Institute for Sustainable Energy, UNIVERSITY OF MALTA

*SUSTAINABLE ENERGY 2012:*
*THE ISE ANNUAL CONFERENCE PROCEEDINGS*
Tuesday 21 February 2012, Dolmen Hotel, Qawra, Malta

# DESIGN OF A REGENERATIVE LOAD TO INCREASE EFFICIENCY DURING RELIABILITY TESTING OF DC SUPPLY EQUIPMENT

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ABSTRACT: The paper is concerned with the design & construction of a regenerative load that redirects the electrical energy used for testing back to the grid instead of wasting it as heat. Manufacturers of DC supply equipment, such as DC power supplies and battery management units, apply burn-in testing at full load for 24 hours to detect early failures and reliability issues. The power drawn during full-load testing of DC supply equipment is normally dissipated into heat through resistive loads.
The regenerative load has a very wide input voltage range to be able to test various models of DC supply equipment. The regenerative load consists of an efficient wide input voltage range DC-DC converter and a grid-connected inverter. This system will allow the energy drawn from the equipment under test to be fed back to the grid. The only energy consumed corresponds to the losses within the system.

Keywords: DC-DC converter, Isolated-Ćuk, Regenerative active load

## 1 INTRODUCTION

The objective of this research is to build a regenerative load with a very wide input voltage range in order to support a wide variety of DC supply equipment such as DC power supplies and batteries. These are usually tested by active or passive load units (resistive loads) for long periods of time in order to detect early failures and reliability issues. The power drawn from the devices under test are dissipated into heat by the resistive loads. The purpose of the regenerative load is to feed back the energy to the grid, thus losing only a small percentage of the energy.
The regenerative load consists of a DC-DC Converter connected to a Grid-connected Inverter as shown in Figure 1.

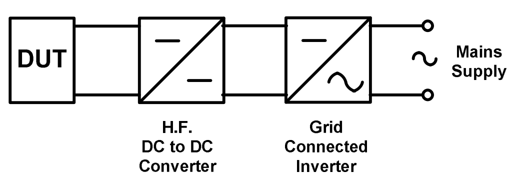


**Figure 1:** Block Diagram of a Device Under Test (DUT) loaded with a Regenerative Load

In order to implement the DC-DC Converter, an initial study was done in order to choose the most suitable topology for this converter. Following an investigation and simulations of the DC-DC converter topologies, the isolated Ćuk converter shown in Figure 4 was found to be the most advantageous topology which best fits the required specifications.

The 'Background' section outlines the specifications and features of the Regenerative load.

The 'Methods' section, briefly explains the operation of the isolated Ćuk converter and the design techniques involved to obtain a high input voltage range DC-DC converter.

The 'Implementation' section, describes the approach of modular converters with interleaved switching and how the remote monitoring and control of the regenerative load was achieved.

The 'Results' section includes the waveforms obtained from the circuit. Although simulations, open loop testing and closed loop testing were carried out, this paper shall concentrate on practical results obtained from case studies done on power supplies and batteries. The efficiency figures and savings obtained from the regenerative load are also presented.

## 2 BACKGROUND

### 2.1 Specifications

In order for the Regenerative Load to be flexible, it should be capable of loading various types and models of DC Supply Equipment. Thus, the Regenerative Load should convert a wide input voltage range into a constant output voltage to be supplied to a grid-connected inverter.

**Table 1:** Specifications of first prototype DC-DC converter

| *Input Voltage (V)* | *20 – 350* |
|---|---|
| **Max Input Current (A)** | 35 |
| **Max Input Power (W)** | 1000 |
| **Output Voltage (V)** | 200 |
| **Max Output Current (A)** | <5 |
| **Max Output Power (W)** | <1000 |
| **Switching Frequency (kHz)** | 75 |

This converter was connected to a grid-connected inverter with a maximum handling power of 1.1kW.

### 2.2 Modular Converters

This involves connecting two or more separate converters together in order to widen the input voltage range, the inputs of the two separate converters are connected either in parallel or in series as shown in Figure 2 depending on the input voltage requirements.

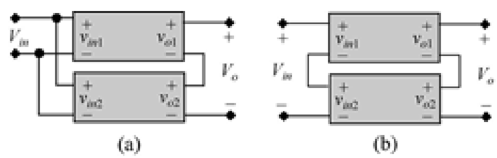


**Figure 2:** Block diagram of Modular converters

The second prototype involved two modular converters with their outputs connected in series and their inputs connected either in parallel or in series depending on the input voltage requirements. The specifications of the second prototype are listed in Table 2.

**Table 2:** Specifications of second prototype modular DC-DC converters

| *Input Voltage (V)* | *20 – 700* |
|---|---|
| **Max Input Current (A)** | 70 |
| **Max Input Power (W)** | 2000 |
| **Output Voltage (V)** | 400 |
| **Max Output Current (A)** | <5 |
| **Max Output Power (W)** | <2000 |
| **Switching Frequency (kHz)** | 75 |

These modular converters were connected to a grid-connected inverter with a maximum handling power of 2.5kW.

A drawback of switching DC-DC converters is the ripple currents they generate. Filters are usually used to filter out these ripples. To reduce the filtering required in this project, interleaved switching shown in Figure 3 was employed. By interleaved switching, the converters are set to switch at a 180° phase shift from each other resulting in a reduction of 50% or more in the ripple current.

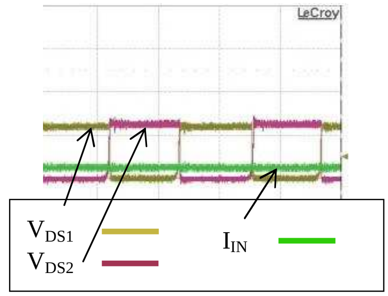


**Figure 3:** Interleaved Switching

### 2.3 Converter Operation

This research involves Delta Malta Ltd. and Abertax Malta Ltd. as project partners and a case study was carried out with each partner. In the case study of Delta Malta, power supplies were loaded with the Regenerative Load at their full power for a considerable amount of time to test their reliability. This case study was done with the first prototype 1kW Regenerative Load.

The second case study was done with Abertax Malta in which they required a setup which automatically cycles (charges and discharges) batteries. The discharging had to follow a discharge profile to monitor the batteries' performance at their normal operating conditions. Another requirement was to remotely (through the network) monitor and control the status of the setup. This setup was achieved with Power Supply Controllers (PSC). The setup will be described in more detail further on.

## 3 METHODS

The isolated Ćuk converter is shown in Figure 4. This DC-DC converter topology has a number of advantages when compared to other similar topologies. It has low input and output current ripples since inductors $L_1$ and $L_2$, and capacitors $C_{IN}$ and $C_2$ filter out such ripples.

$$V_{OUT} = V_{IN} \times N \times \frac{\delta}{1-\delta} \qquad \text{Eq. 1}$$

*…where N: Transformer's Turns Ratio*
*δ: Duty Cycle*

According to the isolated Ćuk converter's equation, it needs a high duty cycle in order to step up the voltage and a lower duty cycle in order to step down the voltage. The converter's operation avoids high peak input currents, making it less difficult to find the appropriate high current capable switches.

In this converter, the current flowing in the transformer is bipolar. This means that the transformer will be fully utilised and more power can be transmitted through it. Another advantage when using a transformer in such converters is that the input circuit is totally isolated from the output circuit and this is essential for high power applications in case of a fault. The transformer's turns ratio was used in order to centre the duty cycle range around 50% so that it does go neither close to 0% causing high peak currents nor close to 100% which may reach instability.

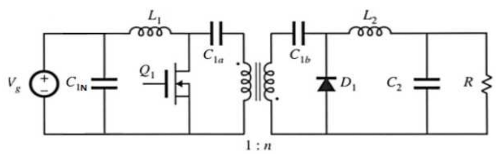


**Figure 4:** Isolated Ćuk Converter Topology

The isolated Ćuk converter shown in Figure 4 operates via capacitive energy transfer [1]. Capacitor $C_{1a}$ stores the source energy and when switch $Q_1$ switches on, this energy is transferred through the transformer forming a negative current on the transformer's primary winding, which in turn forms a positive current on the secondary winding, passing through capacitor $C_{1b}$ and finally released in inductor $L_2$, capacitor $C_2$ and to the load R. Concurrently, while the switch is switched on and capacitor $C_{1a}$ is supplying its energy to the load, the inductor $L_1$ is being charged from the source $V_g$. When switch $Q_1$ is switched off again, the energy from the source and inductor $L_1$ passes through $C_{1a}$, forming a positive current on the primary winding of the transformer. A negative current is formed on the secondary winding forward biasing diode $D_1$ and finally released in inductor $L_2$, capacitor $C_2$ and to the load R.

Switching DC-DC converters can operate in two different modes of operation which are the Continuous Conduction Mode (CCM) and Discontinuous Conduction Mode (DCM). Eq. 1 assumes that the converter is operating in CCM.

A DC-DC converter enters the DCM operation when the load decreases beyond a certain threshold or is unloaded. This is not a problem if the converter's control is designed to operate in CCM because it will remain stable if it shifts to DCM but one designed to operate in DCM tends to become unstable once it shifts to CCM. A converter designed to operate in CCM cannot remain operating in CCM unless it is always loaded. Once a converter's output is open circuit, it always shifts to DCM. When designing a converter to operate in CCM, the design is straight forward because the input to output voltage gain depends only on the Duty Cycle [2].

3.1 System Setup, Control and Protection

The design of the DC-DC converter involved the selection of the switching frequency, the magnetic component design (two inductors and transformer), over voltage snubbers (which are partly regenerative), the gate drive circuits, suitably rated Mosfet switches, power diodes, their respective thermal heat sinks and the capacitors. During design stage, the three main important criteria were maximum efficiency, size and minimal voltage and current ripples.

When designing the magnetic components a compromise was reached between their inductance which directly affects the current ripples, their resistance which increases its operating temperature and affects the converter's efficiency and their physical size. During the design of the inductor, the current handling capability was found to be a limiting factor on the inductance due to the fact that a high current requires windings with a high cross-sectional area and thus limits the number of turns available in the core. Since the inductance varies with the square of the number of turns, its value is limited. This results in higher ripples especially at higher input voltages.

Since the converter is designed to operate at 75 kHz, Mosfet transistors have to be used. In this application, the switch will have a voltage stress higher than 500V and a current rating of 35A, thus three 650V IPW60R045CP n channel Mosfets were paralleled together to obtain both high voltage and high current capability. When designing the gate drive, care was taken not to introduce any delays between the Mosfets' switching, and as a precaution, a separate gate resistor for each Mosfet was implemented. The gate drive supplied a peak current of 1.5A to the gates of the Mosfets.

Diode $D_1$ was chosen to be a Silicon Carbide (SiC) diode. These types of diodes have a zero reverse recovery current resulting in no dynamic/switching losses and both lower voltage drop and leakage current resulting in lower static/conductive losses. Also, the temperature coefficient of such devices is positive and so the current is split exactly between them when paralleled. The maximum reverse voltage on the diode was theoretically calculated to be around 800V. Three 1200V C2D05120 SiC diode were paralleled together [5].

The switching of the power electronic circuit can result in voltage stresses higher than the power semiconductors ratings, which may result in their destruction. In this respect, over voltage snubbers were implemented for the mosfets and diodes in order to reduce switching stresses to safe levels [3-5]. Both snubbers are partly regenerative which allow energy to be discharged to $V_{IN}$ and $V_{OUT}$ respectively rather than discharging it to ground, thus achieving better performance with a considerable decrease in the losses incurred.

3.2 Control Methods

For simplification purposes, this section will focus on the first prototype. An SMA Sunny Boy SB1100 grid-connected inverter was connected to the output of the isolated Ćuk converter. The grid-connected inverter was set to operate with a Constant Voltage Mode of 200V. Thus the inverter synchronises to the grid once a voltage of 200V or higher is applied on its DC link. Once it synchronises to the grid, it will start to increase the power fed to the grid until the DC link voltage declines to 200V. This happens when the output current of the DC-DC converter reaches the set value. A block diagram of the Device under test and the regenerative load together with its control is shown in Figure 5.

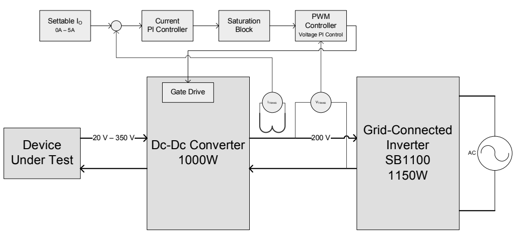


**Figure 5:** Regenerative Load block diagram with control

The converter's control is made up from two separate blocks, the voltage control block and the current control block each of which have a PI controller to control the set value of voltage and current. In the case of the voltage control block, a constant voltage reference is used to control the output voltage to be fixed at 210V. In the case of the input current controller (constant current), the current reference is set via either a pot or a PSC when remotely connected, so that the output current is maintained at a settable value of 0A to 5A. If the set current value is exceeded, the output voltage declines in order to maintain an input current equal to the set value. The voltage and current control systems drive a PWM Controller in order to switch the Mosfets at 75 kHz. The PWM controller used which is a UC3823A is also responsible of soft starting the circuit. The output current is fed back by means of a current transducer and the output voltage is fed back by means of a voltage transducer. The PWM signal from the Control circuit is then fed to the Gate Drive through an opto-coupler.

Apart from the control circuit, a protection circuit was implemented. This circuit is able to shut down the converter within 1µs in order to protect it from certain abnormal conditions that may result in damaging the circuit itself. All the protection circumstances present in the protection circuit are listed in Table 3.

**Table 3:** Protection Circuit

| ***Error*** | ***Condition*** | ***Action*** |
|---|---|---|
| **Low/No Input Voltage Present** | $V_{IN} < 20V$ | Shut Down |
| **High Input Voltage** | $V_{IN} > 350V$ | Shut Down |
| **High Output Voltage** | $V_O > 250V$ | Shut Down and Latch |
| **High Snubber Voltage** | $V_{OVS} > 600V$ | Shut Down and Latch |
| **Overload** | $I_O > 5A$ | Shut Down and Latch |

## 4 RESULTS

The following graphs were plotted from the data collected during the testing of the Regenerative Load. Figure 6 and Figure 7 are graphs of the efficiencies measured from the DC-DC converter of the first prototype.

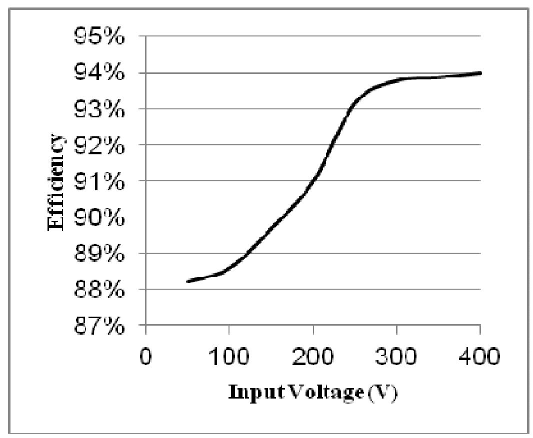


**Figure 6:** Efficiency of the DC-DC converter operating at full power (1000W) against input voltage

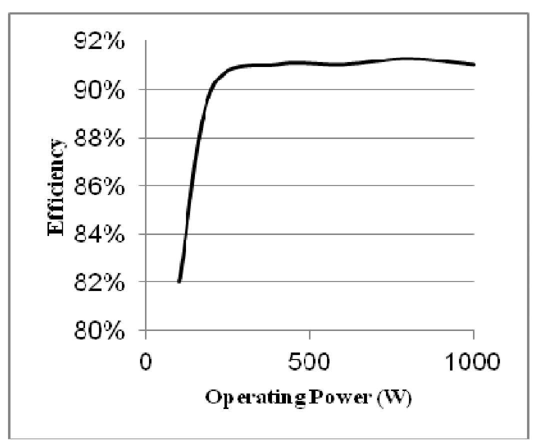


**Figure 7:** Efficiency of DC-DC Converter at an input voltage of 200V against operating power

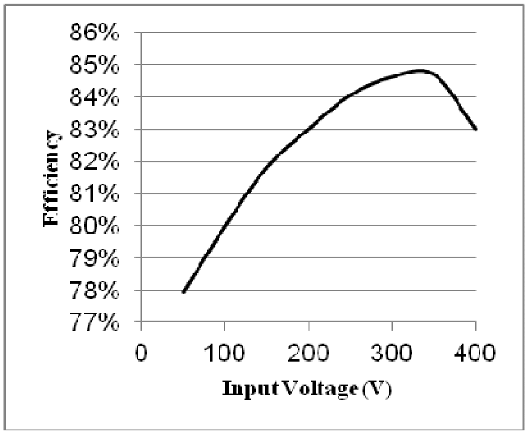


**Figure 8:** Efficiency of Regenerative Load operating at full load (1000W) against input voltage

Figure 8 and Figure 9 are graphs of the efficiencies measured from the Regenerative Load (now including the grid-connected inverter's efficiency).

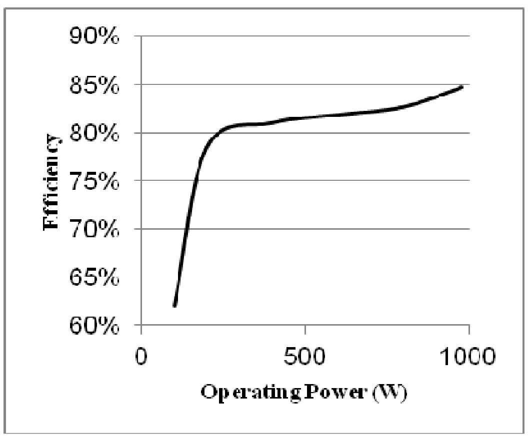


**Figure 9:** Efficiency of Regenerative Load at an input voltage of 200V against operating power

4.1 Case Study 1: DC Power supplies

The first case study was done with Delta Malta Ltd. and consisted of testing DC Power Supplies manufactured by the same company. These power supplies were loaded with the first 1kW prototype regenerative load and the consumption was compared to the consumption when loaded with resistive loads.

In order to measure the power and energy usage, the equipment was set up as shown in Figure 10. The devices under test which in this case study are Delta power supplies were loaded by the regenerative load. The power and energy were measured by a power and energy meter.

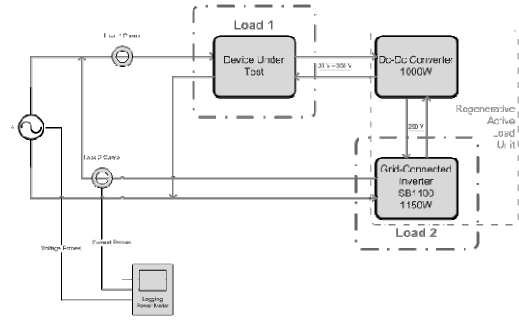


**Figure 10:** Block diagram of the setup built for Case Study 1 including the Power meter

This case study involved five separate tests on different power supply models with a power handling ranging from 150W to 800W. Figure 11 shows the waveforms obtained when testing a 70V 800W Power Supply.

The top waveform represents the power that is being consumed by the power supply. The third trace indicates the power that was being regenerated back to the grid while the lower trace is the difference representing the power consumed within the system: this includes losses within the power supply, the DC-DC converter and the grid-connected inverter. The second graph is the efficiency of the whole system which once again includes the efficiencies of all the three devices. The lower graph is the power that is being lost within all three devices.

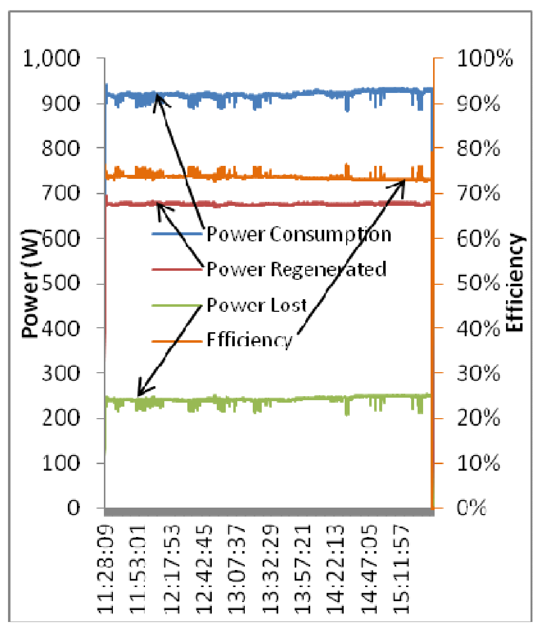


**Figure 11:** The waveforms obtained from the Power and Energy meter when testing a 70V 12A 800W Power Supply

Positive results have been achieved from the tests carried out in this case study. The Regenerative Load has the potential of saving a considerable amount of electrical energy consumption in Industry during the testing phases of DC Supply equipment. The savings that were estimated in all five case studies is listed in Table 4.

**Table 4:** Results of tests carried out in this case study

| *Device under test* | *Power consumed with resistive load* | *Power consumed with Regenerative Load* | *Percentage Decrease in Energy consumption* |
|---|---|---|---|
| 200V 800W | 842W | 195W | 77.0% |
| 70V 800W | 928W | 245W | 73.6% |
| 35V 800W | 964W | 342W | 64.5% |
| 30V 300W | 367W | 127W | 65.4% |
| 30V 150W | 174W | 64W | 63.2% |

4.2 Case Study 2: Batteries

The second case study was done with Abertax Malta; the second project partner. This case study involved cycling of batteries in order to test their performance over different load profiles. Abertax needed a cycling (automatic charging and discharging) setup that was able to control and monitor its status remotely through the company's network.

The second 2kW prototype regenerative load was used for this case study. Two interleaved switched modular DC-DC converters were connected together as shown in Figure 12 to increase the power handling to 2kW with an input current not exceeding 70A. The grid-connected inverter was replaced with a 2.5kW unit requiring an input voltage of 400V. Hence although the converters' inputs were connected in parallel, their outputs were connected in series to obtain an output voltage of 400V. The Device under Test (DUT) for this case study were 5 6V 180Ah lead-acid batteries which add up to a voltage of 30V.

The charging-discharging setup is shown in Figure 13. The Battery Charger was responsible to charge the batteries from the Mains supply once they are discharged.

On the other hand, the Regenerative load was responsible to discharge the batteries once they are fully charged and redirect the energy back to the grid.

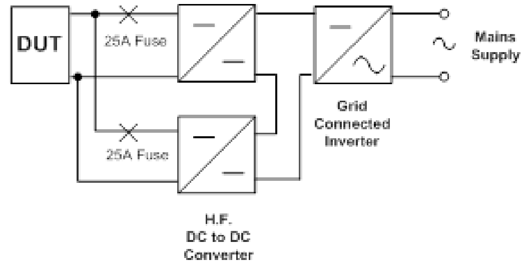


**Figure 12:** Block diagram of Regenerative Load with modular converters

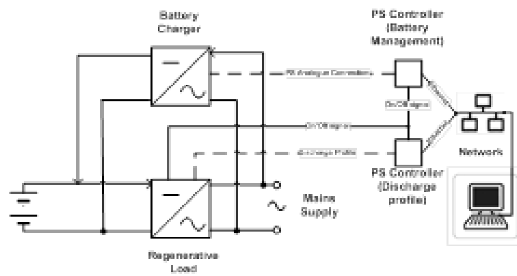


**Figure 13:** Block diagram of the automatic Charge/Discharge setup

The control of the setup was carried out by two Power Supply (PS) Controllers. These controllers were connected to the network through RJ45 (Ethernet) so that the whole setup could be monitored and controlled remotely. The controller supports the Standards Commands for Programmable Instruments (SCPI) programming language.

**Figure 14:** Remotely monitoring and controlling the DC-DC converter through a specified profile

The PS Controller (Battery Management) continuously monitors the battery's voltage through the battery charger's voltmeter, so that it toggles between charging mode and discharging mode according to the battery's state of charge. This controller monitors the battery voltage through the battery charger's voltmeter and after determining the state of charge of the batteries, it toggles between charging mode and discharging mode.

The second PS controller (Discharge Profile) which was also network connected, was used to generate the discharge profile and supply it to the Regenerative load and also to receive the current feedback. The discharge profile was developed and remotely uploaded by its specified graphical software ‘Power Supply Control 1’ shown in Figure 14. The current feedback is also sent back through the network so that the status of the setup can be monitored through the same software.

The power and energy were measured by means of a power and energy meter. Figure 15 shows a graph obtained from the power and energy meter during a discharge/charge cycle. The discharge is marked by negative (regenerated) power and as one can notice, it is following a discharge profile. The charging is marked by a positive (consumed) power. For this test, the charger was set to charge the batteries at a constant voltage of 36V current limited to 15A. The batteries are charged until the current drops to 5A. Then the PSC waits for ten minutes and starts the discharging process automatically. The discharging process follows a discharge profile as uploaded to the second PSC.

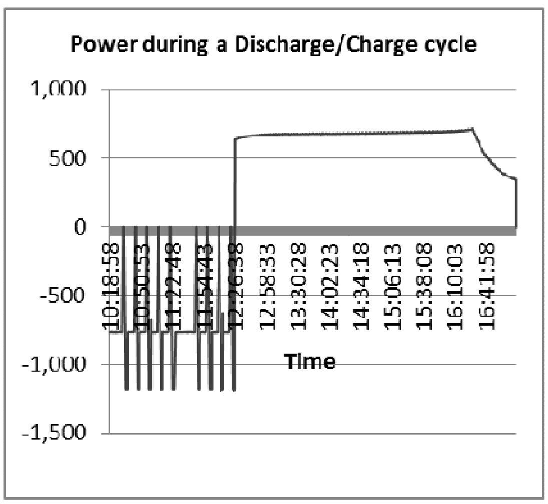


**Figure 15:** Graph of power during a Discharge/Charge cycle

During the discharge process, 1.6kWh of electrical energy were regenerated to the grid. This figure was affected by the inefficiencies of the regenerative load. The DC-DC converters operated at input currents as high as 70A and the efficiency diminished to an average of 87%. The average efficiency of the grid-connected inverter was 91%. Hence the regenerative load performed at an efficiency of 79%. This means that the batteries gave out 2kWh of electrical energy.

The charging process consumed 3.1kWh of electrical energy. The efficiency of the battery charger is 85% and so the batteries were fed with 2.64kWh.

Hence the batteries’ charge/discharge efficiency is 76%.

Only 52% of electrical energy was regenerated from the 3.1kWh consumed, since there are a lot of inefficiencies in the setup that we had no control on them. These inefficiencies are present in the batteries, the battery charger, and the grid-connected inverter.

## 5 CONCLUSION

The overall efficiency of the Regenerative load ranged from 77% up to 88%. If instead of using active and passive loads, industrial organisations opt to use such regenerative load, a considerable amount of electrical energy will be saved. Further savings will result when the load units are located in cooled air-conditioned areas since the load units are now dissipating less heat to their environment.

The Regenerative Loads found on the market have a limited voltage range thus limiting their flexibility and practicality. The regenerative load designed and developed in this research has a wide input voltage range which can therefore be used to test a wider range of DC equipment. The design of such a wide input voltage and current range converter introduces problems in component selection and design due to the wide range of conditions that must be catered for. Also, snubber circuits have to introduce low losses at all input voltages but must be most effective at high input currents which result in high voltage overshoots possibly damaging the switches.

The results and savings obtained from the system were satisfactory and further work is being done. Modular converters (two converters connected together either in parallel or in series depending on the input voltage conditions) were employed in order to support an extended input voltage range up to 700V and an operating power of 2kW. This allows more configurations and types of DC supply equipment to be supported by the same Regenerative Load.

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## 8 ACKNOWLEDGEMENTS

The authors would like to acknowledge funding for this research under the Manufacturing Research Platform project ERDF-083, Operational Programme I - Cohesion Policy 2007-2013 "Investing in Competitiveness for a Better Quality of Life", project part-financed by the European Union European Regional Development Fund (ERDF).