicted phase current waveforms for 40kW charge and discharge operations. It can be seen that the time-domain model predicts the phase current waveforms adequately Figure 5 shows charge and discharge cycles of the flywheel, where the recovery region has been set between 595V and 605V and the maximum power output was limited to 50kW. The DC-link was varied and the power of the flywheel was recorded. Again, it can be seen that the time-domain model represents the behaviour of the flywheel system adequately.



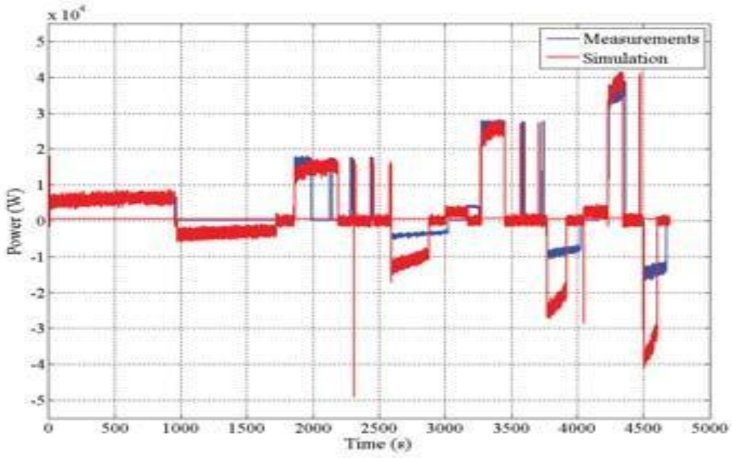
(a).40kW charging.



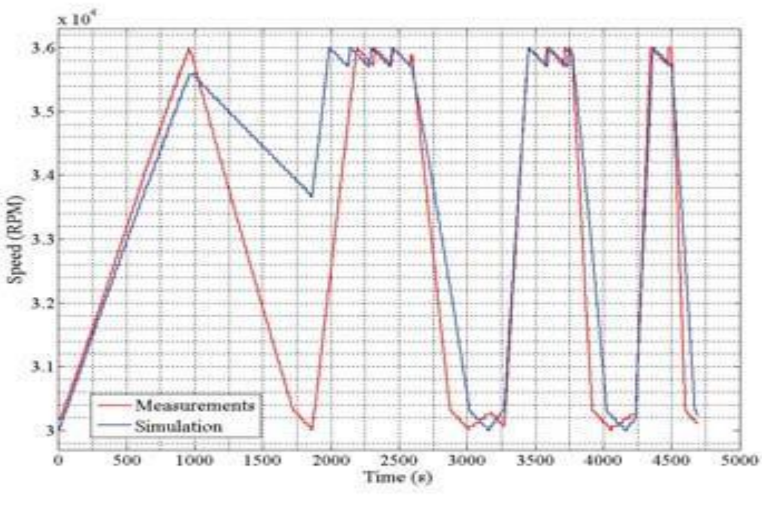
(b)40kW dis-charging.
Figure 4: Phase current waveforms



(a) DC-link voltage



(b) Power of the flywheel



(c) Speed of the flywheel

Figure 5: Flywheel power flow for varying DC-link voltages

Fair Isle:-The Fair Isle is located in northern Scotland, lying around halfway between mainland Shetland and the Orkney Islands. There are around 80 residents living in 30 houses connected to an isolated micro- grid, and relies heavily on wind power . In fact, the Fair Isle is the first place in Europe which commercially operated a wind energy scheme, supported by council and government development agencies. The average daily energy consumption is typically 1,100kWh with a peak energy consumption of 50,692 kWh recorded in November 2012.

The micro -grid consists of two networks, a heating network where two wind turbines, WT1 and WT2 rated at 100kW and 60kW, respectively, are connected, and a service network where two diesel generators, rated at 32kW each, are connected, as can be seen in Figure 1. The two networks can be directly connected when sufficient power is produced by the wind turbines, or connected through induction couplers when the diesel generators are required. Dump loads are also connected to the heating network, in order to ensure the frequency doesn't exceed 52.4Hz under high wind conditions. The heating load is controlled by frequency relays located at each house to consume the remainder of the power of the WTs.

III. MICRO-GRID CONTROL METHODOLOGY:-

There are two modes of operation in the Fair Isle micro-grid. The first one is called guarantee hours where the power supply to the service load is guaranteed and it starts from 06:30 AM to 11:30 PM. The second one is a non-guarantee hours where the power supply can be discontinued depending on the availability of power from the wind turbines. The minimum allowed supply frequency is 45Hz below which power is turned off.

The control methodology can be summarised as follows:

- In guarantee hours, when the output power from one of the WTs is higher than the service load plus a manually set power margin of 0 kW, 3 kW, 6 kW, 10 kW, 15 kW or 20kW, for more than 8.0 minutes, the controller disconnects the DG and directly connects the WTs to the service network. Although electrically disconnected, the DG will remain running at no load for a while and then turned off.
- Outside the guarantee hours, there is no measurement of the service load demand. The controller compares the output powers of the WTs. If the power output of a WT is sustained for more than 2 minutes between 28kW and 36kW, it will take up the service load, if both satisfy the condition, WT1 will be connected to the service network
- In light winds where the lead WT1 is unable to provide enough power to the service network a soft induction coupler is energized to also connect the second WT.
- If the WTs cannot supply the service load, the power to the heating network is reduced, until the service frequency reaches 45Hz, when the WTs are disconnected from the service network. If this happens during guarantee hours, the DG is connected to supply the service network and the WTs will supply the heating network. During non-guarantee hours, the WTs are reconnected after each 2 minutes to supply the service loads, and this process is repeated until the WTs are capable of supplying the service network or the guarantee hours start.

IV. SIMULATION AND EXPERIMENTAL RESULTS

Five loggers are installed to measure the power, frequency and voltages of the service loads, the heating loads, the WTs and the DGs, as can be seen in Figure 1. Figure 6 shows the

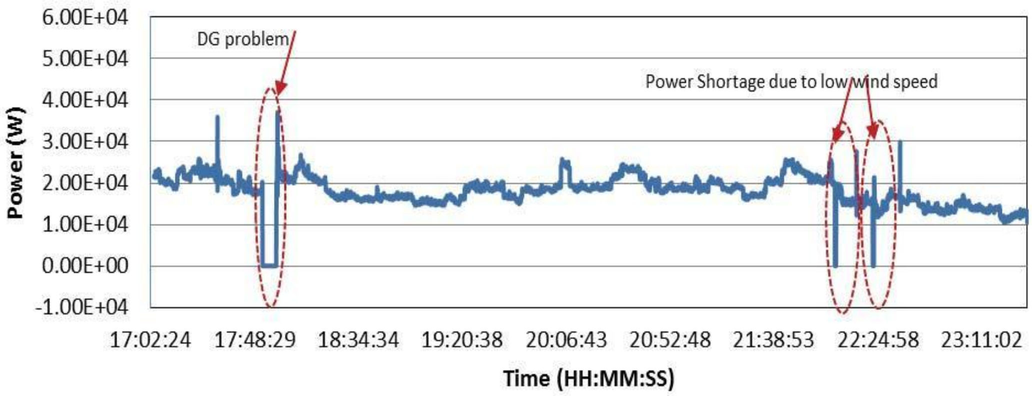


Figure 6: Measured service load power during the guarantee hours

Measured variation of the service load power during guarantee hours of a day in November 2013, where it can clearly be seen several power shortage events occurred due to reduced wind speed or DG issues. Figure 7 shows the measured variation of the service load frequency during guarantee hours. Again, frequency reached the minimum threshold of 45Hz several times. It may also be seen that there are two frequency ranges, when the WTs are supplying the service load, the frequency is between 50.7Hz and 52.1Hz, and when the DG is supplying the service load, the frequency is between 49.75Hz and 50.25Hz.

In order to assess the benefits of connecting a MLC200 flywheel to the Fair Isle micro-grid, a HIL set up is adopted, as shown in Figure 8. In the set-up, the model of the Fair Isle micro-grid and the grid-tie inverter are run on the real-time simulator, while the physical flywheel is connected to a programmable power supply. The power demand from the flywheel is achieved through the control of the power supply voltage, as shown in Figure 3, and a droop control methodology is employed in order to smooth the service load frequency. The power demand of the flywheel is given by:

Pdc=Kd*(Fd-FS)

Where P_{de} is the power demand from the flywheel, f_d is the demand frequency, f_s is the service load frequency, and Kd is a constant.

Two cases are considered, the first one is concerned with the smoothing of the service load frequency and the second is concerned with reducing the DG operating hours and guarantee to supply the service load.

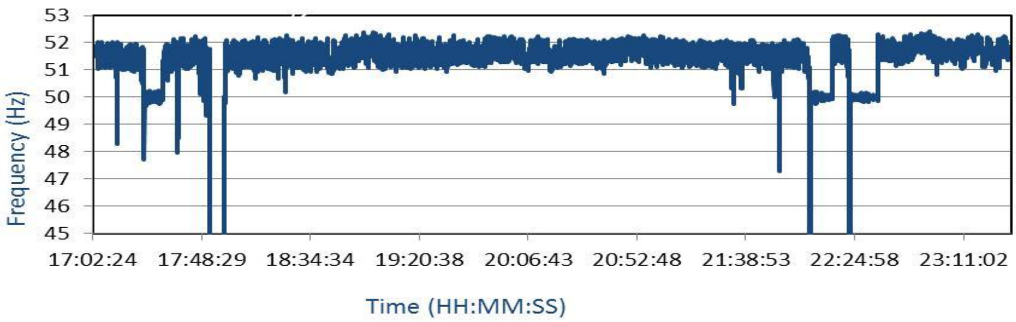


Figure 7: Measured service load frequency during the guarantee hours

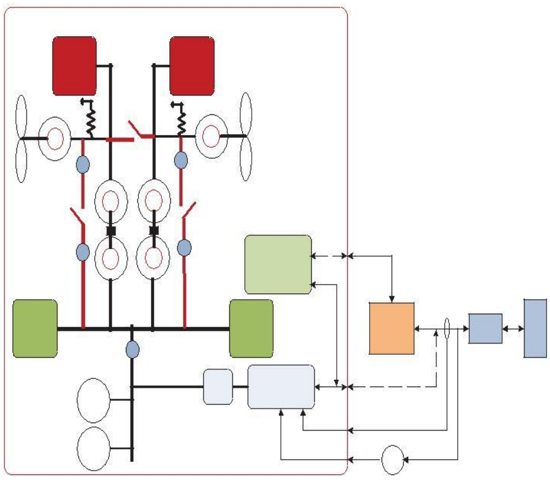


Figure 8: Schematic of the HIL set-up

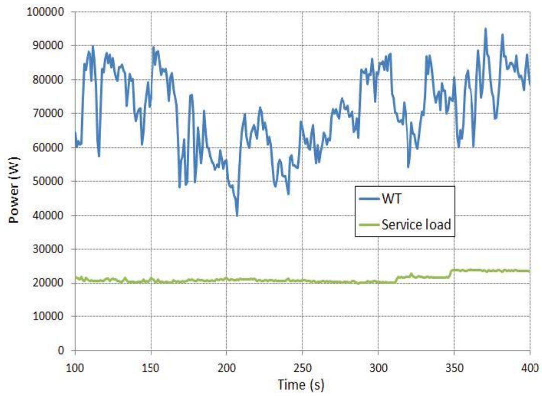


Figure 9: Measured WT and service load power

Case 1: smoothing of service load frequency

In this case the WTs supply the entire Fair Isle loads (Heating and service) as shown in Figure 9. The main purpose of the Flywheel is to smooth the service load frequency. Figure 10 shows the variation of the service load frequency, with and without the flywheel. The frequency variation without the flywheel is measured on the micro-grid at the Fair Isle, while the frequency variation with the flywheel is predicted by model of the Fair Isle, with the flywheel as hardware in the loop and as a model in the loop, when the powers measured on the Fair Isle are used as inputs. It can be seen that the introduction of the flywheel has resulted in reduced frequency fluctuations. Over the time interval of Figure 10, the average frequency is not affected by the introduction of the flywheel, being 51.48Hz for the Fair Isle measurements, and 51.43Hz and 51.48Hz, for the cases of flywheel in the loop and the flywheel model in the loop, respectively. However, the introduction of the flywheel has a significant impact on frequency fluctuation, with the standard deviation being 0.32Hz for the Fair Isle measurements and 0.19Hz and 0.2Hz for the cases of flywheel in the loop and the flywheel model in the loop, respectively

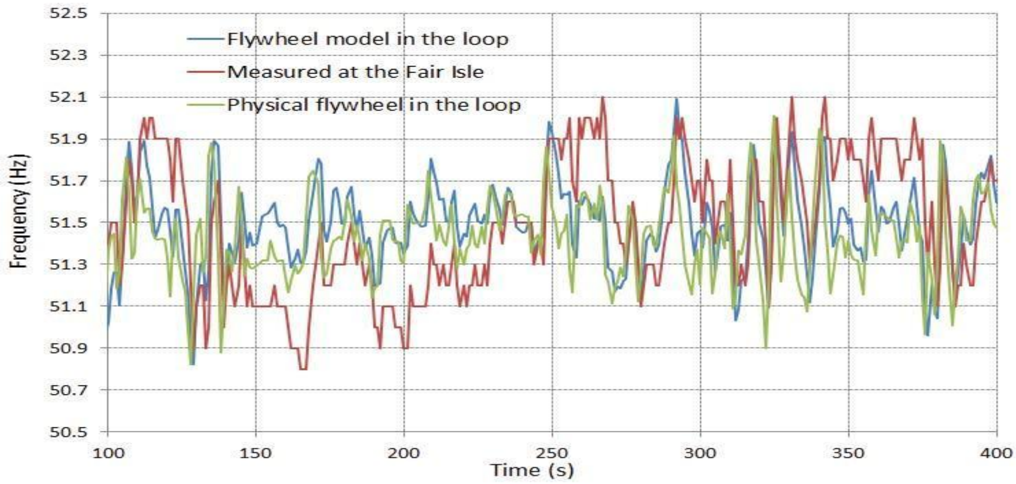


Figure 10: Service load frequency with and without Flywheel

Case 2:- Guarantee of supplying service load and reducing DG operating hours

In this case a changeover from WT to DG due to low wind speed is considered as shown in Figure 11. This results in a power cut lasting 26 seconds. The main purpose of the flywheel is to supply the power in order to keep the service load frequency higher than 45Hz, and avoid the power cut.

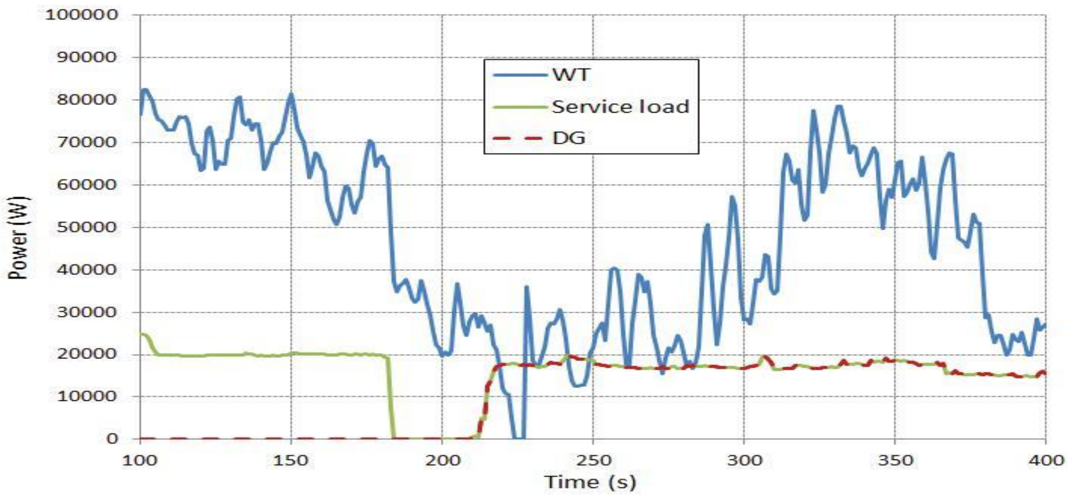


Figure 11: Measured DG, service load and WTG power

Figure 12, shows the variation of the service load frequency with and without the flywheel. It can be seen that the introduction of the flywheel maintains the service load frequency above 45Hz during the changeover between the WT and the DG, and hence, the power cut is avoided. As a result, the DG operating hours will be reduced, and the start and stop cycle will be minimised which should help extend the life of the DG and it components. Furthermore, it can also be seen that the flywheel model in the loop predicted adequately the behaviour of the physical flywheel.A model of the micro-grid is developed and run on a real time simulator with the physical flywheel being the hardware in the loop. The inputs to the micro -grid model are powers measured using loggers installed at specific locations of the micro-grid. It has been shown, that the flywheel can reduce frequency fluctuations and minimise the number of events when the diesel generators have to be called upon during temporary low winds.

Furthermore, a time-domain model for the flywheel system is also developed and experimentally validated. It has been shown, that when the Fair Isle micro -grid model is run with the developed flywheel model in the loop, similar results as those with the physical flywheel in the loop are achieved. Therefore, the developed model can be confidently employed to assess the benefits of the MLC200 flywheel systems.

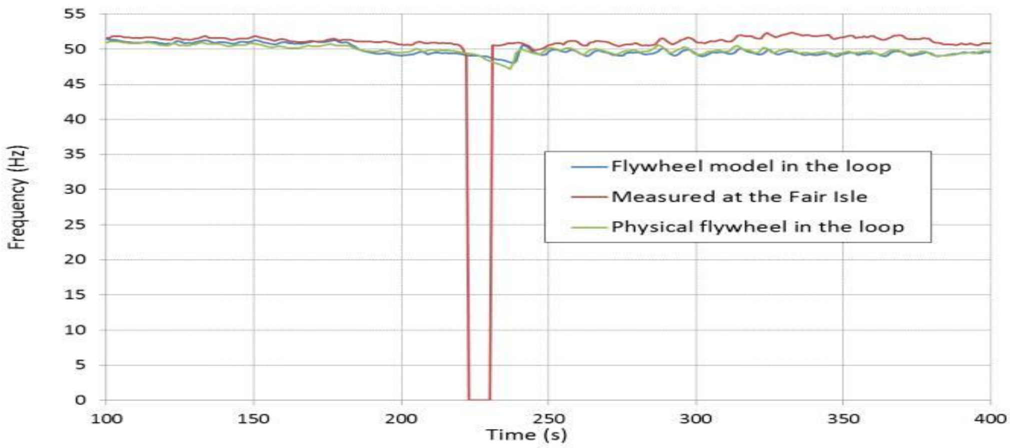


Figure 12: Service load frequency

V. CONCLUSIONS

The Fair Isle micro-grid is selected in order to demonstrate the benefits of employing a flywheel (MLC200) to improve the power quality, through frequency stabilisation, and increase the penetration of renewable sources, by minimising the need for diesel generation during temporary low winds.

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