dti

CHARACTERISATION OF 5KW FUEL CELL BASED UPS

Final Report

CONTRACT NUMBER: F/03/00284/00/00

URN NUMBER: 06/921

The DTI drives our ambition of 'prosperity for all' by working to create the best environment for business success in the UK. We help people and companies become more productive by promoting enterprise, innovation and creativity.

We champion UK business at home and abroad. We invest heavily in world-class science and technology. We protect the rights of working people and consumers. And we stand up for fair and open markets in the UK, Europe and the world.

`

A STUDY TO CHARACTERISE THE PERFORMANCE OF A 5 KW FUEL CELL BASED UPS

F/03/00284/00/00

Contractor

SiGEN Ltd

Prepared By

Karthik Rajendran
Stuart Graham

First published 2006

EXECUTIVE SUMMARY

Objective: This report endeavours to understand the technical aspects of a 5kW fuel cell based UPS. Suitable testing is done to determine whether the performance of the system is equivalent to a battery based UPS. The Economic analysis deals with the feasibility of fuel cell UPS in today's economy.

Introduction: Significant sales of fuel cells have yet to make an impact within the UK stationary power market. This may be due to the initial capital involved and of the market to accept new technologies. The fuel cell system requires a wide range of engineering skills for product design, development and assembly. Traditional methods of planning a UPS system still apply for a fuel cell system. Some additional expertise, gas safety for example, will be required. The absence of an impartial guide to selection of fuel technology, planning and their economics does not help their cause. Despite hydrogen being one of the most commonly used industrial gasses, the risks associated with the storage and use of hydrogen, as a fuel, has been poorly perceived. A thorough risk assessment together with risk reduction measures greatly reduce the probability of accidents. Expertise from battery hydrogen management for UPS systems can be incorporated easily into the fuel cell market.

The above-mentioned factors including a detailed description of the gas storage and delivery system are explained as they are an unknown factor for many familiar with a battery UPS. Selection of electrical subsystem for UPS is also discussed. References are included that could be used for carrying out a risk assessment locally. A life cycle analysis is included to help ease the decision of choosing a UPS based on autonomy and lifetime.

Summary of the work carried out: The initial tasks involved the selection of a suitable fuel cell system. Factors such as units in the field and system performance were used to select Plug Power's Gencore® unit. Telecom grade inverters and rectifiers provide a double conversion mains UPS system whilst also ensuring a high degree of reliability.

Since a cabinet, manifold, and delivery system already existed for the testing laboratory, no major works were required to ensure supply. Load banks, both resistive and capacitive, were constructed to simulate real life inverter loads. A control panel with emergency stops and leakage circuit breaker for safety was used for operator safety during the test program.

Testing was then carried out to verify the operation of the fuel cell and establish weather performance was equivalent with battery-operated UPS. The influence of temperature and stack power over start-up time was studied. To establish the dynamic operation of the fuel cell, load-switching tests, both of active and reactive nature, were carried out. Consecutive runs of soak tests were done to verify long hours of operation.

Once the performance of the fuel cell was satisfactorily concluded, study of life cycle economics was carried out. This included the influence of autonomy on the capital costs and annual operating costs were studied for selection of a UPS.

Summary of results: The fuel cell has proven capable to equal the performance of a battery bank, to the inverter and then AC load, the fuel cell is just a battery which never drains. Testing in lower operating temperatures has shown start up is not affected by long hours on non-operation. Though the optimum fuel cell stack temperature is higher than 50°C, it starts up in less than a minute with rated loads at an ambient temperature of less than 20°C. Start up is not affected when operated with active and reactive loads.

The influence of temperature can be observed in the tabled data. Higher stack temperatures result in quicker start up times which result in less stress on the transitional battery.

The transient period has been observed and documented to understand the behaviour of the system. This phase is a complex interaction involving the fuel cell, mains rectifier, inverter system and batteries sharing a common DC bus which work together to ensure the AC load is seamlessly met.

The system does not deviate from normal operating parameters for long hours of operation as seen during soak tests. With dynamic loads, the fuel cell has a limitation. It cannot provide for high transients and the system has to use the transient battery provided. This reliance still on batteries is seen by some as a system weakness. Newer models of other manufacturers use ultra–capacitors instead, to increase the system reliability. With the test system, the output power ramps up to meet the load requirement within a minute. Battery support is generally only required for load transients greater than approximately 1.2 kWdc, the system functions normally for both active and reactive load transients. Tests involving periodic loading and unloading up to rated load were conducted and it was found that the fuel cell performed well.

Efficiency is calculated using derived values, which confirms with this class (PEM) of fuel cell. Life cycle modelling is done to investigate the economic validity of choosing a fuel cell UPS over an equivalent battery operated UPS. Both capital cost comparison and operating cost comparison favour the fuel cell system over a battery system when it comes to extended autonomy. This advantage becomes more obvious when hydrogen is available on site, either as product or as by-product of a process industry.

Recommendations:

The relative advantages and cost benefit of a fuel cell based UPS does not translate into significant sales in the U.K. Lack of field data and absence of formal infrastructure are believed to be the reasons why plant managers are resisting the adoption of this technology. This could be addressed by way of either incentives or deploying the fuel cells in sufficient quantities to increase product confidence and awareness.

Tax breaks and capital allowances offered for other low carbon and low pollution technologies could also extended to fuel cell UPS equipment. This would allow increased uptake of these systems in the U.K. Public procurement of fuel cell systems is ideal for studies in long-term reliability. It also could lead to additional publicity and engaging the fuel suppliers formally.

The use of fuel cells as virtual power plants for exporting power to grid has a potential for renewable energy. Since storage of energy by generating hydrogen during low demand is an attractive environmentally, this could be re-used for generating power during peak demands, operating much like pumped-hydro-electric schemes. This grouping of multiple fuel cells and their performance could be investigated.

INDEX

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

Fuel cell technology is well established as an efficient and clean way of producing power. Beginning with the fuel cells used in space programs, the technology of fuel cells today has advanced greatly using various electrolytes and fuels. One of the major drivers is the automotive sector where fuel cells, due to their low noise operation, low volume, weight, and very low pollution, are an attractive source of primary power. The Polymer Electrolyte Membrane (PEM) based hydrogen fuel cell has emerged as a first choice for the automotive sector. PEM fuel cells are based on a solid electrolyte with a low operating temperature. They require pure hydrogen but can operate with relatively high impurities in the air intake for oxidant. This focus has also helped develop PEM based fuel cells for stationary power generation.

Back up power systems use large battery banks, generator, or both to provide AC or DC power for your load irrespective of the mains supply condition. Battery technology has seen tremendous improvements in storage capacity and reliability. Nonetheless, the weight and volume of batteries require significant site alterations to accommodate the installation. The influence of temperature on lifetime and re-charging time are significant factors to be considered during the planning stage. Environmentally friendly disposal adds to the cost of replacement. Above a certain threshold, battery based backup becomes economically unattractive and generators tend to be used, normally in conjunction with a small battery to power whilst the generator starts. Essentially combustion engines, they produce noise and emissions while burning expensive fossil fuel. These factors have led to fuel cells being pursued as an alternative back up technology to generators. In turn, it offers significant reduction in weight and volume, over batteries, with run time limited only by the availability of fuel.

Requirements of backup solutions range from providing power to a single server to complex networks and emergency systems. Products available today vary from 1kW to 15kW and more. The larger of these systems tend to be of modular design. This offers the choice of increasing capacity with minimal changes to an existing installation. Component redundancy is also very easily achieved. A fuel cell system along with its power conditioning equipment can easily be retrofit into an existing UPS system, by replacing the battery bank.

Fuel cell based backup products have not achieved significant sales in the U.K. for various reasons. Some of the doubts related to adopting new technology include viable fuel supply infrastructure, safety of hydrogen-based systems and performance against existing solutions. The end user for such a product could be a SME, willing to invest in new technology, or a large enterprise, with the ability to adopt environment friendly systems. Any investor would analyse the cost benefit before such an investment. These issues have to be addressed by providing information on fuel cells, their operation and the economics involved so that even small enterprises begin to consider this as a viable option.

This report offers a brief description of the fuel cell as a system and each component of the system along with the overall operation. A detailed explanation of the storage and delivery system is included for the benefit of engineers unfamiliar with pressurised gas systems. The process of risk assessment, an integral part of the planning process, is briefly addressed. A brief note on efficiency is also included. The economics associated with the selection of the fuel cell system over a battery-operated system are explained with respect to initial capital outlay and annual operating costs. The influence of capital allowances are also laid out.

The fuel cell, due to its nature of construction, has some inherent limitations. In a system, these limitations are addressed in various ways through design, such that it is no different from a battery bank in performance. Due to proprietary design, products of different manufacturers tend to have different specifications and performances even for similar power ratings. Testing is done for all realistic situations to assess the performance of the fuel cell in simulated conditions. The operation of the fuel cell is tested at various ambient temperatures with both active and reactive loads[1], across the whole operating range. Performance during long hours of operation was also tested and care was taken to look for system anomalies which may not have appeared during short runs. Dynamic performance was tested using switching loads. The conclusions of the testing are noted along with suggestions for improvements of the design.

[1] Reactive load: Inductive and capacitive loads such as motors and ballasts, present a power factor of less than unity to the supply. A power factor of 0.8 lead (Capacitive) or lag (Inductive) at rated loads are usual with 0.5 Lead or Lag considered extreme conditions.

2 SYSTEM DESCRIPTION

Whist the chemical reactions are very simple, the fuel cell operation, as a system, is significantly more complex than a lead acid battery. A wide variety of activities is carried out to maintain the optimum state of operation. These include regulation of the air flow, power conditioning, monitoring for loss of mains condition and a host of other functions. All these sub-systems are packaged into a single unit with inlets for fuel and connectors for DC power output. They are also provided with a means of communication for monitoring and diagnostic purposes. A fuel cell system manufacturer specifies the acceptable range of pressure for fuel inflow. Not every manufacturer supplies complete solutions for fuel storage and delivery. These are to be sourced by the customer along with any emergency cut-offs and safety systems they feel is appropriate for their installation. A suitable rectifier and inverter unit may need to be chosen for mains applications. For ease of description, the complete system can be divided into:

1. Fuel cell system
2. Electrical power interface
3. Fuel storage and delivery

2.1 Fuel cell system

The fuel cell used in this investigation is from Plug Power, USA; model Gencore® 5B48 Fuel cell system. The model is built for data communication applications with a wide operating temperature range of –40°C to 46°C and certified by UL, CE and FCC for safe operation. It is rated for continuous power of 5kW within the selectable range of 42-56VDC. Plug Power has already installed more than 600 fuel cell systems around the world. Four units have already been installed in U.K., which have been functioning reliably.

The Gencore® unit is a self-contained system with inlet for fuel, ports for diagnosis (serial port) and scaling (LAN) and connections for output DC power and remote DC bus sense. Air supply and cooling are also fully self-contained. A bidirectional DCDC converter provides power interface from customer DC bus to the system, drawing on bus power during standby and exports power during mains failures. Four batteries of 12V, 33AH each are transitional provide support. The unit contains a chassis mounted radiator for removing excess heat of the stack. Active air circulation is maintained using ventilation ducts and fans. The output potential of the DC-DC converter can be user defined and is generally set lower than the rectifier output. With mains present, this ensures the rectifier:

1. Provides power to the load through the inverter
2. Recharges the battery
3. Provides power to the fuel cell subsystem
4. Ensures the system does not run on false low bus incidents

Since the potential of the stack varies widely, DC power conditioning equipment is required to provide constant output voltage. The fuel cell unit also consists of associated sub-systems like fuel management, thermal management, power management, system management, and safety systems. It also includes communication interface for carrying out diagnostic procedures.

Figure 1. Picture of the Gencore® fuel cell system

2.1.1 Operation of fuel cell

The oxidation of fuel, hydrogen in this case, produces energy. Instead of combustion as in a typical engine, energy is produced by catalytic oxidation in a fuel cell. This directly produces electricity and heat. To achieve this in a controlled manner a PEM cell uses a special electrolyte membrane, which has the ability to transfer protons across itself but block electrons. Each cell consists of a sandwiched layer of a membrane between two electrodes with a catalyst on each side. The catalyst, usually platinum, splits the hydrogen molecule in to mono-atomic hydrogen. The proton and electron in the hydrogen atoms split with the protons migrating to the cathode side by means of the membrane. The electrons released at the anode, going through the external circuit, recombine on the cathode side forming water and releasing heat.

A fuel cell stack consists of cells arranged in series for higher potential. Hydrogen is provided at the anode side of the cells and oxygen on cathode side of the cells. The oxygen in air is sufficient for air to be used on cathode side. Blowers force hydrogen and air into the anode and cathode channels respectively, of every cell. The air intake is cleaned of any particulate matter and pollutants, as these can physically block the gas channels and reduce the effectiveness of the catalyst. The cathode exhaust contains water, which is reused to maintain the moisture content of the air intake, by a humidity exchange unit. Hydrogen exhaust from the anode is fed back by means of a recirculation blower in to the inlet of the anode for re-use of unused fuel. This technique ensures that hydrogen as present in equal quantities throughout the stack. A continuous hydrogen bleed ensures that impurities do not build up within the anode gas stream. This bleed gas is channelled to the air intake for the cathode side of the stack, where the hydrogen forms water and heat on combining with oxygen in the presence of the catalyst. This ensures hydrogen is not released out into operating environment or wasted as the heat improves efficiency at low powers.

Since the cathode reaction is exothermic, a large amount of heat is generated necessitating cooling. The coolant mechanism pumps the deionised water and glycol coolant through the stack through special channels. A radiator system removes excess heat. The membrane should not be subjected to high temperatures. The thermal management system ensures a balance between optimum stack reaction temperature and state of hydration of the electrolyte membrane. The membrane based humidity exchange unit also has a peak efficiency temperature similar to that of the stack. When stack temperature is not sufficient for optimum production of power, possible in cases of low loads and low ambient temperature, heater assemblies are used to increase temperature quickly.

Upon mains failure, the fuel cell system draws power from the batteries for starting up. Once the start-up sequence is completed, it begins to provide power to the external DC bus, connected to which is an inverter load. The Gencore® system has a limited response time; it cannot ramp up its power production immediately to the value of the load. The batteries support the load during this phase.

Inadequate fuel supply is detected by rapidly falling cell voltage. Stack voltage under loaded condition is continuously monitored. Under these conditions, the monitoring software isolates the stack to prevent damage at low inflow. Similarly, the monitoring system keeps track of the stack temperature, enclosure temperature and isolates the system at any unsafe operating condition. Shut down is the last resort as the system attempts to recover from any malfunction. Should the system fail, the batteries can support the load for a brief time.

2.2 Electrical system.

The true online double conversion UPS mode defined in IEC 62040-3 is the preferred UPS systems of higher power rating. The process of rectification and re-generation of AC output offers precise regulation of output voltage and frequency. It provides transition free transfer of load from mains to battery. The load is also isolated from mains harmonics and spikes. This is an expensive configuration due to additional electronics but the advantages easily outweigh this cost.

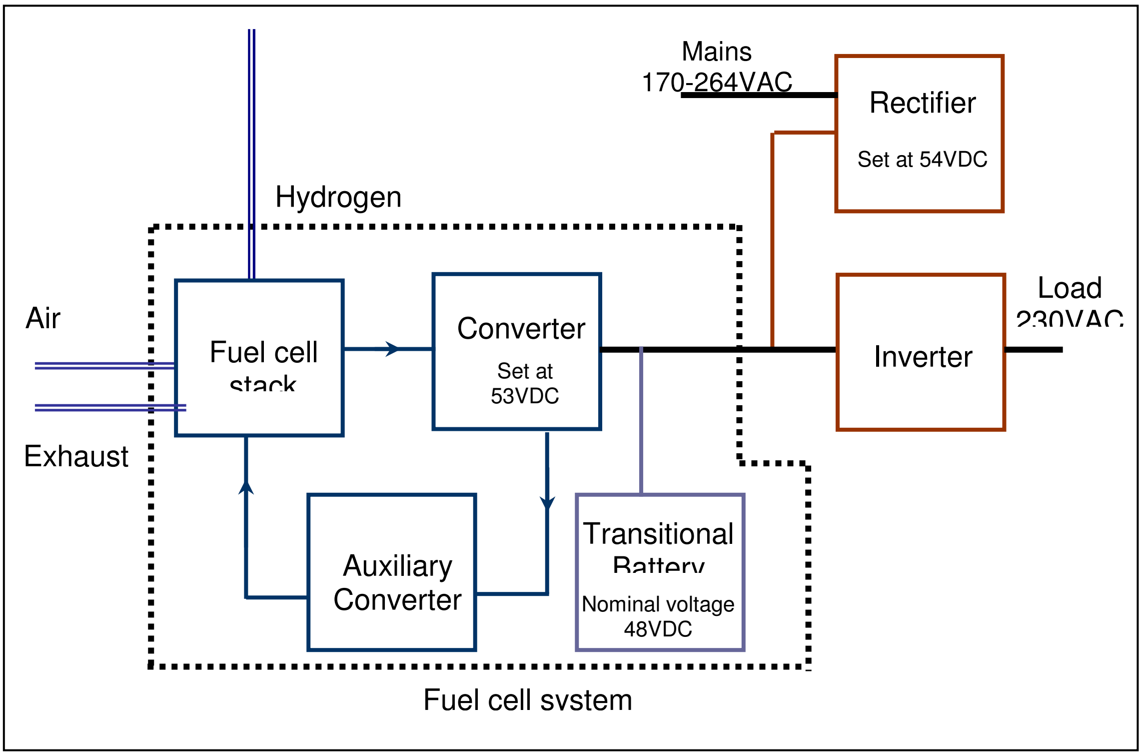


Figure 2. Schematic diagram of interconnection of fuel cell and true online interconnection

The inverter provides a clean sinusoidal voltage and frequency regulated output voltage. Since transformers and other devices with Switch Mode Power Supplies tend to draw very high transient currents, the inverter should withstand the surges without disconnecting the load. The fuel cell is rated to provide 5kW output power and draw a maximum of 1.1kW input for the auxiliary circuits. The auxiliary supply provides power for the system software, ventilation, heaters, and sensors. It is not practical to connect loads close to 5kW on the inverter since any slight overloading will cause the inverter to disconnect. A safe practice is to connect 75% of the output rating of the inverter as load. The maximum output load should be restricted to 4.5kW. The model used is of Unipower Telecom's INV5000-HS-50, 5000 VA with a wide input DC voltage range (42VDC – 56VDC), and 230VAC 50 Hz output. The overload capability extends to 300% beyond which the circuit breaker trips. It also has electronic shutdown, which acts first, in case of short duration overloads. The circuit breaker responds to prolonged overload conditions.

The rectifier either is a separate unit or integrated along with the inverter. The rectifier generates the DC bus during on mains conditions; this provides power to the inverter, fuel cell and recharges the batteries. Since the initial battery, currents are of transient nature and high, the rectifier should be able to protect itself from such short-term overloads without disconnection. Usually by imposing a constant power, voltage limit. It has to be rated to provide the battery charging current. The unit chosen is of Unipower Telecom RRS series consisting of two modules of 50A each with hot swap capability. The output can be varied using potentiometers from 47VDC to 57VDC. This is necessary to limit the battery charging current. It also has manual voltage limit capability necessary while charging batteries, which tend to draw high transient currents in discharged condition. Overload will result in a power limit being imposed, causing the output DC voltage to fall. The rectifiers are also power factor corrected.

The inverter and rectifier chosen for this setup belong to the telecom grade, with hot swappable features. The rectifier and inverter confirm to CE standards, and are compatible with each other.

2.3 Hydrogen storage and delivery

Hydrogen provision solutions vary from local generation (reformed hydrogen), metal hydride cylinder storage, liquefied storage and compressed storage. As the infrastructure exists for the storage and delivery of compressed hydrogen cylinders, they are a practical choice for the UPS. In the U.K., there are many suppliers capable of industrial grade hydrogen supply, in standard K-class[2] cylinders. These cylinders are filled at 172-175 bar to hold an equivalent of 7.26Nm^3 (Normal m^3). This roughly translates into 21.5 kWh[3] per cylinder. The number of cylinders on site varies linearly with the back up time required.

The location of hydrogen cylinders has to confirm with the code of practice CP-25 of the British Compressed Gas association. This is to ensure safety of personnel, operating in the vicinity of, or with the cylinders. A foam insulated stainless steel cabinet fitted with cylinder racks typically holds four cylinders. The cabinet confirms to IP 56 (EN 60529:2000) and rated for protection against fire. Since hydrogen is a flammable gas, certain regulations and guidelines have to be followed with relation to the manifold design[4] and piping.

The cylinders are divided into two banks, with one as reserve. Each cylinder is connected to the manifold by a flexible tailpipe. An isolation valve is provided on the manifold for each cylinder. A bank consists of two cylinders, a vent valve, high pressure gauge, and isolation valve, leading to the automatic changeover regulator. This mechanism automatically switches to the bank with higher pressure ensuring uninterrupted supply of hydrogen. A manual over-ride is also provided. Changing of a cylinder bank involves isolating the bank using the cylinder valves and, and replacing the cylinders. Check valves help to ensure safety. The connections to the manifold are vented of any impure gas before opening the pipeline valve. Cylinders can be replaced even when the fuel cell is in operation.

The main valve low-pressure indicator and regulator are used to set the supply pressure as required. Fuel cell systems have an internal pressure regulator allowing

---

[2] K-class cylinder Dimensions: 1460mm (H), 230mm (D), Weight: 65 kg.
[3] Lower heating value of hydrogen: 33.39kWh/Kg, 1m^3 of hydrogen = 0.89 grams.
[4] CP-4 of BCGA

them to be supplied at 3-5 Bar (1 Bar = 10^5 Pa). A flame arrestor is connected in series with the main valve on the distribution side to prevent any flames reaching the cylinders should a site fire impinge upon and enter the pipework. Stainless steel piping is used through out distribution. A fail-safe solenoid valve interlocked with safety sensors indoors contained in the pipeline near the gas source. This cuts off hydrogen supply in event of gas or fire detection. Further recommendations are available from HSG243 for setting the detection level for the hydrogen sensors.

Figure 3. Hydrogen storage cabinet with vent pipes

3 Risk Assessment.

Hydrogen like any other energy carrier is highly flammable and can form explosive mixtures with air even at low concentration. The flammability range is varies from 4% (Lower Flammable Level) to 75 % by volume in air. Being odourless and colourless, it also burns in virtually invisible flame in daylight. Its smaller molecular size increases the chances of leakage through cracks and joints. Since the human body cannot recognise signs of decreasing percentage of oxygen in air, leaking hydrogen in a close environment can lead to asphyxiation. The nature of the risks involved has to be clearly understood from the onset. Nonetheless, hydrogen has been used in the food and petrochemical industry with an excellent safety record. The perception of hydrogen as an unsafe fuel has to be tackled with strict adherence to safety measures.

A risk assessment has to be carried out locally at the site of installation to take in to account possible hazards with preventive measures imposed if required. It also should include hazards arising due to accidents and misuse of the equipment to a reasonable extent. Information on the nature of risks can be found on the 'Health and Safety Executive' booklet 'HSG243' on fuel cells and their risks. Every hazard has to be addressed to minimize the risk as low as reasonably possible.

The HAZOP analysis for the installation used for this report was carried out earlier for a different investigation. The gas storage and fuel cell system were the principal area for HAZOP analysis. This was carried out with BOC who were best placed to provide informed opinions of the possible risks and reviewed with aid of the HSE. The measures undertaken included using a flame arrestor, pressure relief valve, and earth bonding of the pipes used for fuel delivery. Details of this can be found within the DTI report URN '2342343' titled 'Investigation into 1 kW fuel cell based UPS'. For this report, the fuel supply was routed to a different location by a certified agency. This was leak tested using nitrogen and hydrogen to be certified safe for use. A fail-safe hydrogen sensor in the area was connected to an existing safety control system, which opens the incoming supply solenoid valve. This was tested for closing of the solenoid valve before using the fuel cell system.

The right method of placing hydrogen using equipment, adequate passive ventilation, hydrogen sensors, and fire detectors minimise the danger by isolating supply in case of leakage during the testing. Use of suitable connectors and earth bonding minimise the fire risk due to friction or static discharge ignition. It is also safe practice not to use equipment capable of producing sparks or naked flames in the vicinity. Thermally protected fuel cell and equipment such inverter and rectifier reduce the chance of fire in the equipment by minimising operation temperatures. They also include current limiting function preventing the danger of short circuit conditions. These are by no means exhaustive but serve only to illustrate the various ways of addressing the hazards.

A fuel cell UPS installed can draw on battery risk assessment expertise. VRLA or open cell batteries can vent hydrogen gas into the battery room. Safety practices observed in these situations can be applied to the fuel cell installation. The only difference being that in any normal condition, the fuel cell and supply system do not release gas, where as batteries do.

4 TESTING

A comprehensive test programme improves the understanding of the system, its operation under different loading conditions, and the influences of parameters like temperature, output power etc. Some of the parameters are not directly mentioned in the specifications as they are generally not relevant for most users. Parameters like time to start up under various conditions, time to ramp up or down to a certain power output, can only be found by extensive testing. This data helps gain a deeper understanding of the system, which in turn, increases user confidence. Since the general characteristics of a PEM based fuel cell are known, it is possible to test how well the shortcomings have been taken care of in designing the product.

These parameters characterise the response of the fuel cell system with change in load - whether a step or gradual change; Quicker the transition time, lower the transitional battery capacity required - it also signifies the improved dynamic characteristics of the fuel cell. Knowledge of these specifications helps to choose the right application for the fuel cell of a particular manufacturer. The fuel cell per se may be light in weight, but due to the transitional support required from batteries, make it unsuitable for a particular portable application.

Testing can also provide information on efficiency in various ranges, which helps distinguish one product from another. The key parameters, which are of interest during the tests, are

Fuel cell Power
Parasitic Power
Mains Output from system
Gas Consumption
Efficiency
Response time
Adequacy of Battery capacity

4.1 Particulars of testing

The rectifier and inverter adhering to EN norms are not tested for their operational characteristics. The basic tests done on the rectifier and inverter only are to confirm their operation. However, the effect of them if any, on the fuel cell has to be studied.

In standby mode (mains available operation), the DC bus (generated by mains rectifiers) through an auxiliary converter within the Gencore® powers all the auxiliary functions in the fuel cell system. When the system comes online, it should do so in a manner transparent to the inverter. As this is not possible, the DC bus paralleled batteries within the Gencore® make this transparency. Since the fuel cell has limitations in responding to a step change in requirement, a the battery bank used in the Gencore® unit provides transient currents. Essentially, the fuel cell system replaces the large battery bank in a UPS setup. The ability of the fuel cell system to perform in a similar manner as a battery bank is verified by different tests.

Active and reactive loads, on the inverter, are used to find the response over the whole range of operation. Switching loads are used to find the dynamic response of the system.

The behaviour of the stack, including its response varies with the state of humidification, ambient temperature, and amount of loading. The response of the fuel cell system is also tested after long hours of standby for start up reliably in low ambient temperatures. To concentrate on the behaviour of the fuel cell, the tests of electrical nature focus on the loss of mains condition where the control system detects drop of DC bus voltage starting the system.

1. Stable transition and operation of fuel cell stack from 'No-load' to 'Full-load' ranges in any mode of start-up - The regions of interest are No-load, 50% and 100% in Unity power factor and leading power factor conditions. Since the operation of the stack is affected by humidity, operation under dehumidified conditions is also observed. This can be simulated by after long periods of stand-by.

2. Response of the stack and inverter to a step increase or decrease in loads at various power factors - These dynamic load tests are conducted on active and reactive loads on a range of output powers. The fuel cell system cannot ramp up its power output instantaneously. These tests also find the amount of step increase in load the fuel cell can supply with out support from the batteries.

3. Soak tests - These test simulate long and repetitive conditions of power loss.

Additional tests are carried out on the inverter and rectifier to determine the inverter characteristics and waveform quality. There should not be any change in the waveform when whilst DC bus transients exist the load from mains to Battery/Fuel cell or vice versa.

Since the operating efficiency of the inverter is 90% (mfrs spec) the maximum output loading, which can be theoretically achieved, is 4.5kW. This is due to the fuel cell system being rated for 5.00kW. Therefore, the maximum load is limited to 4.5kW in all tests conducted.

4.2 Transition of Fuel cell system from standby to online

In standby mode the rectifier powers the load through the inverter; they share a common DC bus. The transitional batteries in the Gencore® unit are re-charged by virtue of being paralleled onto the DC bus. The rectifier unit also supports the fuel cell standby activities. These activities include operation of the sensors, ventilation, and heating units.

The fuel cell can respond to transients but only for a limited increase in power. Batteries are used in the transition period until the fuel cell develops the required power. The fuel cell system consists of blowers and other elements, which introduce a delay in developing power. This transition time varies between manufacturers and technology used. Stack temperature and power delivered also influence this time slightly. Detailed investigation of this phase also confirms the adequacy of the battery capacity required. It is quite possible that there may some worst case conditions which demand more power than available from the batteries. In this case, the available battery capacity may have to be increased. Previous tests on 1kW models have concluded this to be an important test parameter to be investigated before field deployment.

The fuel cell system continuously monitors the battery voltage and current. Either it starts, if the battery voltage drops below, or current drawn is higher than a threshold. The stack rated at 6kW, begins to supply power to its system, charging current for the battery and load power. If power is restored within a certain lockout period, the system ensures the batteries are fully charged before switching to standby mode. This ensures brownouts and dips do not result in the multiple starts of the fuel cell. It also ensures the batteries are ready to provide rated load during next failure. To ensure this ready condition, the system also starts the fuel cell once every four weeks to perform a self-test and conditioning cycle. In performing this cycle and potential problems can be identified before an actual mains failure occurs.

If the power demand is higher than the fuel cell can provide for, the overload protection power limits the output to exactly 5kW. This results in loss of power after some time as they batteries provide the overload power. In any case, the inverter's overload protection circuitry should prevent such high loads reflecting on the output of the fuel cell.

4.3 Static Load tests

Humidity in the stack improves efficiency of power generation. The humidifier unit retains the moisture from the exhaust and feeds into the air inlet. Long periods of standby pose problems due to dehumidification and cell flooding. Water condensation in a particular cell, blocks the activation sites on the catalyst reducing the amount of hydrogen available to them. Cell flooding is not a problem when the stack has sufficiently warmed up, but start up times could be significantly increased in a dehumidified stack. In such cases, the battery capacity could be a critical factor for a successful start up.

As with every fuel cell system, the Gencore unit has a stack conditioning cycle - wherein it reconditions the stack by powering it up to full load. This results in an always-ready condition, since it also includes self-tests. To test this condition of start-up in a dehumidified state of stack, a series of tests are done with considerable period of standby in between, to simulate as close to possible a real-life situation. Of particular interest in these tests are the times taken to start-up at various ambient temperatures. The fuel cell is tested at different output powers by means of connecting loads to the inverter. A resistive bank and a capacitive bank form the load. A fuel cell does not differentiate between active and reactive loads given the DC bus and mains inverter. Nevertheless, using real-life load conditions offers the chance to test the operation of the whole system. Reactive loads due to higher current flow may impose a higher loss in the inverter; hence draw slightly higher power from the fuel cell.

Data logging equipment for external parameters and data provided within the unit are used to reconstruct the parameters during a test. The Gencore® provides online data logging facility to monitor internal parameters, inaccessible through external test instruments. The coolant fluid flows through the fuel cell stack through special channels. Therefore, the coolant temperature is taken as an approximation of the stack temperature. 'Time to full load' is calculated from captured data and has an error of +/-2 seconds. Battery transition current similarly is calculated from captured data.

The power differences between Load, converter and stack power are due to internal power consumption within the Gencore® and the inverter efficiency. Some losses are incurred in power transmission too.

4.3.1 Cold Start Resistive load.

Load (kW)	Power Factor	Coolant temp (°C)	Time to Full load (s)	Transition battery current (Peak, Amps)	Converte r Power (kW)	Stack power (kW)
1	UPF	21	18	23.98	1.219	2.14
3	UPF	21	24	55.34	3.329	3.77
4.5	UPF	19.6	23	77.01	4.678	5.23

UPF – Unity Power Factor.

Table 1. Performance of Resistive loads at Cold start-up condition

The tests are done at selected points covering the output range. The results are captured and plotted in a graph. This helps to understand the behaviour of the stack through various parameters. The system initially has to start the blowers of the anode and cathode sides of the stack at full power to quickly power up (figure 4). These slowly settle to the value of load and losses after the battery has been recharged. Operation of the coolant pump and radiator causes small fluctuations from the steady state value.

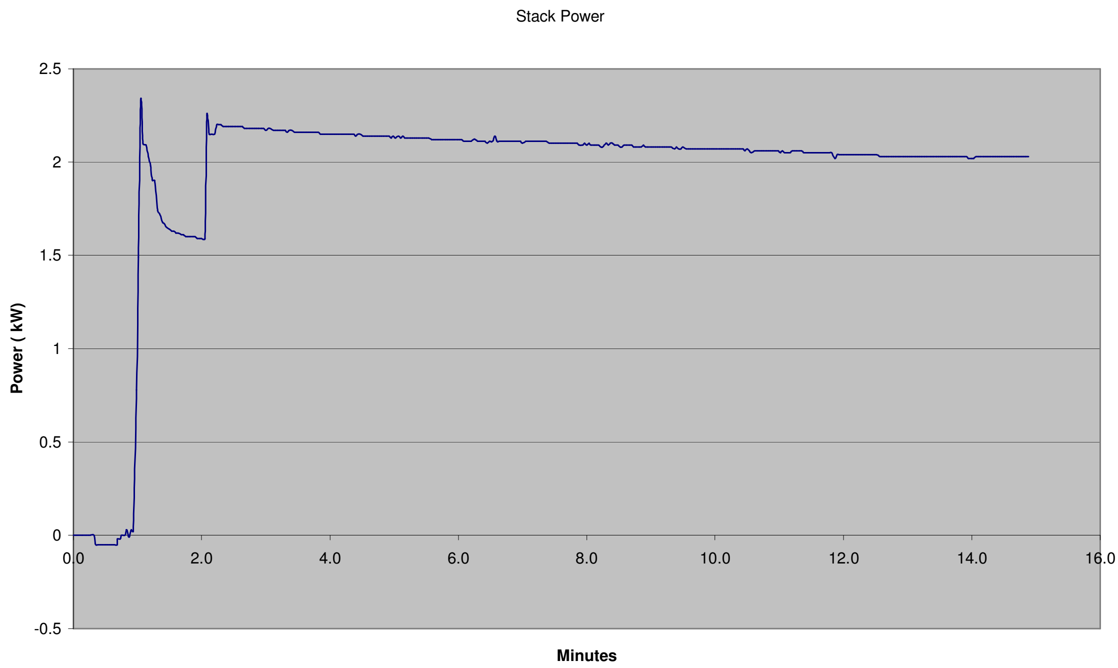


Figure 4. Cold start resistive load, 1kW. Stack Power Vs time

The stack power decreases to 1.6kW approximately. Since the temperature is only 21°C, which is below optimum, the control system switches on the heaters, which will reduce the time to attain optimum stack temperature. This is seen in figure 8, where the coolant temperature has risen to 50°C with a 1kW load approximately after 15 minutes.

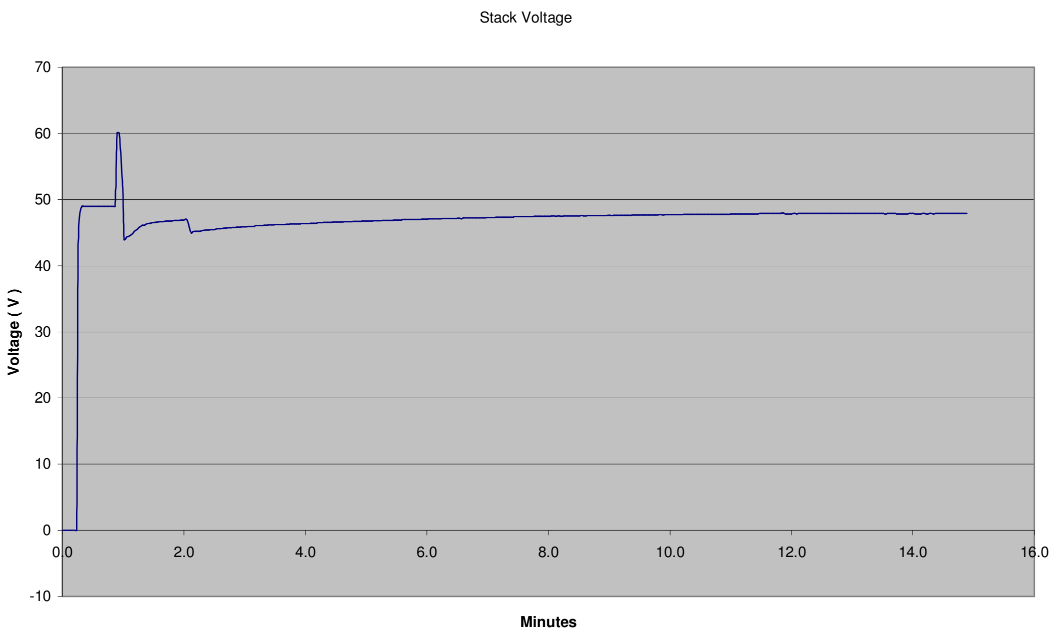


Figure 5. Cold start resistive load, 1kW. Stack Voltage Vs time

The stack voltage (figure 5) undergoes a transient phase before settling to a steady state. The output voltage is a function of the output power being delivered. It decreases as power drawn increases. This is a result of internal resistance within the stack.

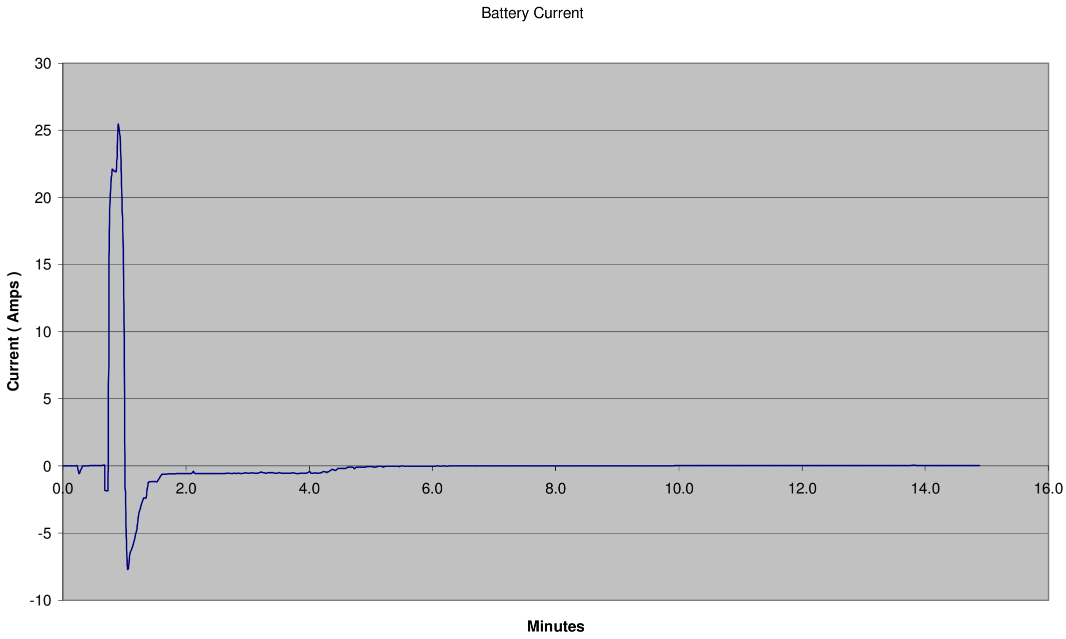


Figure 6.Cold start resistive load, 1 kW Battery current Vs time

The battery current (figure 6) increases instantly as it provides power to the load, after mains power failure. Once the fuel cell starts up, the DC-DC converter supplies power at a slightly higher voltage than the battery. This now charges the battery, seen by the negative battery current. The fuel cell ensures that it needs no longer supply power to be bus and that the batteries are completely charged, before powering down. The battery voltage (figure 7) follows the converter voltage once the fuel cell has started up. The converter voltage is set higher than battery voltage at 53V. This figure has been set by us as it its 1v lower than the rectifier – this results in it taking priority power supply on the DC bus.

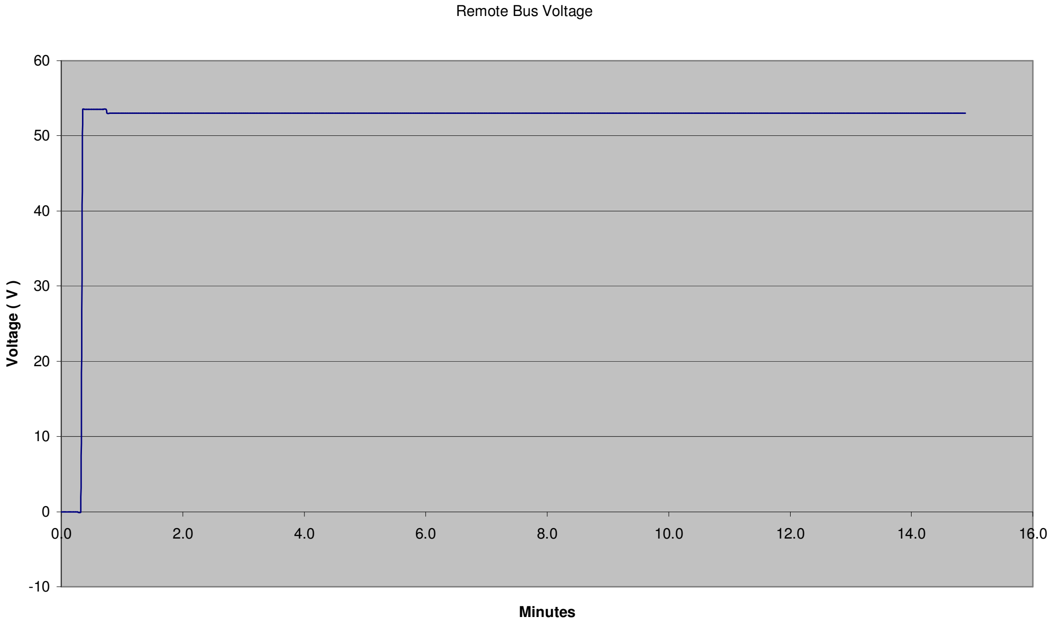


Figure 7. Cold start resistive load, 1kW. Battery Voltage Vs time

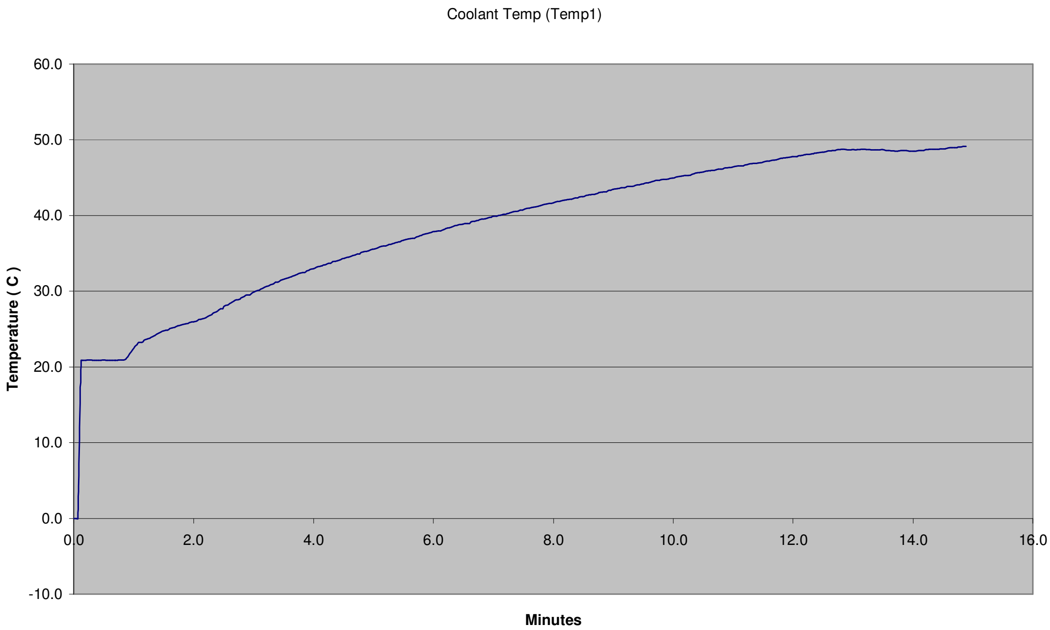


Figure 8. Coolant temperature Vs time

Figure 9, depicts the events during the transition phase from load transfer from mains to fuel cell. The increase in battery current (positive) corresponds to power drawn by the load as well as the bidirectional converter for powering up the fuel cell system. The increase in stack current corresponds with the decrease in battery current.

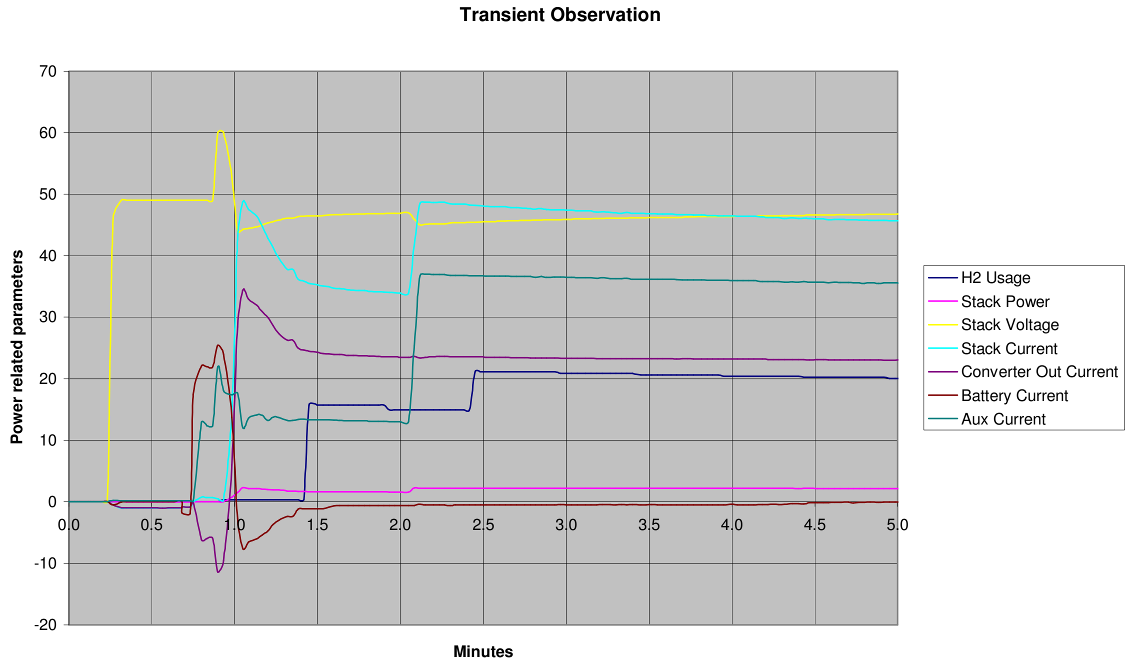


Figure 9. Cold start resistive load, 1kW. Transient parameters Vs time

Fuel intake increases, while stack voltage decreases and current drawn increases. Auxiliary current increases during transition to power up the blowers and settles to a steady value quickly. The fuel cell begins to output power within 10-15 seconds, whereas the whole process takes about a minute, to settle to the optimum values.

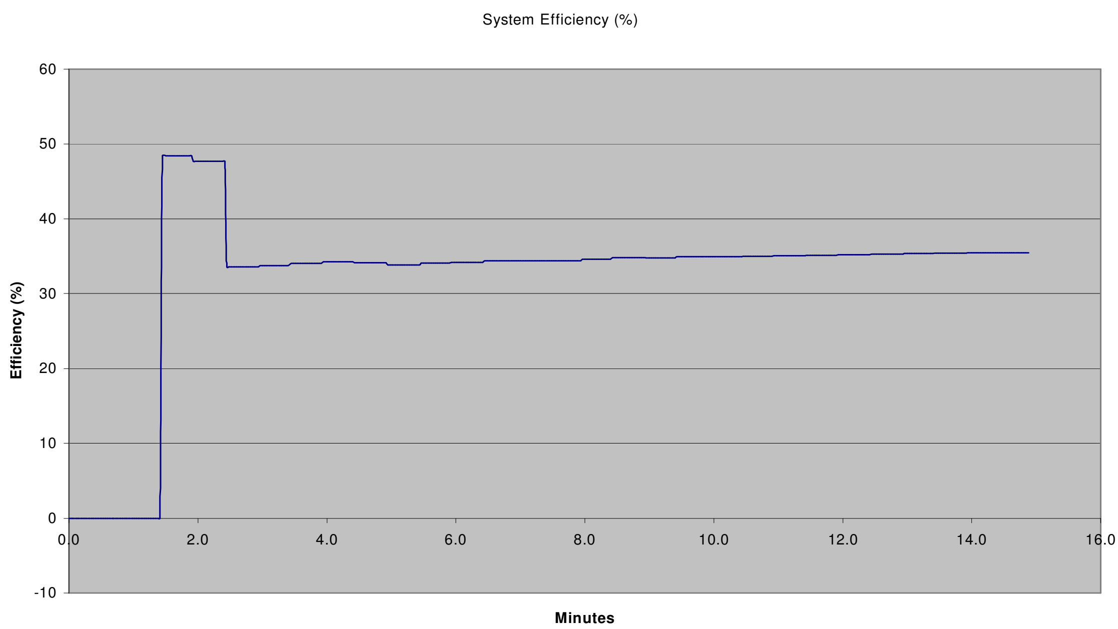


Figure 10. System efficiency for 1kW load

The efficiency (figure 10) is a calculated figure. The amount of hydrogen used is calculated indirectly, using stack voltage and current values as well as knowing the Auxiliary power consumption, values for system efficiency can be determined. The graph indicates that the system is more efficient at higher power in the initial stages. This is confirmed with figures of efficiency at higher power delivered. Figure 11 shows the estimated consumption of hydrogen, in standard litres per minute during the test duration. This too, is a calculated value based on the power delivered. It should be noted that fuel cell stack efficiency reduces at higher power; this is due to internal resistance within the cells.

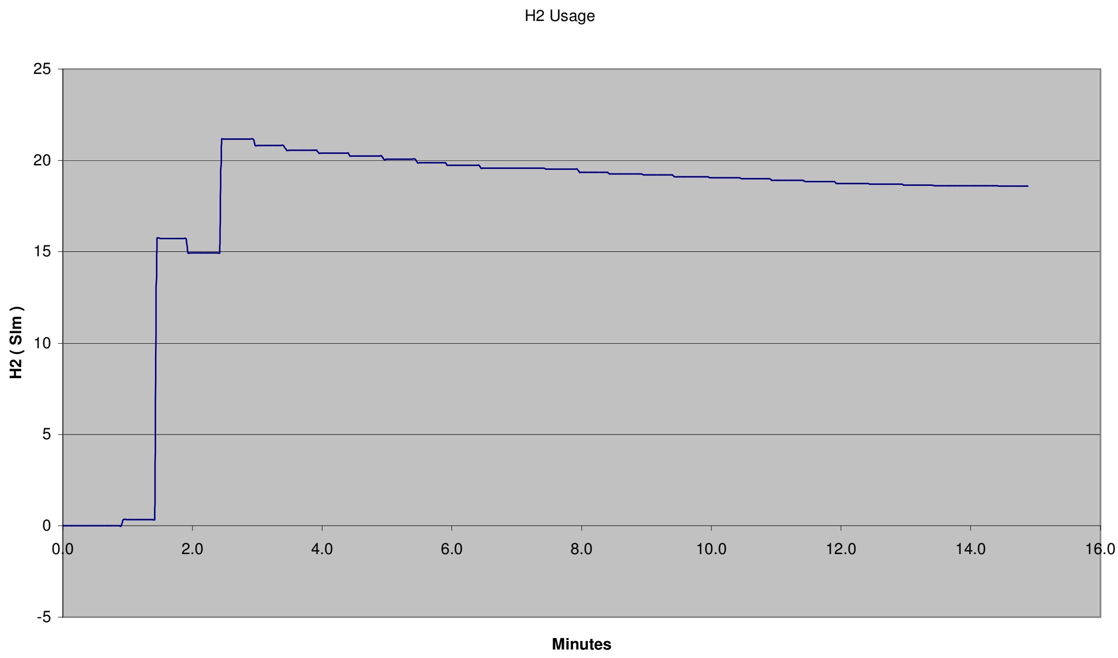


Figure 11. Cold start resistive load, 1kW – Estimated use of hydrogen

The change in stack voltage becomes clear when a higher load like 4.5kW is connected. In figure 15, the voltage of the stack at 60VDC at open circuit drops to 42VDC when connected to 4.5kW.

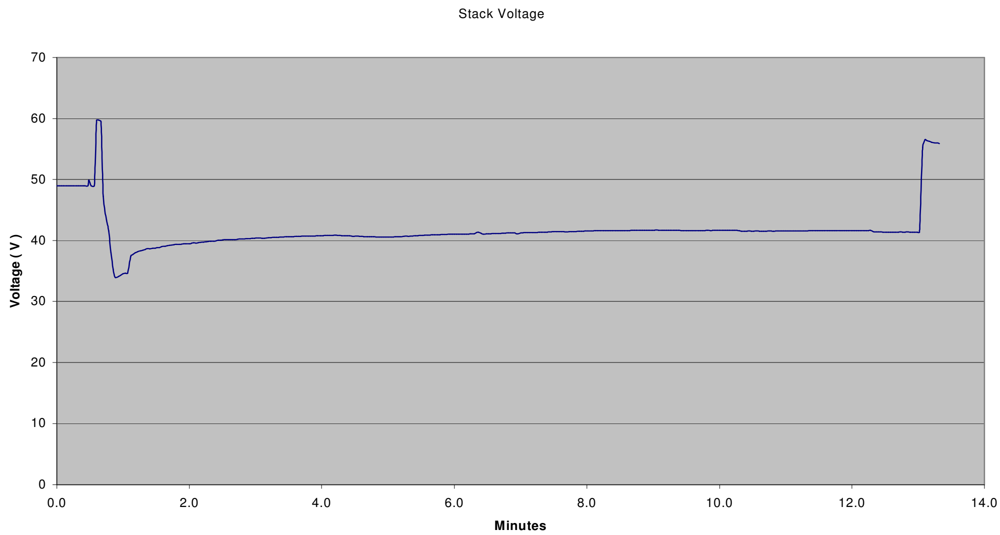


Figure 12. Cold start resistive load, 4.5kW. Stack Voltage Vs time

The stack current peaks at around 170 A (figure 16) for a peak load in the inverter for 4.5kW.The stack is generating slightly greater than 5.9 kW with a rate of consumption of 53.05 slm (Standard Litres per Minute).

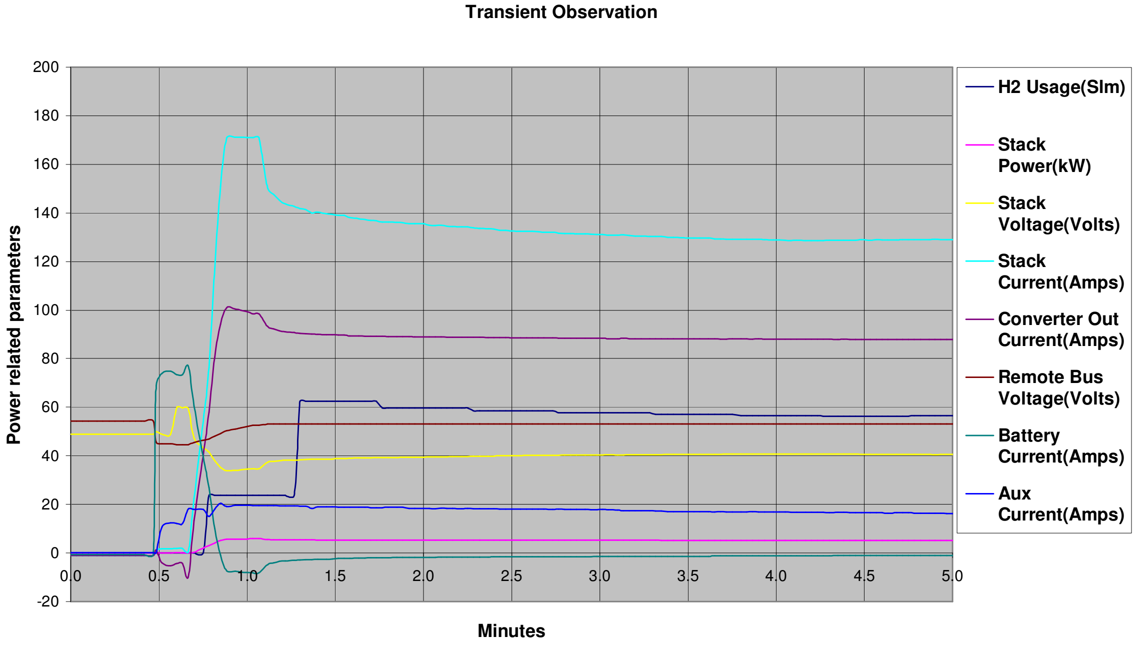


Figure 13. Cold start resistive load, 4.5kW. Transient parameters Vs time

4.3.2 Cold Start Capacitive load

A reactive load imposes higher losses in the inverter, thereby increasing the power demand on the fuel cell. Reactive loads could be inductive or capacitive. Inductors of such power rating are not easily available. Therefore capacitors are used to set extreme power factor conditions. The loads vary in the power factor range of 0.8 Lead to a severe condition of 0.5 lead, which reflects a possible real life situation.

Load (kW)	Power Factor	Coolant temp (°C)	Time to Full load (s)	Transition battery current (Peak, Amps)	Converter Power (kW)	Stack powe r (kW)
2	0.8 Lead	21	20	40.7	2.256	2.62
2	0.5 Lead	22	22	42.81	2.392	2.76
4	0.8 Lead	21	26	71.88	4.261	4.77

Table 2. Capacitive loading with cold start-up condition

4.3.3 Conclusion.

It is seen from various tests, the fuel cell system ramps to full output power within a minute. The operation of the Fuel cell-UPS system is satisfactory for all both active and reactive loads on a cold start up. The system is unaffected by relatively long periods of standby and starts up reliably in event of power failure. Cell flooding is avoided by regular maintenance cycle incorporated in the system.

4.3.4 Resistive tests.

Stability is investigated for the whole range of active and reactive loads at longer test durations. The resistive tests are conducted at steps of 1kW. The reactive tests are conducted at selected points between 0.8 Lead and 0.5 Lead.

Load (kW)	Power Factor	Coolant temp (°C)	Time to Full load (s)	Transition battery current (Peak, A)	Converter Power (kW)	Stack power (kW)
1	UPF	31	20	24.98	1.219	2.11
2	UPF	32	15	39.18	2.249	2.63
3	UPF	43	7	28.28	3.126	3.46
4	UPF	52	18	68.35	4.131	4.51
4.5	UPF	50	15	74.27	4.65	5.1

Table 3. Performance at various resistive loads

4.3.5 Reactive (Capacitive load) Tests.

Load (kW)	Power Factor	Coolant temp (°C)	Time to Full load (s)	Transition battery current (Peak, A)	Converter Power (kW)	Stack power (kW)
1.25	0.8 Lead	33	23	25.09	1.251	2.15*
1.25	0.5 Lead	45	16	30.48	1.569	1.85
2.5	0.8 Lead	46	19	47.33	2.797	3.14
2.5	0.5 Lead	35	18	49.93	2.930	3.32
4	0.8 Lead	44	15	66.79	4.330	4.81

*Additional power due to Heater and Heater fan

Table 4. Performance at various capacitive loads

4.3.6 Conclusion

In figure 14, an increase of 610 Watts from the third minute to eight minute is attributed to the heater assembly activating to warm up the cabinet. Since the stack is only at 31°C, the heaters are switched on to heat up the stack. This has a two-fold effect of heating by increasing the power demand on the stack thereby increasing the heat output of the stack, and secondly the heaters act on the coolant and internal air.

During the previous report of a 1kW fuel cell configuration, the transition time was in the range of 20-30 minutes. This is not acceptable for a product that has to match the characteristics of a battery bank. Recent developments have brought this time down to less than a minute, which is a vast improvement due to research and development.

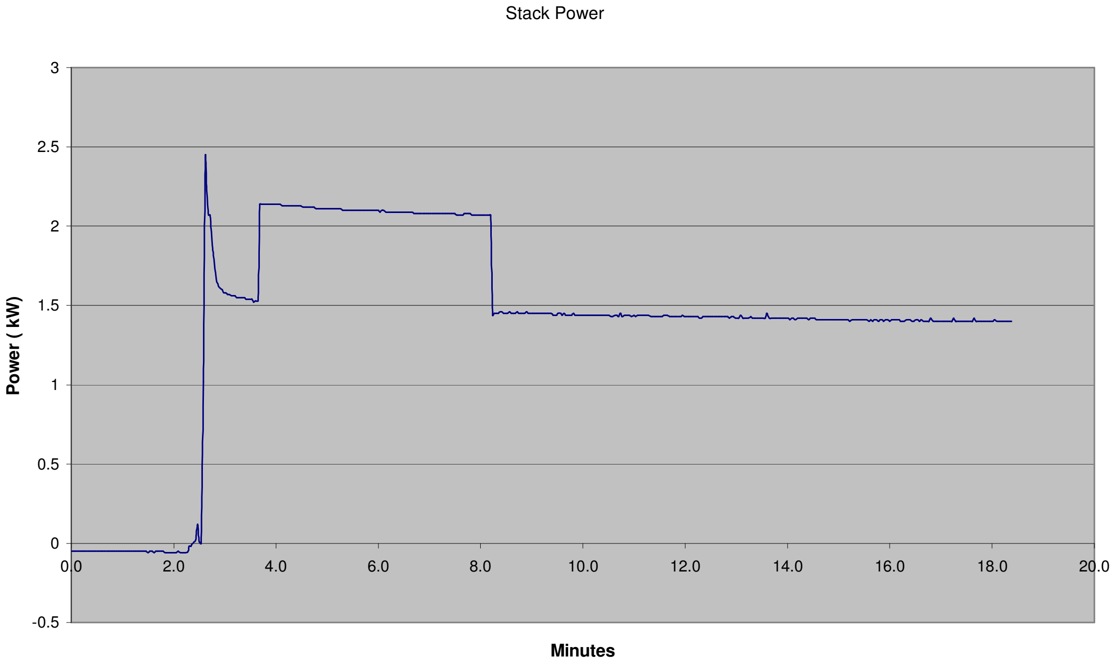
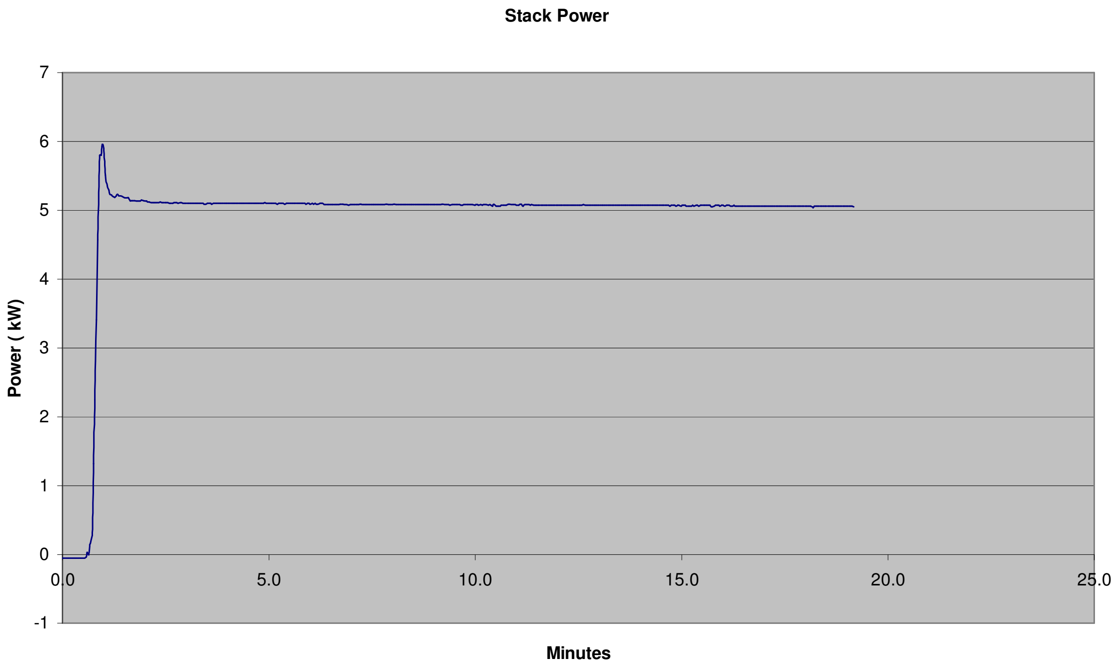


Figure 14. Stack power at 1kW load



.

Figure 15. Stack power at 4.5 kW load

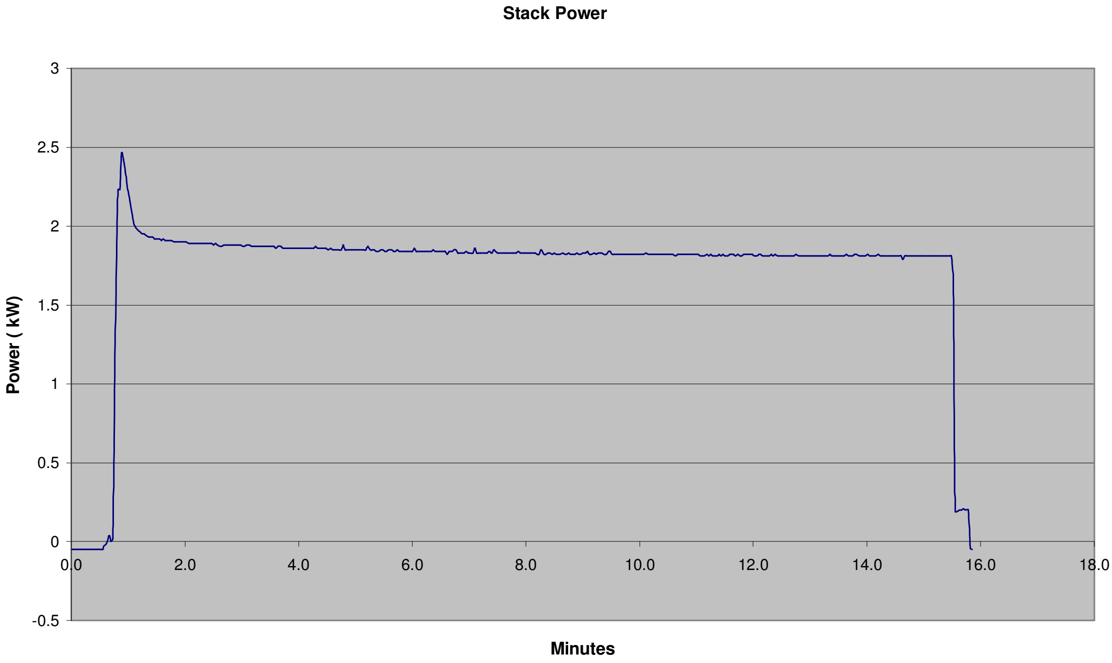


Figure 16. Stack power 1.25 kW 0.5 Lead

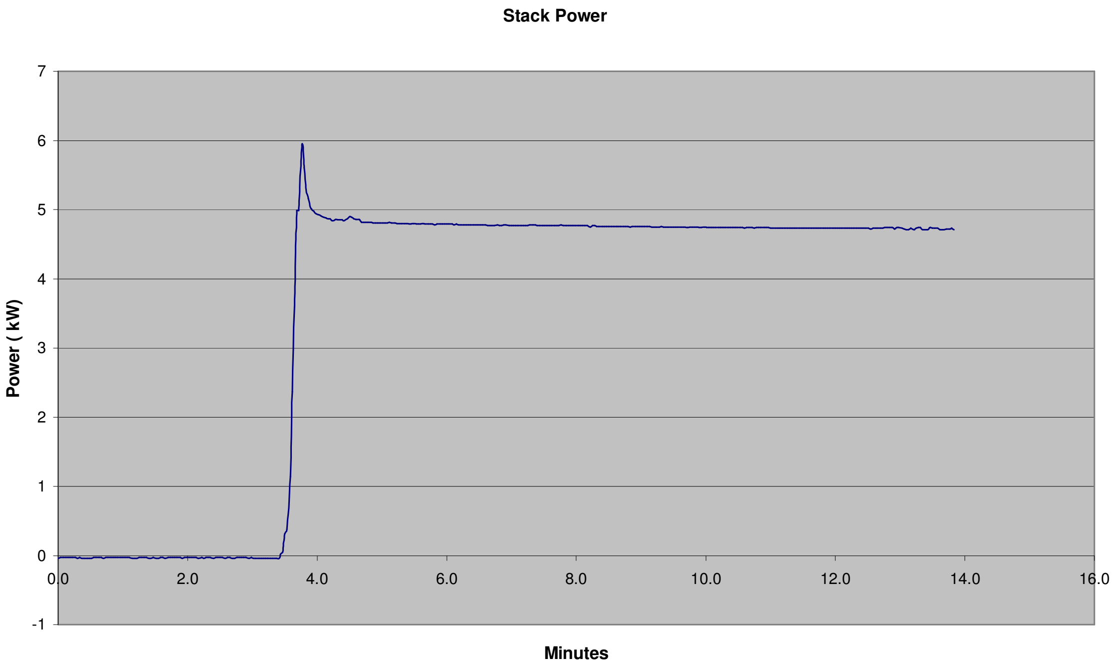


Figure 17. Stack power for 4kW 0.8 Lead

The tests indicate satisfactory operation for both active and reactive loads in different ranges. Undue fluctuations are not noticeable in the output voltage and power. The system usually reaches stable operation under steady state quickly as indicated by the graphs. Higher coolant temperature, an approximate indication of the stack temperature, results in a quicker start up time. The efficiency also increases slightly with temperature.

4.3.7 Soak Tests.

Soak tests are conducted to detect variations in performance while simulating actual mains loss condition for relatively longer durations. Unlike a battery operated UPS, a fuel cell run time is only limited by availability of hydrogen.

This test is conducted at rated load (though back up systems are recommended not to operate at rated output), for duration of an hour. Variation in the fuel cell system is observed and verified for deviations from normal. This is repeated after an interval of 30 minutes twice successively.

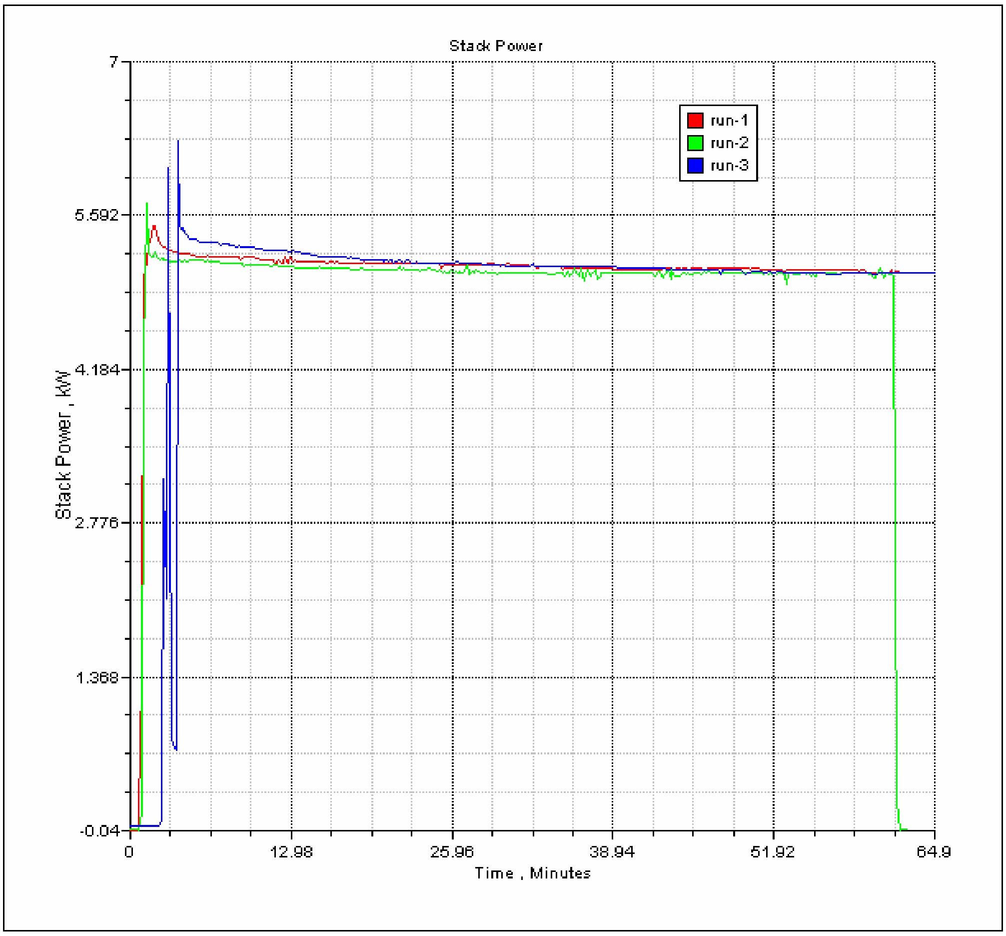


Figure 18. Stack power during three successive runs

The system stabilised quickly and performed with steady power output during all three runs. The thermal management maintains an optimum stack temperature at all times. The efficiency of the process increases as the temperature reaches a steady and optimum value.

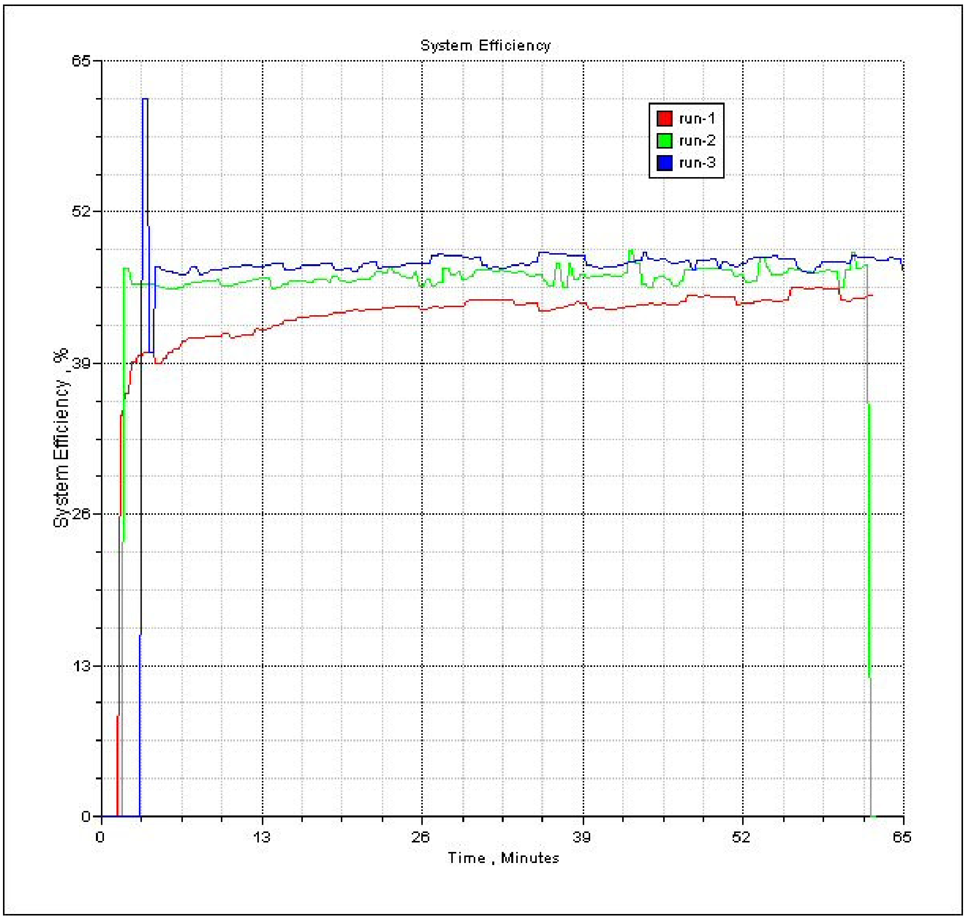


Figure 19. System efficiency during soak tests for three consecutive runs

4.3.8 Conclusion

The soak tests demonstrate the ability of the system to operate long hours continuously without any malfunction. It is also able to regulate its temperature within the specified range, and maintain its operational efficiency. This is the scenario faced during a serious failure, where mains power could be unavailable for two hours or more. It demonstrates the fuel cell is capable of reliably serving as a backup system. The system never failed to start on any occasion; this further is a testament to the system reliability and the reliability of modern fuel cell systems.

4.4 Dynamic Load test

A typical back up application is a server room, key lighting, or communication backup. Most of these are steady loads, without large fluctuations in demand. It is important to understand the behaviour of the fuel cell system for switching or ramping loads.

The test setup consists of resistive and reactive loads added and removed in different sequences to simulate switching loads. Fuel cells are capable of supplying any load. This is achieved by means of power conditioning. For pulsed loads, the controller will generally seek to output the average power, using the transitional source to meet the peak. This promotes better system efficiency whilst minimising stress on both transitional source and fuel cell stack alike.

4.4.1 Load switching tests- Active.

Resistive loads are added and removed in steps of 1kW and 2kW. To observe the worst-case, steps of 4kW are used. The period between successive increases is two minutes and three minutes for 1kW and 2kW loads, respectively. It is reduced to one minute for the 4kW sequence. The key parameters observed is the transient battery current drawn during an increase in load, using which the maximum step increase of load, sustained by the fuel cell could be found.

4.4.1.1 Load switching with 1kW increment.

@ Coolant temp 53 °C

Load (kW)	Stack Power (kW)	Converter Power (kW)	Transition Battery Peak Current (A)	Load Duration
1	1.52	1.26	19.94	2 min
2	2.52	2.2	0.3	2 min
3	3.54	3.2	0.8	2 min
4	4.54	4.1	0	2 min
4.5	5.1	4.6	0	2 min
4	4.58	4.1	0.17	2 min
3	3.54	3.15	0.1	2 min
2	2.48	2.18	0.04	2 min
1	1.46	1.2	0.09	2 min

Table 5. Performance while switching 1kW loads

4.4.1.2 Load Switching with 2kW increment.

Load (kW)	Stack Power (kW)	Converter Power (kW)	Transition Battery Peak Current (A)	Load Duration
2.5	3.22	2.79	47.08	3 min
4.5	5.22	4.65	12.93	3 min
2.5	3.14	2.75	0	3 min

Table 6. Performance while switching 2kW loads

4.4.1.3 Full Load Switching

Load (kW)	Stack Power (kW)	Converter Power (kW)	Transition Battery Current Peak (A)	Load Duration
0.5	1.19	0.87	9.61	1 min
4.5	5.34	4.71	39.91	1 min
0.5	1.04	0.75	0	1 min
4.5	5.25	4.69	11.63	1 min
0.5	1.01	0.74	0	1 min
4.5	5.27	4.71	42.7	1 min
0.5	2.11	1.8	0	1 min
4.5	5.44	4.86	41.08	1 min
0.5	1.01	0.75	0	1 min
4.5	5.21	4.68	27.48	1 min

Table 7. Performance while switching 4kW

4.4.2 Load switching tests - Reactive.

In reactive tests, the loads are added and removed in steps 1kW to 1.5kW while maintaining the power factor at 0.8Lead. The worst-case test is carried out with steps of 3.5kW.

4.4.2.1 Load switching at 0.8 Lead.

Load (kW)	Power Factor	Stack Power (kW)	Converter Power (kW)	Transition Battery Peak Current (A)	Load Duration
1	0.8 Lead	1.67	1.31	0	2 min
2	0.8 Lead	2.63	2.24	0	2 min
3	0.8 Lead	3.64	3.21	0	2 min
4	0.8 Lead	4.66	4.18	0	2 min
3	0.8 Lead	3.61	3.19	0	2 min
2	0.8 Lead	2.54	2.21	0	2 min
1	0.8 Lead	1.49	1.21	0	2 min

Table 8. Performance while switching 1kW loads with reactive load

4.4.2.2 Load switching at 0.5 Lead.

Load (kW)	Power Factor	Stack Power (kW)	Converter Power (kW)	Transition Battery Peak Current (A)	Load Duration
1	0.5 Lead	1.44	1.17	23.74	3 min
2 .5	0.5 Lead	3.12	2.77	3.92	3 min
1	0.5 Lead	1.39	1.14	0	3 min

Table 9. Performance while switching reactive loads of at 0.5 lead

4.4.2.3 Full Load switching at 0.8 Lead.

Load (kW	Power Factor	Stack Power (kW)	Converter Power (kW)	Transition Battery Peak Current (A)	Load Duration
4	0.8 Lead	4.55	4.13	44.13	1 min
0.5	UPF	1.39	1.13	0	1 min
4	0.8 Lead	4.55	4.18	26.71	1 min
0.5	UPF	1.39	1.14	0	1 min
4	0.8 Lead	4.55	4.14	23.46	1 min
0.5	UPF	1.39	1.13	0	1 min
4	0.8 Lead	4.55	4.14	23.12	1 min
0.5	UPF	1.39	1.13	0	1 min
4	0.8 Lead	4.55	4.15	10.38	1 min

Table 10. Full load switching at 0.8 Lead

4.4.3 Conclusion:

The fuel-cell system performs satisfactorily in dynamic load testing. The fuel cell system demonstrates it can handle step increase of rated output with the help of transition batteries. As a system, its operation is similar to a battery bank. It can by itself, supply a step increase of 1.25kW, which is 25% of its rated power without drawing on battery support. This is a key to reliability as stressing the battery increases the chance of battery failure. Should the load change by less than 1.25kW the stack and controller can meet this demand instantly. Greater than this and they battery is called to deliver the shortfall for a brief time.

4.5 Inverter Tests.

A double conversion UPS has the advantage of a continuous output voltage waveform upon transfer of load from mains to battery bank or vice versa. The UPS used adheres to IEC 62040-3 classification of double conversion UPS.

The output waveforms have been observed while providing rated power of 5kW on failure of mains and return of mains. They do not show any dips or discontinuities like phase change. The transition power is supplied by battery and the fuel cell stack starts up within a minute as previously observed. The mains and inverter output are not synchronized, hence the phase difference between the two waveforms (figure 20 and 21).The next set of tests deal with the change in inverter voltage when change in loading in loading takes place. This is observed (figure 22) at while switching in resistive loads of 1kW and found to be very stable.

The mains power factor for the current drawn by the rectifier is measured to be near UPF, confirming the active power factor techniques used by the rectifier.

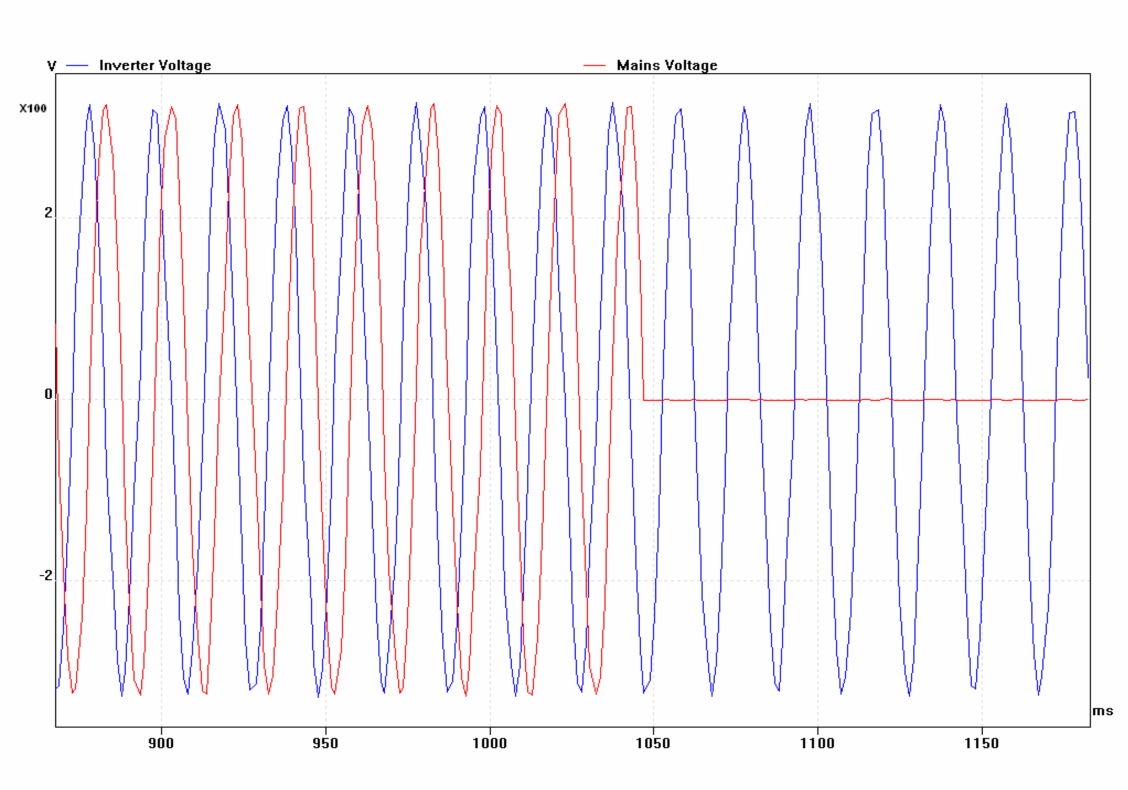


Figure 20. Mains failure at full load of 4.5kW

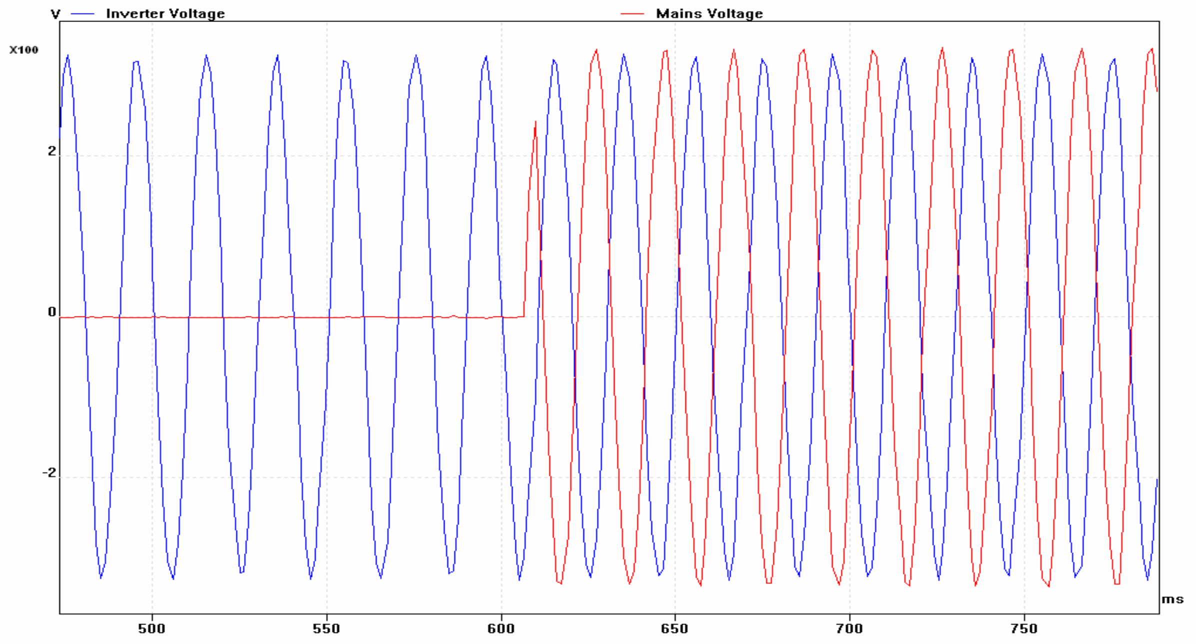


Figure 21. Mains return at full load 4.5kW

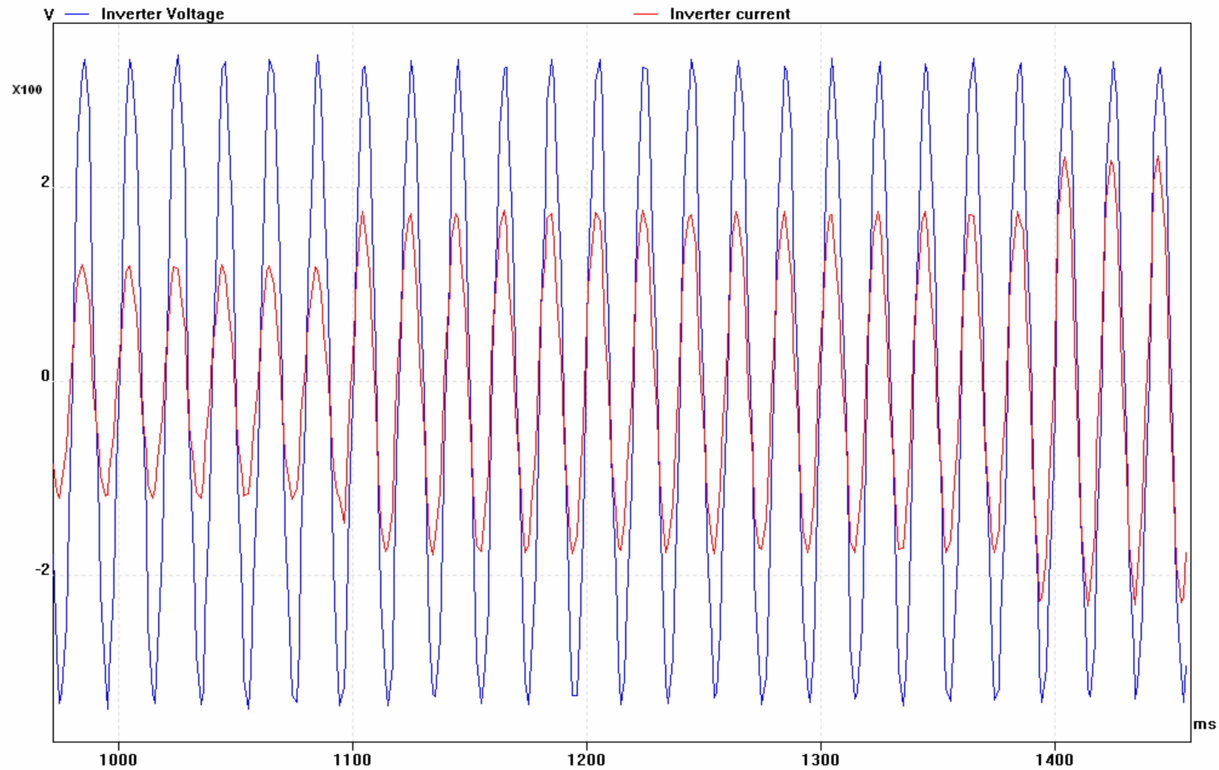


Figure 22. Inverter voltage at increasing step loads of 1kW

4.6 Conclusion

The performance of the fuel cell while providing power to various types of loads has been studied. It has performed reliably under cold – start up conditions and otherwise, in various power ranges. The system was able to handle dynamic loading, up to its rated output without any malfunction. It also was able to run efficiently and properly for the longer duration of testing in soak tests. At any condition the system always start up in less than a minute.

The monthly conditioning cycles were also observed to be effective. The DC bus system always maintains the batteries in charged condition. Either a high battery discharge current or lowering bus voltage, signifying loss of mains power, triggers the fuel cell start up; where by it is able to re-charge the batteries for the next power loss. This also ensures there are no false or nuisance start – up's. The capacity of the batteries are more than adequate, since the batteries themselves can provide rated power up to 15 minutes, whereas the fuel cell always started up in less than a minute.

The software controls are highly informative and allow extensive operator intervention. This allows a trained operator to easily diagnose or recondition the system. During the course of testing the system was subjected to at least 150 start-stops. It has never failed to start up correctly any time. The system has proved it is capable of serving as a reliable back up system. The testing has resulted in a great confidence in the product and its potential in the back up industry.

A figure of slew rate of power is useful, but could not be found without the help of special equipment. By nature, the fuel cell cannot increase its output, instantaneously. The use of batteries itself, though a very small number and capacity, is sometimes seen as a weaker link in the system. Advances in ultra capacitor technology have enabled some manufacturers to eliminate batteries altogether. Ultra capacitors are rated for high number of charge-discharge cycles with high capacity. Other manufacturers may adapt this technology as it offers greater reliability over batteries.

5 DISCUSSION ON EFFICIENCY

Efficiency of Fuel cells unlike combustion engines is not intrinsically limited. Factors such as internal resistance limit the efficiency achieved by fuel cells in practice. In calculating the efficiency achieved in this installation, transmission losses are not taken into account. In addition, due to use of the measured and quoted figures for higher end power range the worst-case efficiency can be arrived at.

The maximum rate of consumption of hydrogen is taken from the specifications. The fuel cell stack uses 64 Standard Litres of hydrogen per minute when delivering a load of 5kW. 64 SLPM is a worst case scenario and was never actually seen during testing. The equivalent electrical energy in the 64 litres of hydrogen using the LHV value of hydrogen is approximately 13.2kW. It can be argued that due to the use of a humidifier in the system you could use the HHV much like in a condensing gas boiler. The stack produces a higher power than output for powering the auxiliary loads. The actual power consumed by the auxiliary circuits is difficult to determine at any given time due to non-periodic operation of the heaters and radiator fan, which consume the most power. Instead of finding the efficiency of electro-chemical energy conversion, a figure of fuel cell process efficiency can be calculated. This takes into account the power consumed by the system. This figure of efficiency also covers the losses in the DC-DC converter used in the fuel cell system. Thus, an overall figure of efficiency for conversion of chemical energy to electrical energy can be derived from these above values, which is 37.8%.

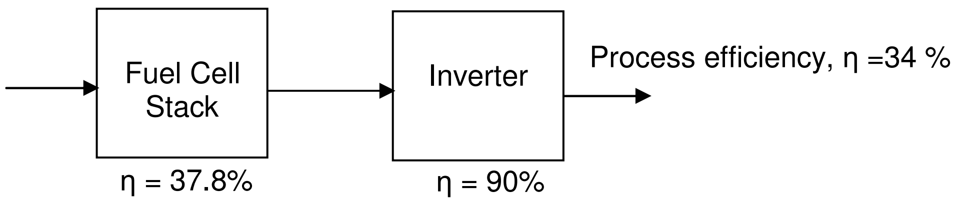


Figure 23. Efficiency in the process

The efficiency of inverters varies between manufacturers. Using the value of efficiency of 90% provided with the specifications of the particular being used, the complete system efficiency is calculated to be at 34%. This figure is around the maximum efficiency achieved in practice for PEM fuel cells.

Improvement in efficiency will serve to extend the run time of a gas installation. If the fuel cell used the gas more efficiently, you can look to see greater runtimes. Although, as the application is UPS, efficiency is not seen as a major hurdle, the load is the priority. Many believe that the fuel cell UPS will provide greater fuel to electrical efficiency over a petrol or diesel genset. This was beyond the scope of this report and will not be commented on further.

6 LIFE CYCLE MODELLING

The future of this technology as a back up system will depend a lot on its perceived cost. Since the technology has not matured like battery UPS', the initial capital cost will definitely put off any interested customer. This section looks deeper into the factors building up the cost at a complete installation in both a battery UPS and fuel cell UPS. The annual costs over a reasonable lifetime are taken and the net present value is calculated. This should offer a clear picture of the costs involved, both initial and annual to make a decision.

Some of the factors considered are,

- Capital costs for acquisition and installation (CAPEX) including battery replacement costs
- Operating Cost every year (OPEX)
- Net Present Value (NPV) of the cost incurred over a ten year period adjusted for capital allowances and tax
- Assumes two failures each year requiring recharging of hydrogen cylinders after each shut down.
- Plug power Gencore 5B48 model is used as a reference for a fuel cell system. Cost of battery UPS are from quotations of best price given.

Both of the systems, battery, and fuel cell type have various associated costs. Some of them may be comparable like, commissioning and installing, annual maintenance, while some of them may be higher in one type than the other may. For example, refilling costs are absent in a battery UPS. Whereas capital cost of the cylinders is not accounted since these are rented, unlike the batteries which are bought upfront. Installation is required in both systems. In a fuel cell system, the manifold, gas cage, and piping are needed. In case of a battery bank, a tower or any other system needs to be installed. Since they are heavy, the floor may need to be prepared or additional reinforcing required. The batteries need to be stored at a constant temperature for the maximum lifetime. Usually for bigger installations, temperature controlled environment is provided. Therefore there are many factors which can be taken into account to make this comparison as detailed as possible. However, a decision can be arrived at be looking at some basic costs and making some assumptions based on similar market price.

Some of the costs not taken into account are

- Cost of delivery off load, transport of the battery banks and tax
- Cost of maintaining the temperature of the battery bank
- Costs associated with space occupied, additional construction work, and disposal.
- It is assumed the battery bank is stored at narrow band of operating temperature ensuring maximum lifetime.

- Cost of renting, refilling of cylinders remains constant during the life time

Certain other factors like period of autonomy also influence the attractiveness of fuel cell system.

6.1 Impact of autonomy

The initial capital outlay for a fuel cell based UPS is higher than of a similar rating battery operated UPS. Together with installation of a Gas storage and delivery system, it does seem an uneconomical proposition for lower autonomy periods. This situation changes as autonomy increases.

The cost of battery-operated units from reputed manufacturers[5] for different autonomy periods is acquired and a comparison is done versus the cost of a fuel cell for the same periods a 5kW load. For higher autonomy periods, data is scarce as a generator set becomes appropriate instead. In these cases, a linear trend is used for comparison. While the cost of a battery operated UPS increases somewhat linearly as the autonomy period increases, the cost of fuel increases in steps. The reason for this being, the cost of the fuel cell unit is not dependent on the autonomy period but the additional cylinders and the manifold required to connect them, add to the total cost.

The factors taken into account are installation costs and battery racking for a battery based UPS. In a fuel cell system, an inverter and rectifier have to be purchased to make a UPS system. In addition, installation of equipment, piping and manifold, control panel are taken into account. Gas delivery and rental charges are also factored to ensure a comprehensive treatment.

---

[5] Data available on request from SiGEN Ltd.

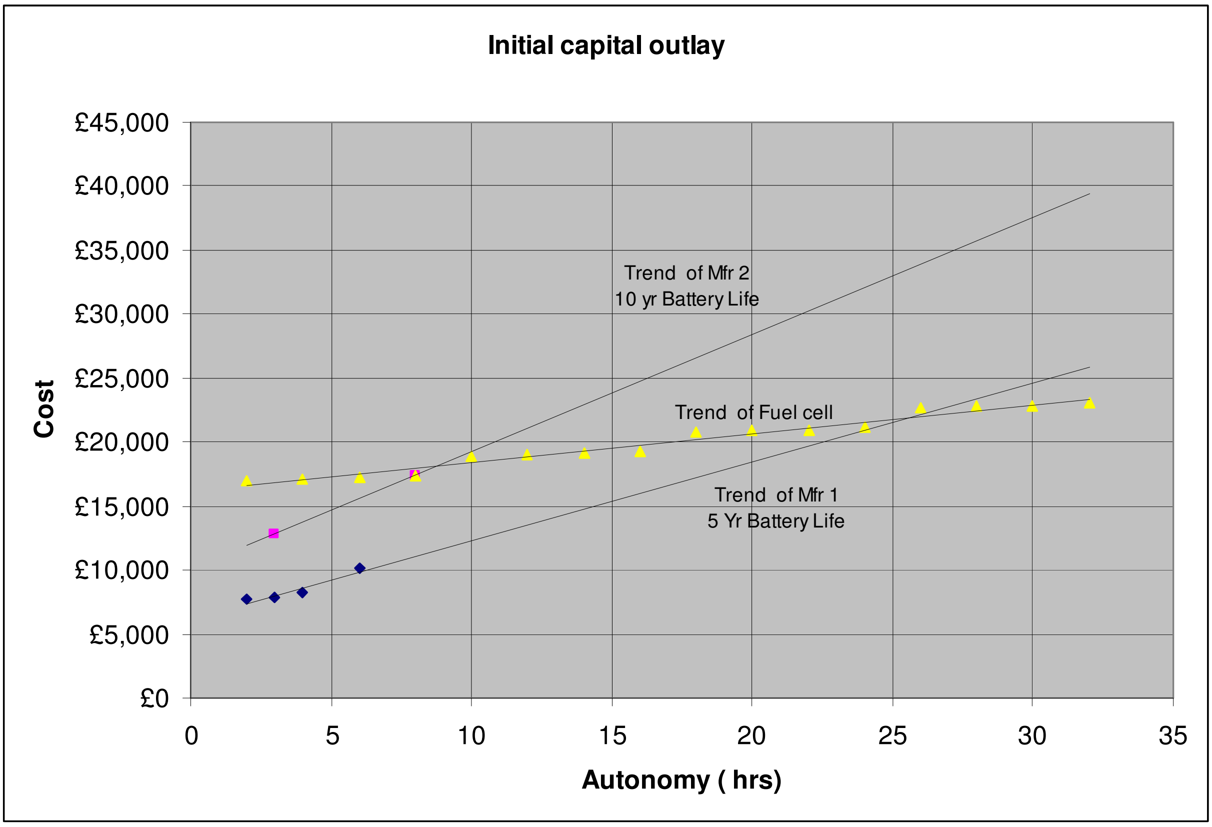


Figure 24. Trend comparison of costs of UPS' over autonomy periods

In the above graph, the initial capital for a fuel cell UPS is comparable to the cost of a 10 year battery UPS at 8 hours of autonomy. A 5-year battery plant needs to be replaced probably earlier than 5 years depending on the usage and storage. This means there would be a very similar capital (the inverter and rectifier electronics form only 30 % of the initial cost) investment in its lifetime. This tends to offset any initial advantage. Calculating its net present value tends to favour the fuel cell ups at around 7-9 hours of autonomy.

It can be concluded that at the present market rates the initial capital investment for a fuel cell reaches economic viability outlay around 7-9 hours of backup. It can also be stated from a different point of view. Plant managers have to predict the useful lifetime of particular installation and always have to plan for additional capacity. In case of a fuel cell system, for example a 5kW system, an additional cylinder connected gives two hours, which in comparison is extremely simple to increasing the capacity of a battery bank.

6.2 Cost of ownership

Along with the initial cost based on autonomy, a decision to invest can be arrived at, by considering the life cycle costs. The base assumptions are

1. 5kW power, 8 hrs autonomy
2. 10 year consideration

3. No of services per year
4. Battery replacement period of 5 years and 10 years

The other assumptions like tax, depreciation, service charges are given in 'base' column of table 15.Using these figures, a 'Net Present Value' for both the systems can be arrived at. Further NPV for the battery-based UPS can be calculated based on 5-year and 10-year battery life. Comparison with these three values should give a clear picture of the advantages of one system over another.

Summary analysis	Battery	Fuel Cell	Fuel Cell Variance
Capex	14,600	15,550	950
Operating costs	800	1,061	261
Total Lifetime costs	8,000	10,605	2,605
Plant replacement costs	9,000	-	(9,000)
Total Lifetime costs	31,600	26,155	(5,445)
NPV	(19,509)	(15,829)	3,681

Table 11. Net present value of fuel cell and 5 year Battery life UPS

In calculating the NPV for a 5-year battery life UPS, the battery replacement costs are taken into account.

Summary analysis	Battery	Fuel Cell	Fuel cell Variance
Capex	17,227	15,956	(1,270)
Operating costs	800	1,061	261
Total Lifetime costs	8,000	10,605	2,605
Plant replacement costs	11,627	-	(11,627)
Total Lifetime costs	36,853	26,562	(10,291)
NPV	(20,333)	(16,127)	4,206

Table 12. Net present value of fuel cell ups and 10 Year Battery life UPS

The variance of the fuel cell ups NPV is not very high; it varies form £4000 to £3500 approximately for the 10 year UPS and 5 year UPS respectively. This may not be a significant sum to influence a decision. There are some factors, which have to be noted at this point

- The fuel cell stack is designed to run at least for 10 years and operate as specified for at least 1500 hours[6].
- Stack degradation reduces the power output slowly. The stack can be replaced once this degradation is noticed to affect system performance.
- Battery systems are very much influenced by operating temperature. If the cost of this is taken into account this will very much favour the fuel cell

6.2.1 Cost projection

The prices of fuel cells have been continuously decreasing since their commercialization. Partly due to improved manufacturing techniques, cheaper membranes and production quantity, fuel cell system prices have seen drops of around 15 % in some financial year periods. On the contrary, battery prices have stabilised, though reliability due to research and manufacturing techniques are being improved continuously. Fuel cell prices, chiefly influenced by the cost of membrane, use of expensive catalysts and assembly costs are predicted to decrease as worldwide research in to alternatives and mass manufacturing yield significant cost advantages.

In comparing the trends of cost (Figure 25), the actual costs of the unit are taken for past values. A reduction of the cost of fuel cell system at the rate of 15% adjusted for inflation is forecasted for the trend in future. The cost of battery UPS is extrapolated at the rate of inflation.

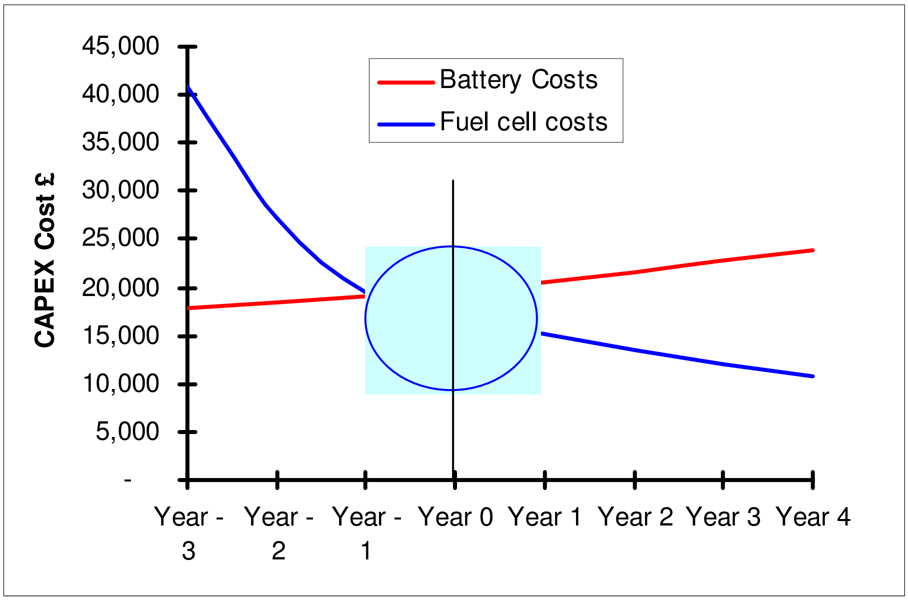


Figure 25. Cost evolution of Fuel cell and battery UPS Summary base case economics

---

[6] 150 hours of run time every year for 10 years.

		Low	Base	High
Both	Battery acquisition costs	£325.00	£350.00	£425.00
	Autonomy	6 hour(s)	8 hour(s)	8 hour(s)
	Failure Frequency	1 time(s) per year	2 time(s) per year	4 time(s) per year
	Tax Rate	25%	35%	35%
	Discount Rate	5%	10%	15%
	Tax Depreciation	3 years	5 years	6 years
	Annual Service costs enginee	£400	£500	£600
	Annual Service costs, consur	£200	£300	£400
Fue cell	Gas costs	£25.00	£29.32	£35.00
	Delivery Costs	£20.00	£25.95	£30.00
	Rental Costs	£55.00	£65.80	£75.00
	Control Panel	£400	£500	£600
	Cabinet	£600	£750	£900
	Hydrogen Installation	£700	£750	£800
5kW	5kW Inverter system	£2,500	£3,000	£3,250
	5kW System Installation	£1,500	£1,800	£2,000
	5kW Battery cabinet/racking	£1,900	£2,000	£2,100
	5kW Battery Monitoring	£900	£1,000	£1,100
	5kW Hydrogen Fuel Cell	£7,000	£8,750	£9,250

Table 13. Summary Values (including assumptions) for capital costs.

6.3 Significant OPEX Cost influences

It is seen as the autonomy increases, the cost of renting, delivery and re-filling of cylinders significantly affects the lifetime costs of a fuel cell. There are many factors affecting the prices of the services, like usage and number of cylinders. If the user already uses hydrogen as an onsite consumable, say is involved in manufacturing, this cost is significantly reduced, since existing facilities can be rerouted for this system.

Summary analysis	Battery	Fuel Cell	Fuel Cell Variance
Capex	14,600	14,050	(550)
Operating costs	800	800	-
Total Lifetime costs	8,000	8,000	-
Plant replacement costs	9,000	-	(9,000)
Total Lifetime costs	31,600	22,050	(9,550)
NPV	(19,509)	(13,517)	5,992

Table 14. Revised analysis with existing hydrogen availability 5-year battery life

Summary analysis	Battery	Fuel Cell	Fuel cell Variance
Capex	17,227	15,956	(1,270)
Operating costs	800	800	-
Total Lifetime costs	8,000	8,000	-
Plant replacement costs	11,627	-	(11,627)
Total Lifetime costs	36,853	23,956	(12,897)
NPV	(20,333)	(14,917)	5,416

Table 15. Revised analysis with existing hydrogen availability 10-year battery life

6.3.1 Impact of capital allowances

Currently hydrogen supplied either as a by-product from the petroleum refinery process and plastics production or specifically manufactured by reformation or electrolysis. Technology and commercial products for electrolysis are already available from the fuel cell industry. For higher efficiency, reversible fuel cells are used for splitting water into its constituent's oxygen and hydrogen. Such an incentive could bring about production of hydrogen with very low carbon input, offering significant environmental benefits. However selling this into the small UPS marked may be difficult. Grid balancing is a possibility however.

The effect of capital allowances offered towards these technologies would significantly accelerate and improve the hydrogen infrastructure.

		Low	Base	High
Battery	Capex	£12,000	£14,600	£17,300
	Operating costs	£600	£800	£1,000
	Total Lifetime costs	£6,000	£8,000	£10,000
	Plant replacement costs	£7,000	£9,000	£11,000
	Total Lifetime costs	£27,600	£31,600	£35,600
	NPV	£15,559	£19,509	£23,533
Fuel cell	Capex	£12,700	£15,500	£16,800
	Operating costs	£940	£1,206	£1,470
	Total Lifetime costs	9400	£12,060	£14,700
	Plant replacement costs	-	-	-
	Total Lifetime costs	£22,100	£27,610	£31,500
	NPV	£13,613	£16,897	£18,995
	Fuel cell Variance	£1,946	£2,612	£4,538

Table 16. Summary values (5 year battery plant) for life cycle values, with tax rate, discount rate, depreciation, and autonomy held constant at base values of table 15.

6.4 Market potential

As a back up power source, the cost advantage is visible only after a threshold of autonomy. Otherwise the fuel cell systems have an obvious advantage in unmanned remote applications where the cost of laying power cables outweighs the initial cost of a fuel cell system. The cost of hydrogen as a raw "fuel" impedes this; however, methanol fuel cells are a realistic possibility.

The use of fuel cells to export power to the grid is already addressed in the Engineering recommendation G83/1. This allows users to store excess energy to export to the grid during periods of peak demand.

6.5 Conclusions

- Fuel cells are economically viable only for over a certain threshold of autonomy.
- The capital cost of the fuel cell system installation is lower than an equivalent battery UPS.
- The operating cost and life time cost of the battery UPS is lower than the fuel cell for low autonomies, the cheaper capital of a five year life battery requires earlier replacement cost, whereas 10 year life battery bank will prove to be expensive in capital cost but delay the replacement cost.

- NPV of fuel cell system compare very favourable to battery based UPS. Savings of at least £5000 can be expected. This increases when hydrogen is available on site.
- The price of fuel cells continues to reduce through improved manufacturing techniques. Commoditised battery systems prices have stabilised with any increase only due to inflation.
- These conclusion are in line with the predictions on the 5kW economics undertaken in a previous report for 1kW fuel cell based UPS[7]. The lifecycle economics 1kW fuel cell based UPS are similar to the 5kW UPS, showing a cost benefit above a threshold for autonomy. The conclusions arrived at, are still valid, with track record and data of fuel cells in field, along with the comfort and confidence of the plant managers to switchover to fuel cell based UPS.

[7] Characterisation of Fuel cell based UPS – URN No 04/1399 (www.dti.gov.uk/renewables/renew_6.1f.htm)

7 CONCLUSION

This report concludes the characterisation programme a 5 kW UPS based on commercially available fuel cell systems. It includes investigation of gas storage methods, delivery systems, fuel cell selection, and selection of electrical subsystem, i.e. inverter and rectifier. A detailed description of the onsite gas storage used is described. Importance of risk assessment on site is emphasised. References are provided for undertaking the assessment. Due importance has been given due to the nature of the fuel being used.

The testing program addresses the concerns associated with a new technology by successfully evaluating the performance of the fuel cell against that of a battery bank. Tests included start-up in cold ambient temperatures, with dehumidified stack for simulating operation in real life where startup may be required after several weeks of standby non-operation. Operation has been verified throughout the range using resistive and reactive loads applied to the inverter. Influence of stack temperature is noted on the time to start up. Performance during longer operation is verified in soak tests. Improvement in efficiency with optimal stack temperatures is also seen during these tests.

Dynamic operation of the fuel cells is also tested using load-switching techniques. The maximum step load the fuel cell can support without battery is found; the system can support switching on of any rated load easily with the support of transitional batteries. Other manufacturers have used ultra-capacitors instead to improve the reliability. Fuel cells UPS systems using ultra capacitors are already commercially available. Tests on inverter verify the stable transition from mains to backup and vice-versa. Efficiency calculations confirm the operating efficiency usually associated with PEM fuel cell[8].

Economic analysis demonstrates the viability of the fuel cell above a certain autonomy period over a equivalent battery operated UPS. When annual operating costs are taken into account over a period of 10 years, the net present value of the fuel cell is significantly lower than a battery operated UPS. The fuel cell stack, the core of the system is rated for 10 years and minimum 1500 hours of generating operation. Since degradation in stack performance at the end of “lifetime” is a gradual rather than instant failure, the time to replace the stack can be significantly extended if full power is not required, leading to lower NPV operating costs.

The decreasing costs of volume production together with alternative materials indicate a continual reduction in the prices of fuel cells. The initial outlay is significantly reduced if the hydrogen infrastructure is already in place. Impact of capital allowances on hydrogen infrastructure is also observed.

---

[8] Fuel cell handbook (seventh edition), EG&G technical services

Continuous advances in technology promises to bring down the costs by using lesser amounts of catalyst and alternative membrane materials. With hydrogen available commercially, it is no longer a constraint to the deployment of fuel cells.

These factors lead to a conclusion, favourable to the fuel cell in the back up power industry.

8 ACKNOLWEDGEMENT

SiGEN would like to acknowledge the support of DTI, critical for this investigation. SiGEN would also like to thank the manufacturers, Plug Power – GenCore ® Fuel Cell product and Unipower Telecom – the Inverter and Rectifier's, for their technical help in carrying out the project. The information of the current prices of equivalent battery UPS systems provided by suppliers is also acknowledged.

9 REFERENCES

- BCGA CODE OF PRACTICE CP 33.The Bulk storage of Gaseous Hydrogen at Users' Premises, 2005-11-21
- Fuel cells, Understand the hazards, Control the risks. HSG243, 2004
- Fuel Cell handbook (Seventh Edition) by EG&G Technical Services, Inc. November 2004
- Characterisation of a Fuel Cell based Uninterruptible Power Supply. URN NO. 04/1399. (www.dti.gov.uk/renewables/renew_6.1f.htm)

10 APPENDIX A – Additional Graphs of tests in section 3

10.1.1 Cold Start Resistive Load, 3kW – Graphs (Refer section 3.2.1)

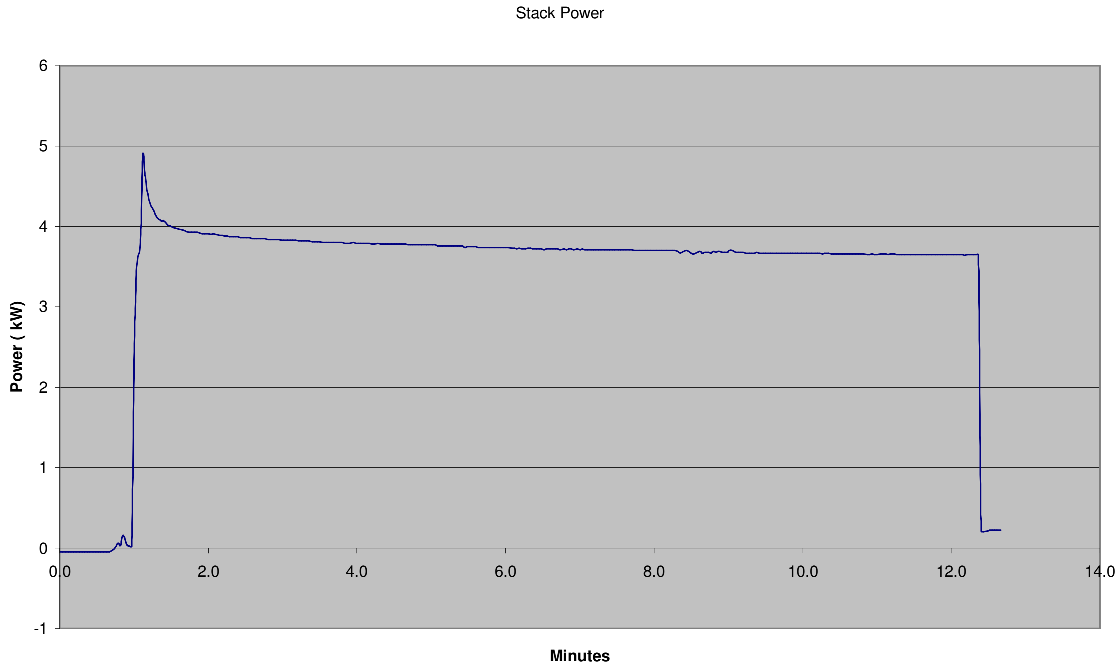


Figure 26. Cold start resistive load, 3kW. Stack Power Vs time

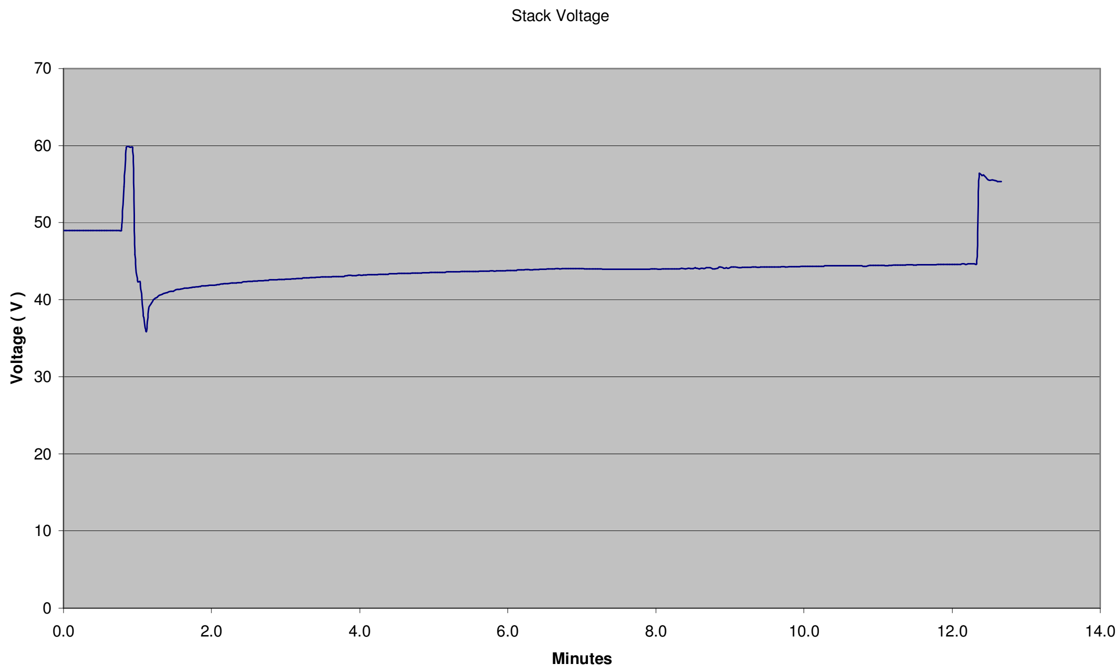


Figure 27. Cold start resistive load, 3kW. Stack Voltage Vs time

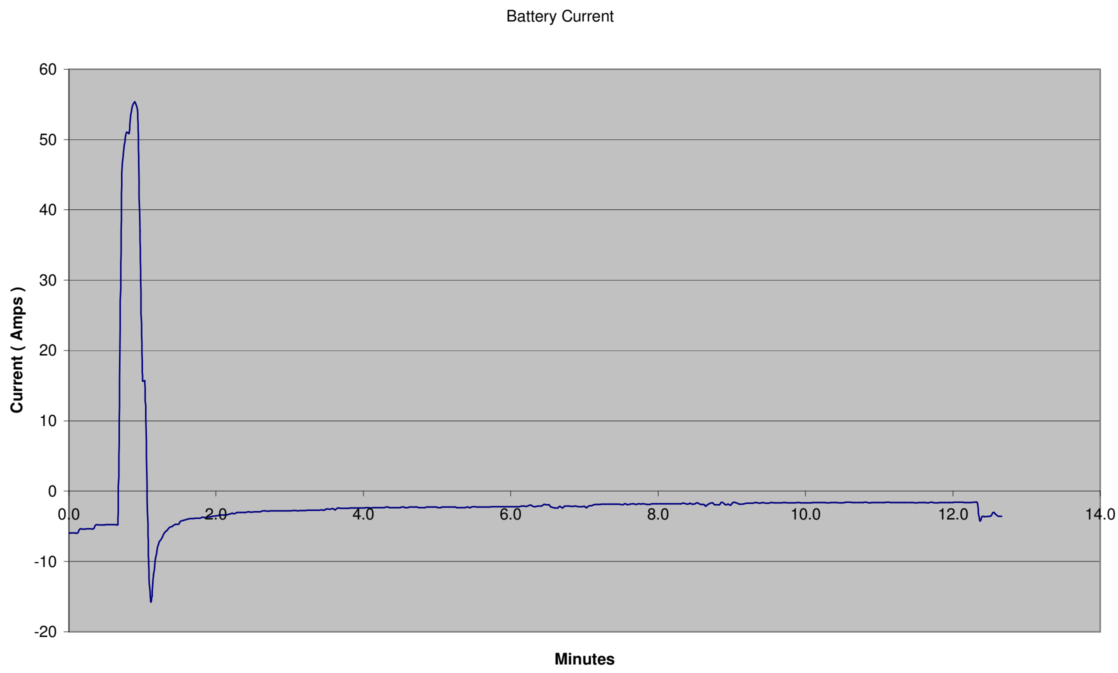


Figure 28. Cold start resistive load, 3kW. Battery current Vs time

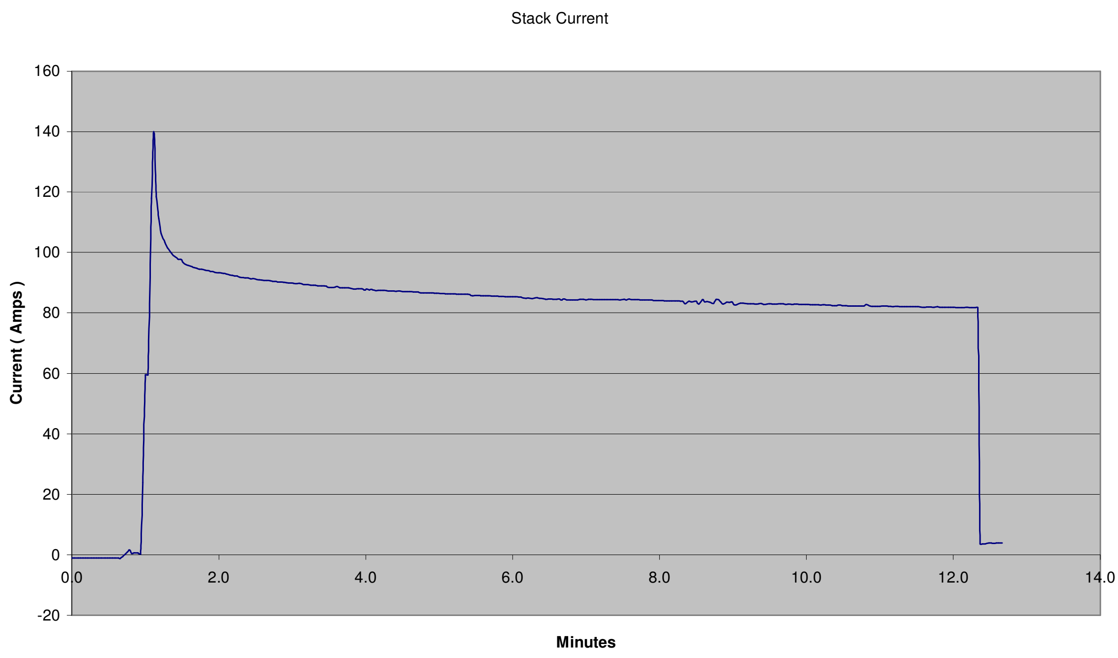


Figure 29. Cold start resistive load, 3kW. Stack current Vs time

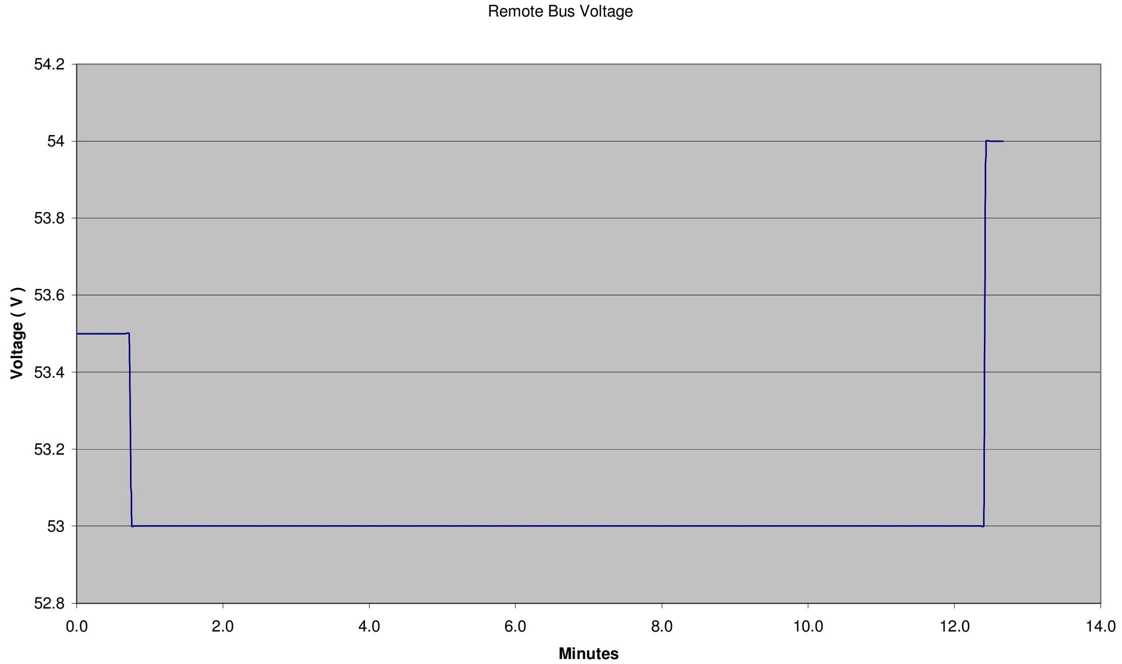


Figure 30. Cold start resistive load, 3kW. Battery Voltage Vs time

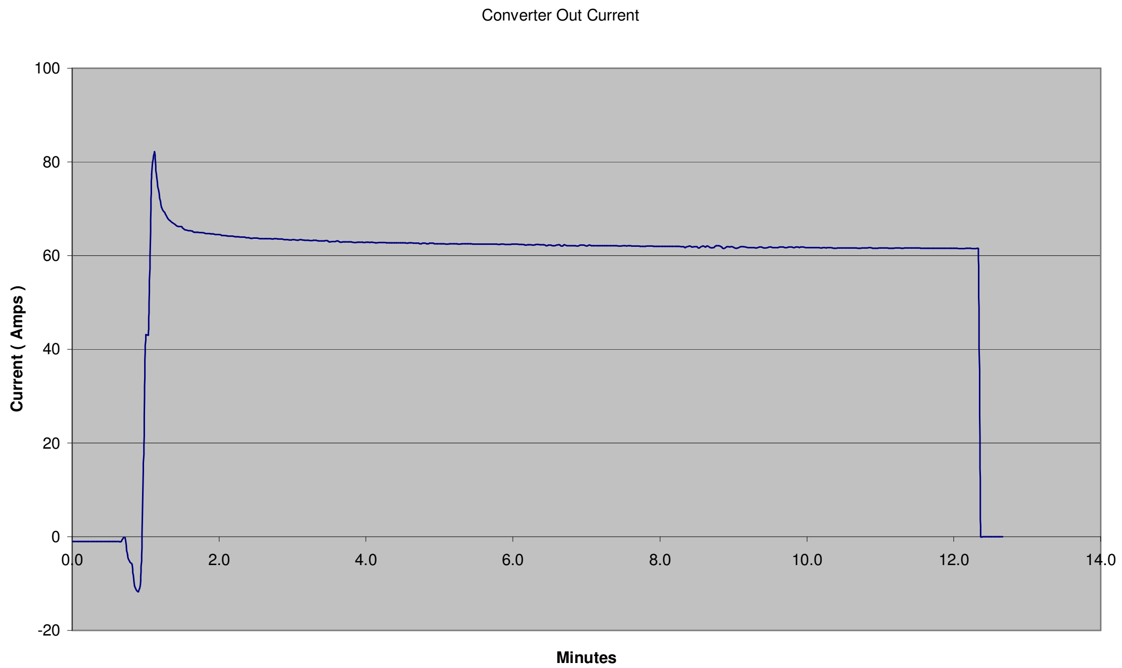


Figure 31. Cold start resistive load, 3kW. Converter current Vs time

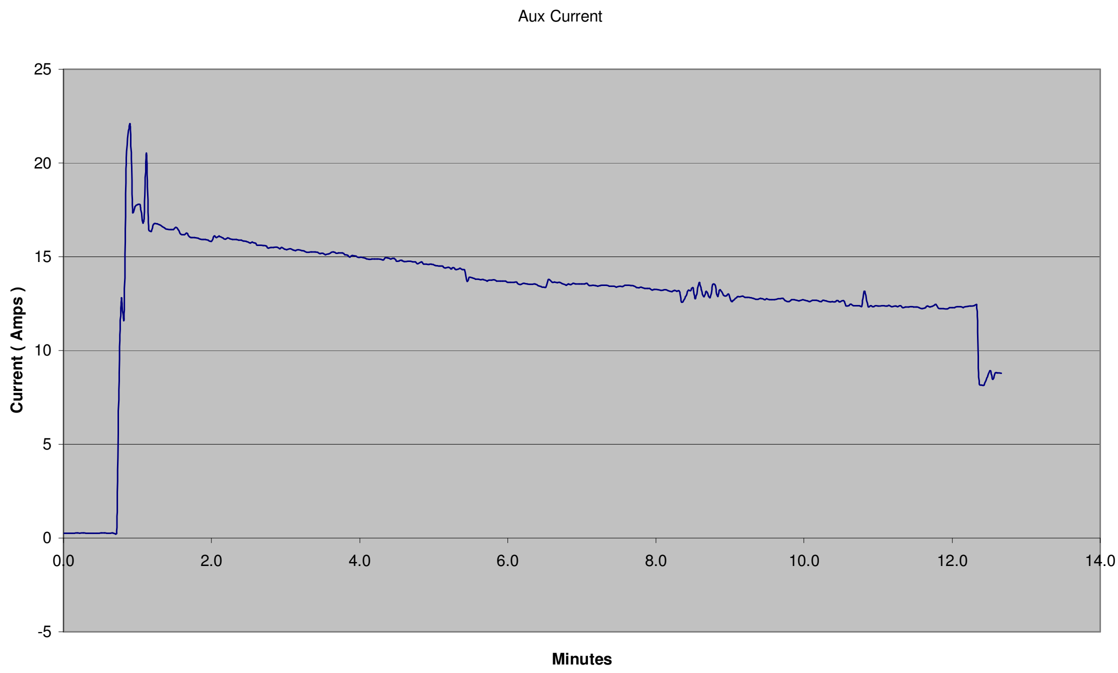


Figure 32. Cold start resistive load, 3kW. Auxiliary current Vs time

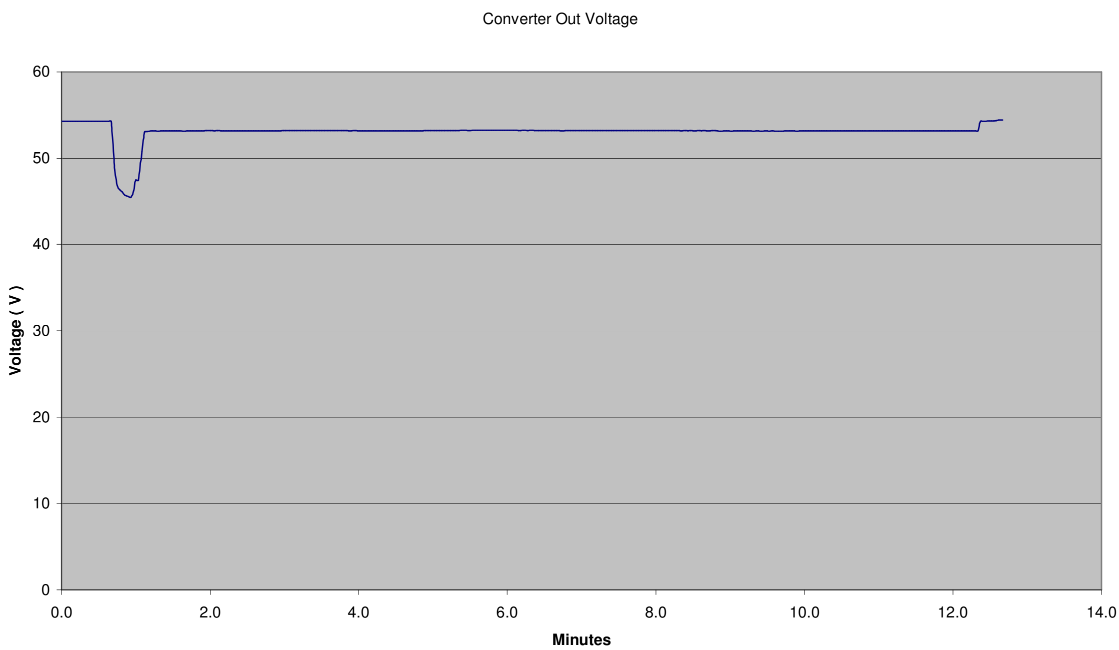


Figure 33. Cold start resistive load, 3kW. Converter Voltage Vs time

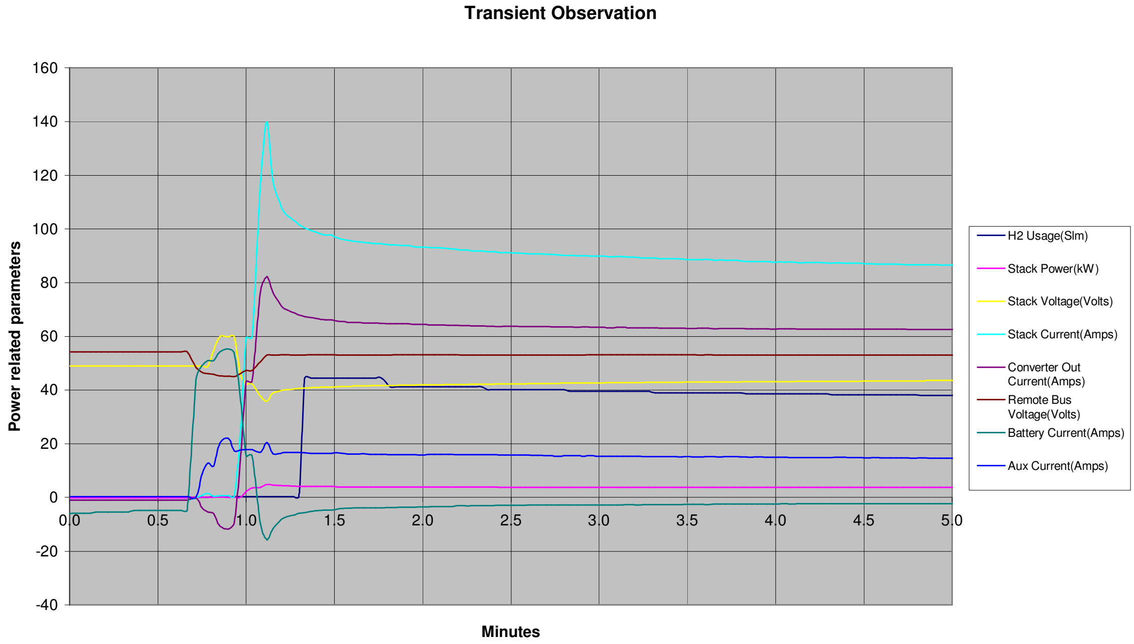


Figure 34.Cold start resistive load 3kW. Transient parameters Vs time

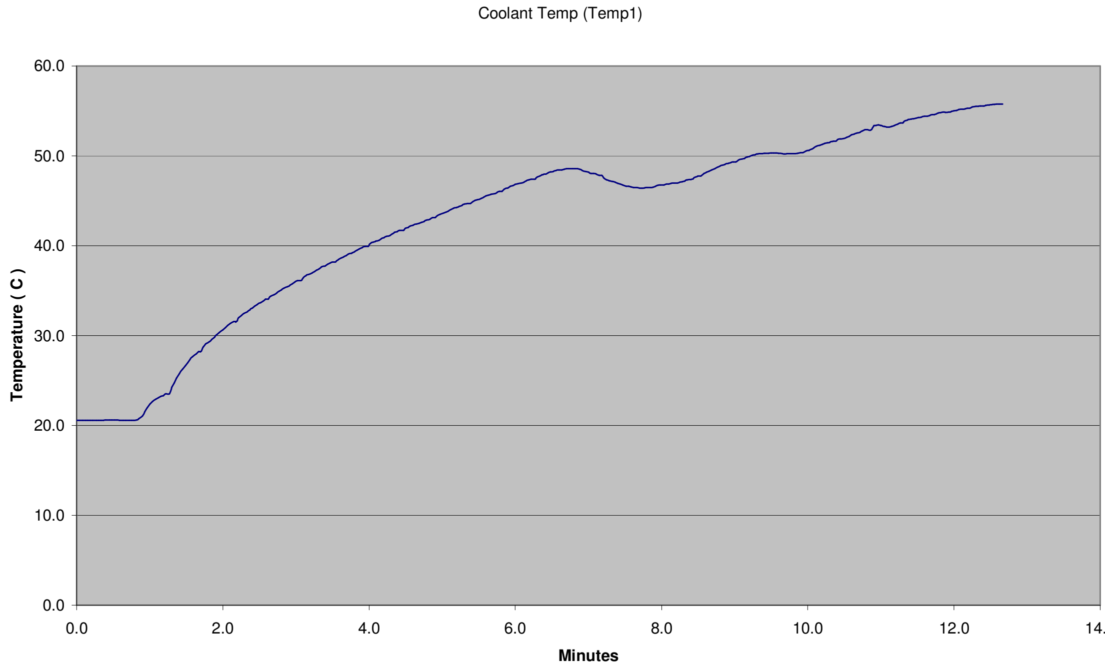


Figure 35 Cold start resistive load 3kW.Coolant temperature with time

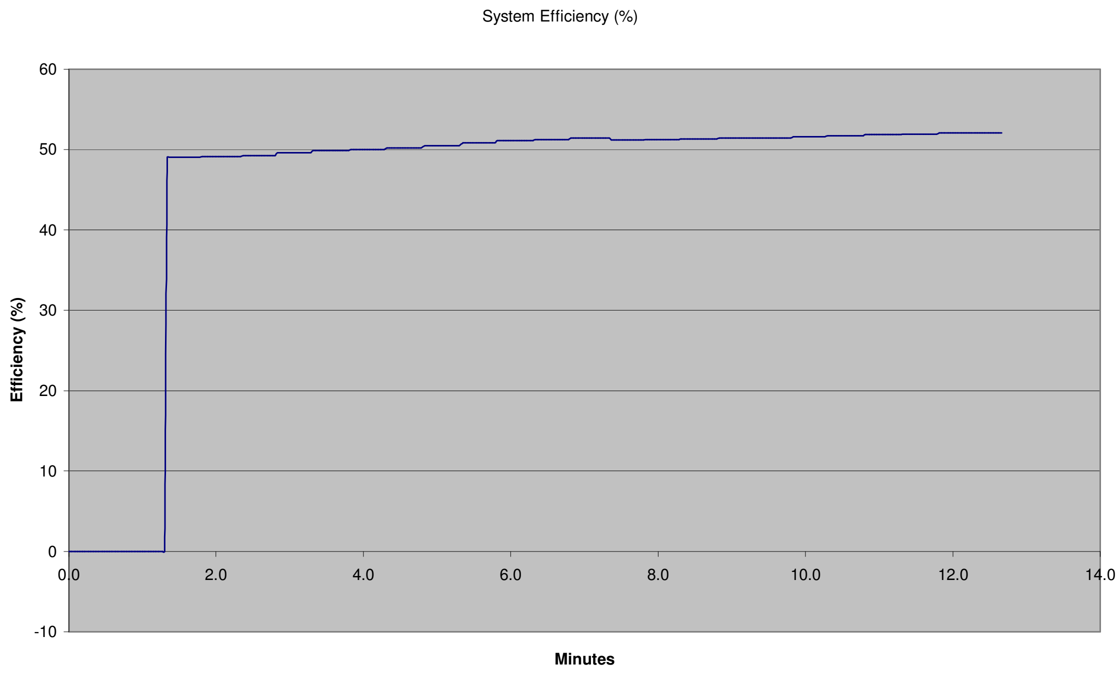


Figure 36. Cold start resistive load 3kW. System efficiency

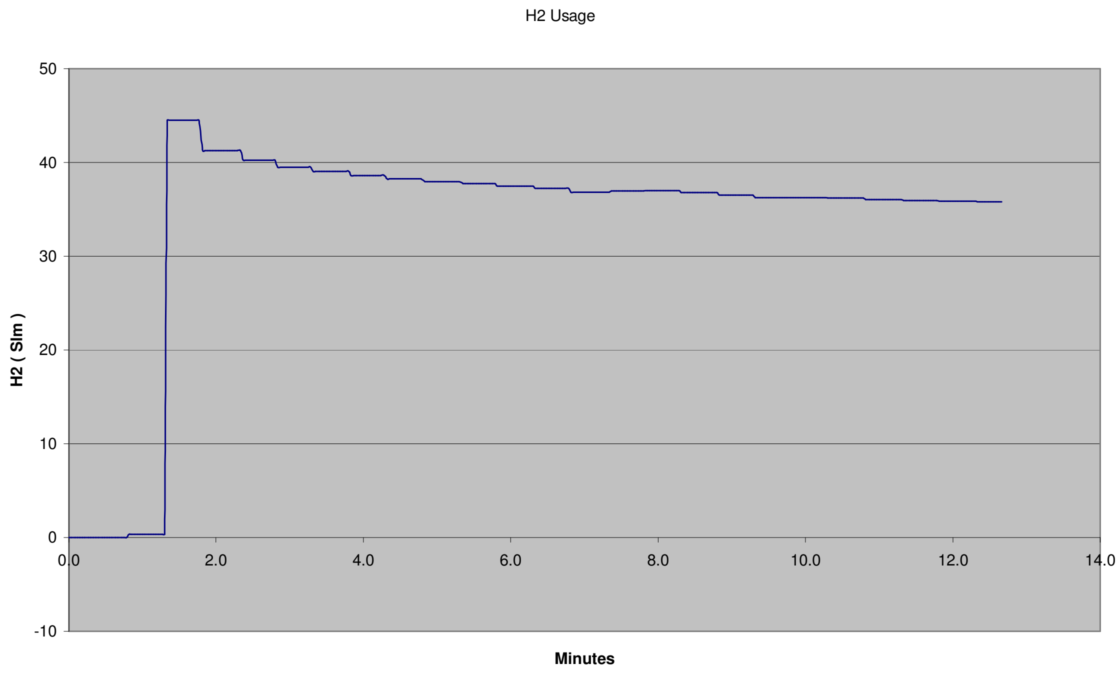


Figure 37. Cold start resistive load, 3kW. Hydrogen consumption Vs time

10.1.2 Cold Start Resistive load, 4.5kW - Graphs (Refer section 3.2.1)

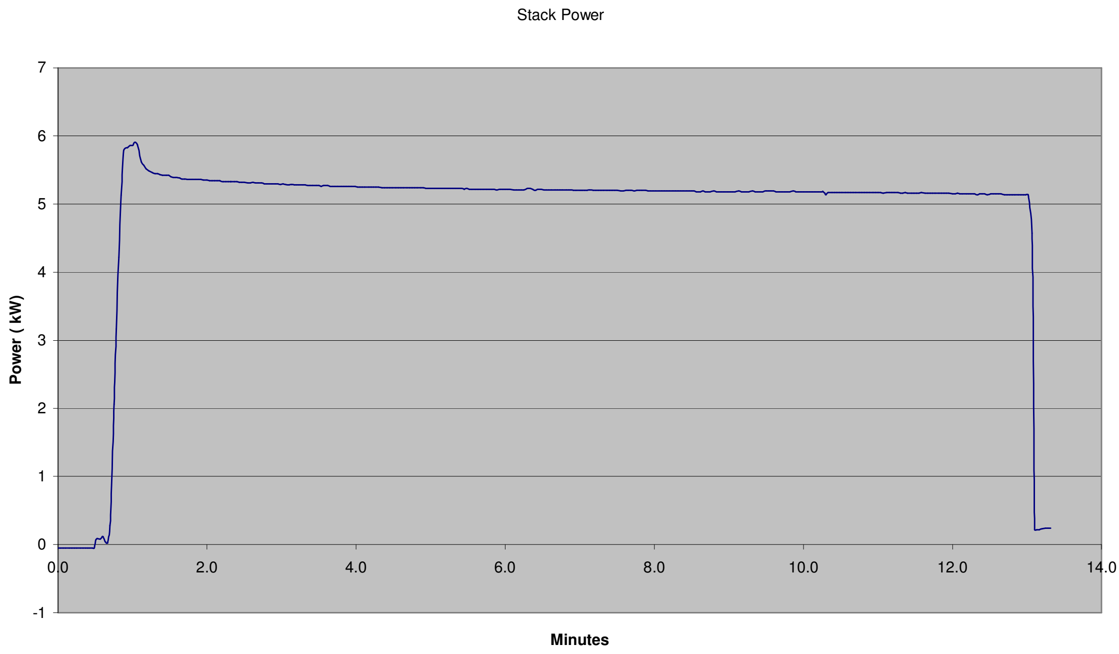


Figure 38. Cold start resistive load – 4.5 kW, Stack power Vs time

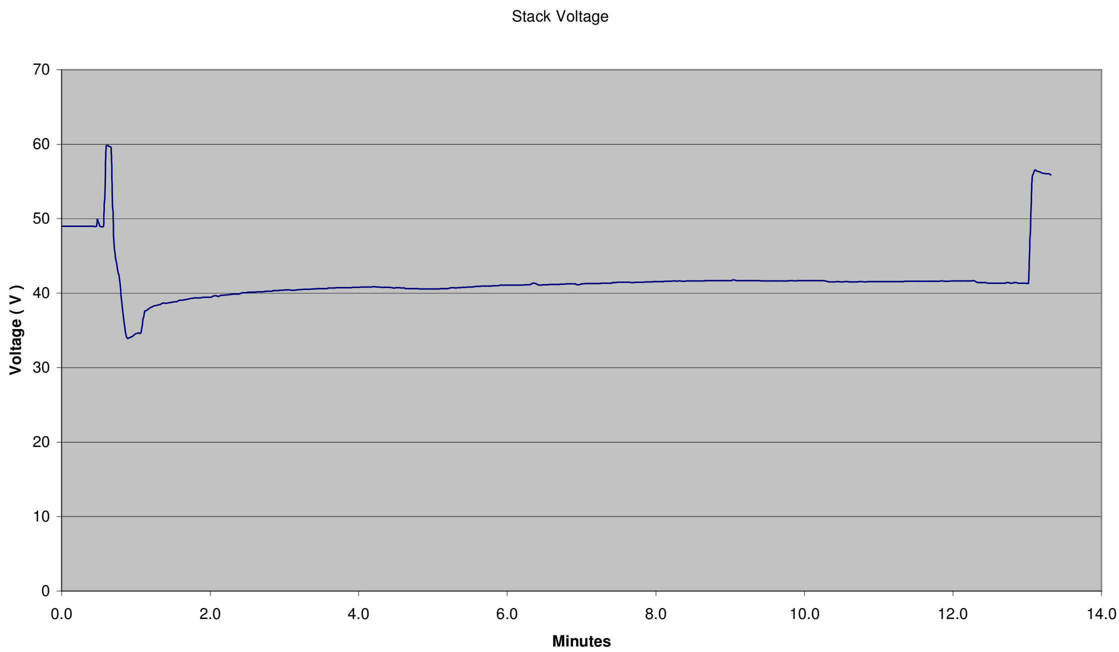


Figure 39. Cold start resistive load, 4.5kW. Stack Voltage Vs time

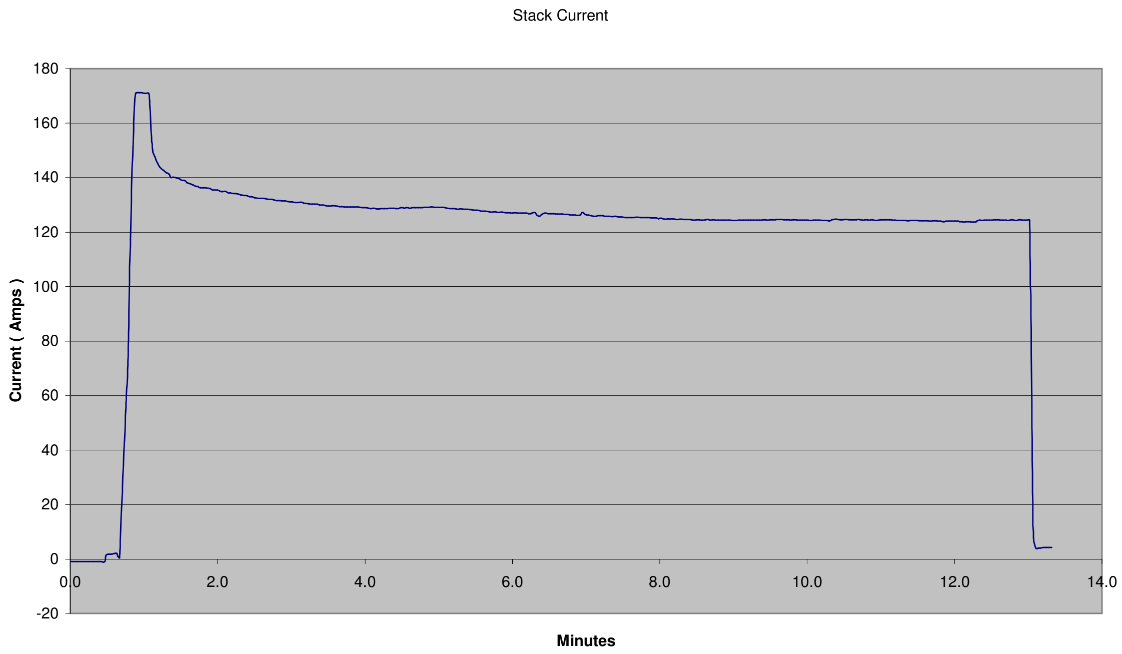


Figure 40. Cold start resistive load, 4.5kW. Stack Current Vs time

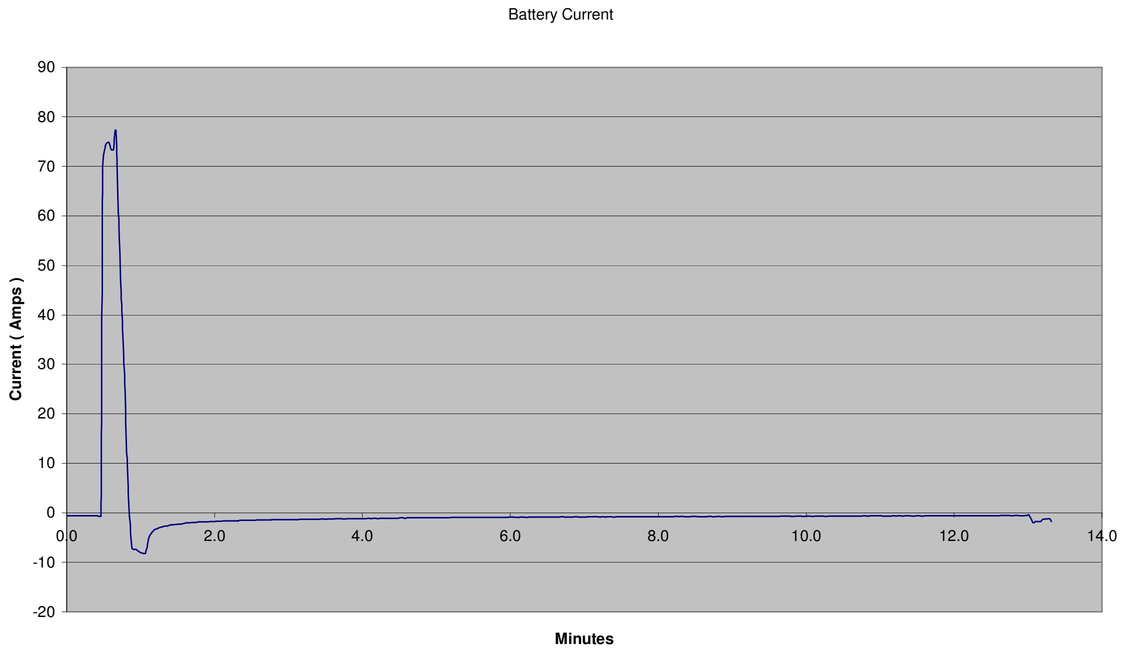


Figure 41. Cold start resistive load, 4.5kW. Battery Current Vs time

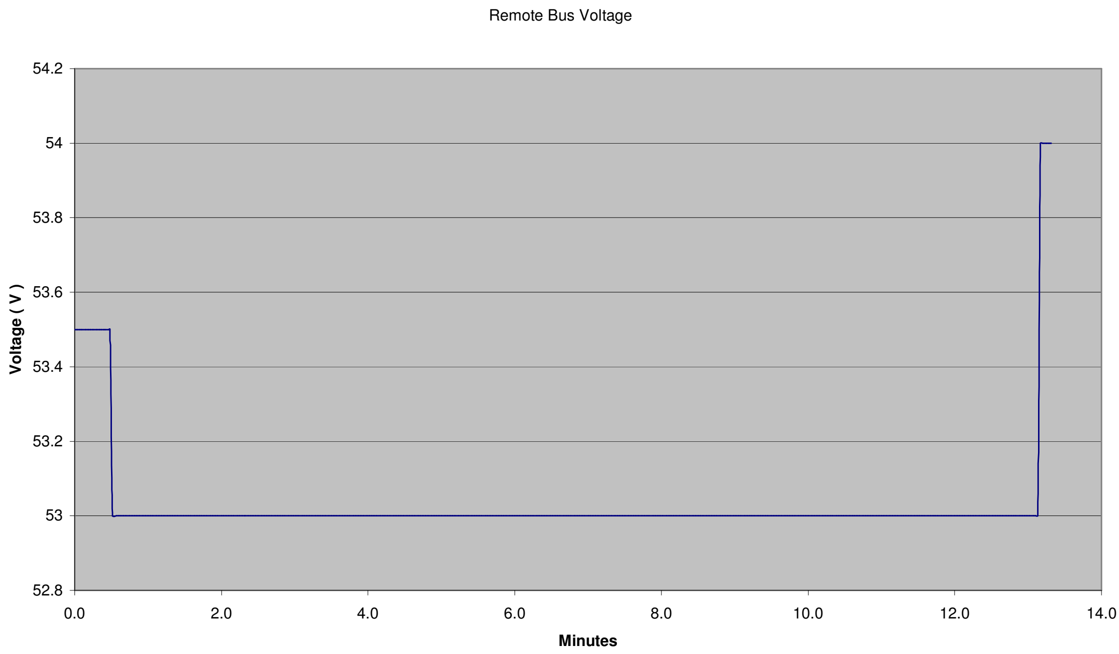


Figure 42 Cold start resistive load, 4.5kW. Battery Voltage Vs time

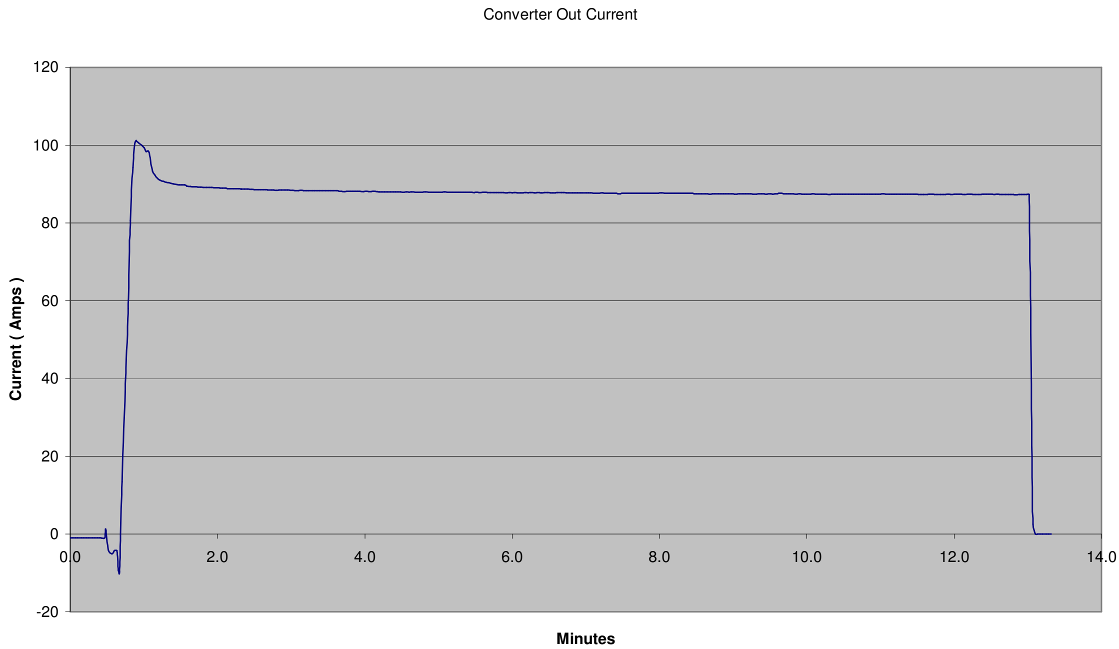


Figure 43. Cold start resistive load, 4.5kW. Converter current Vs time

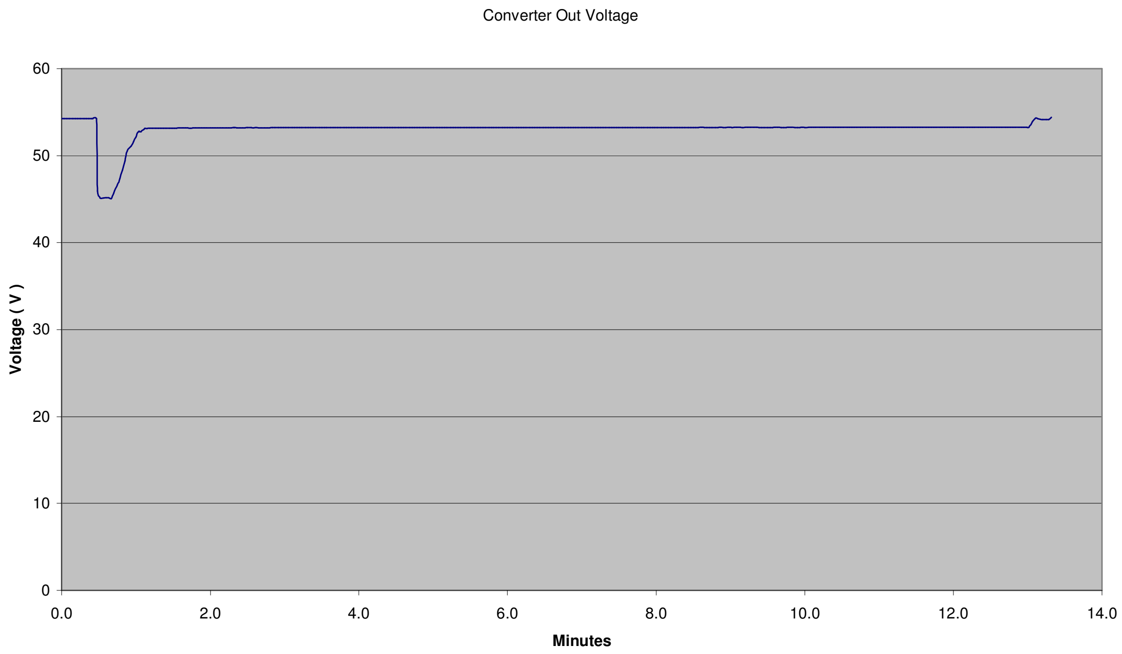


Figure 44. Cold start resistive load, 4.5kW. Converter Voltage Vs time

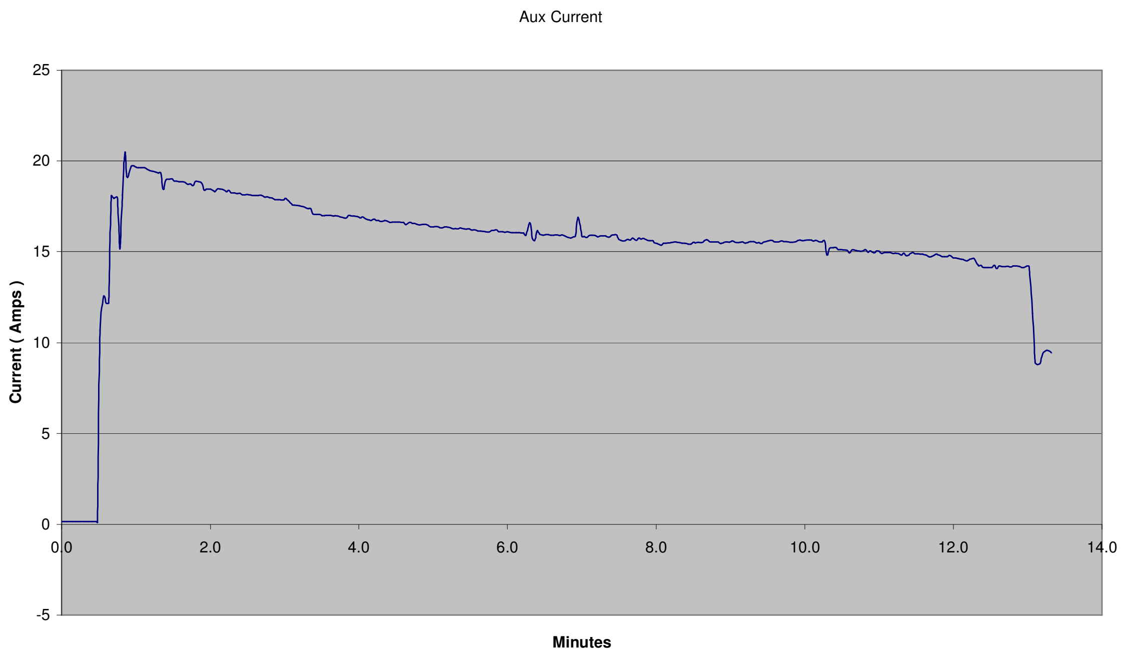


Figure 45. Cold start resistive load, 4.5kW. Auxiliary current Vs time

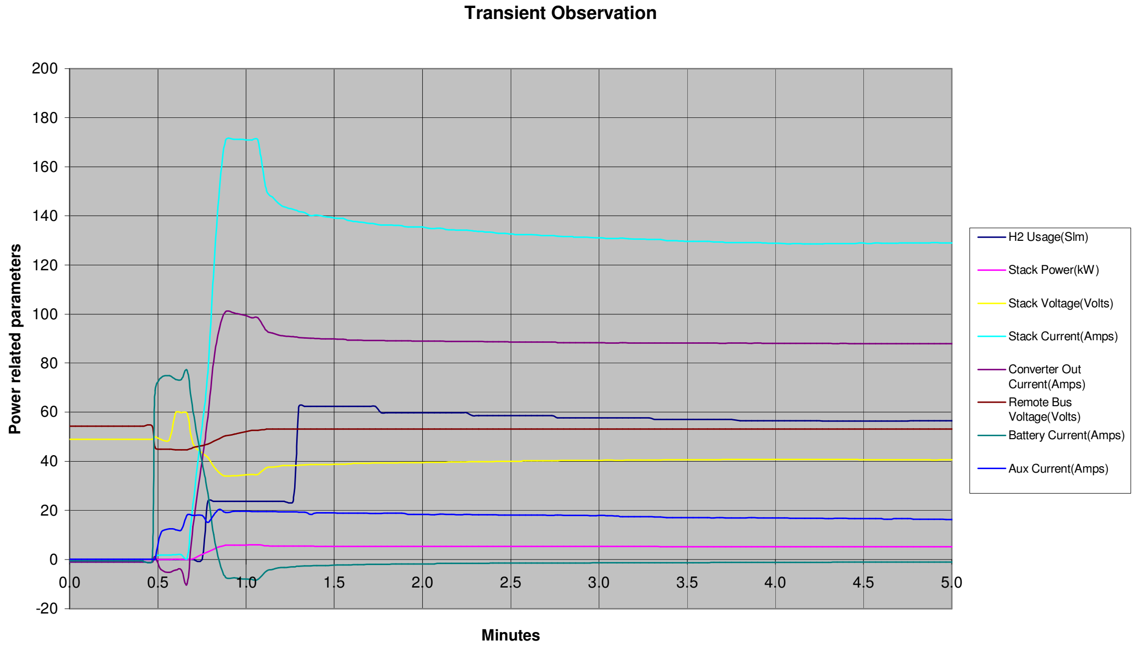


Figure 46. Cold Start Resistive load 4.5kW. Transient observations

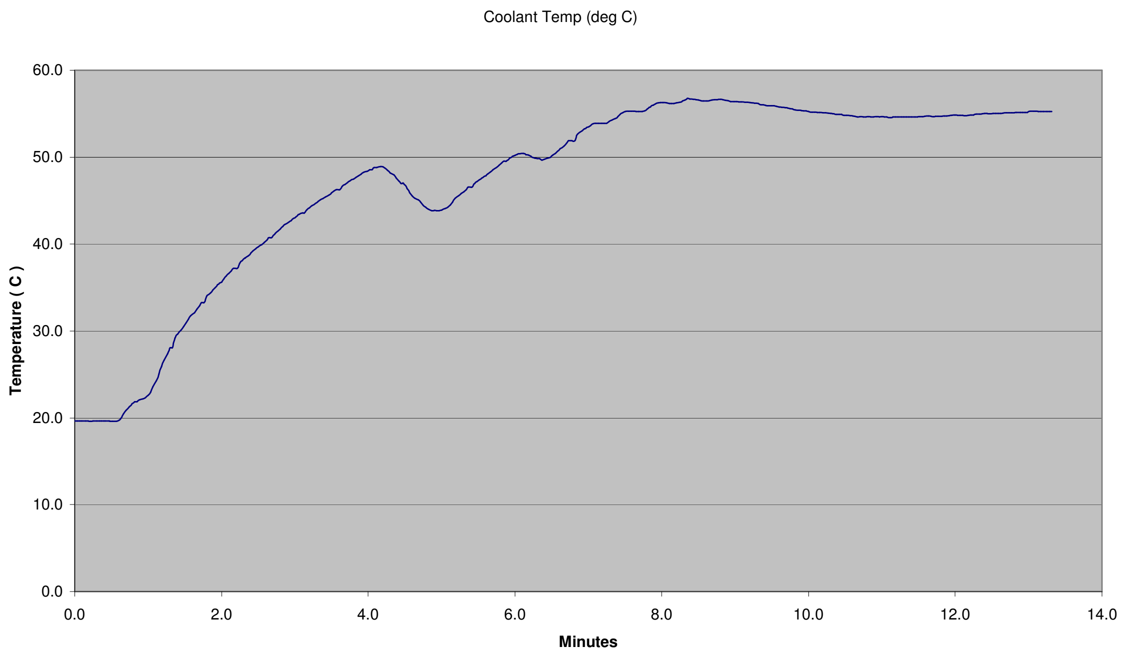


Figure 47. Cold start resistive load, 4.5kW. Coolant Temperature Vs time

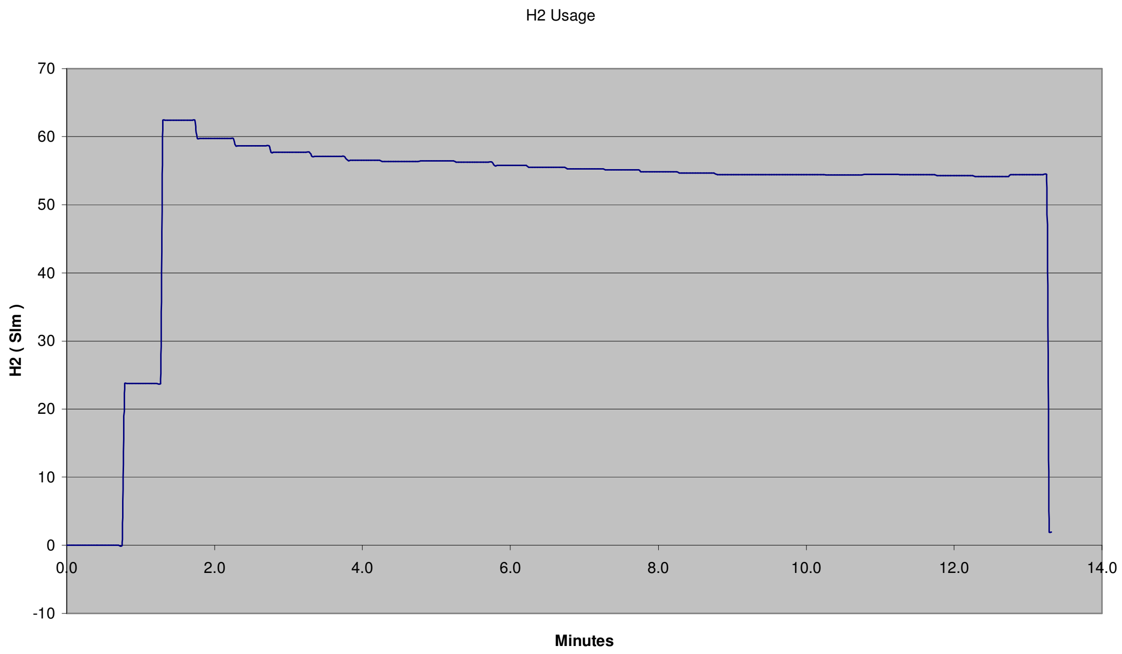


Figure 48. . Cold start resistive load, 4.5kW. Hydrogen usage Vs time

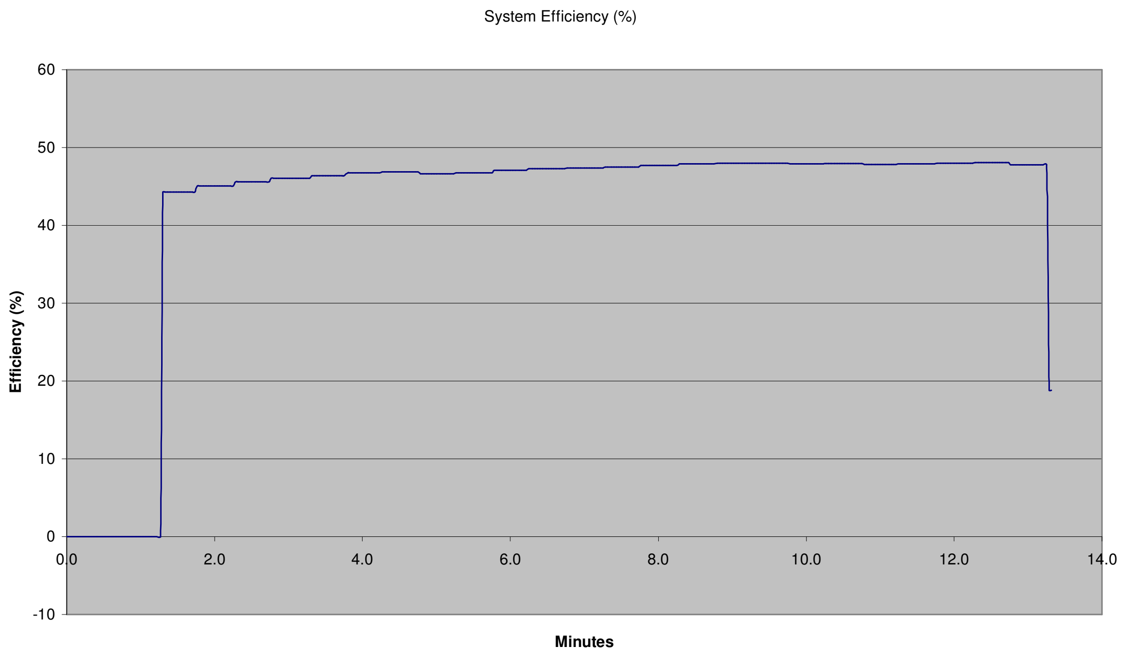


Figure 49. Cold start resistive load, 4.5kW. System Efficiency Vs time

10.1.3 Cold start capacitive load, 2kW 0.8Lead – Graphs. (Refer section 3.2.2)

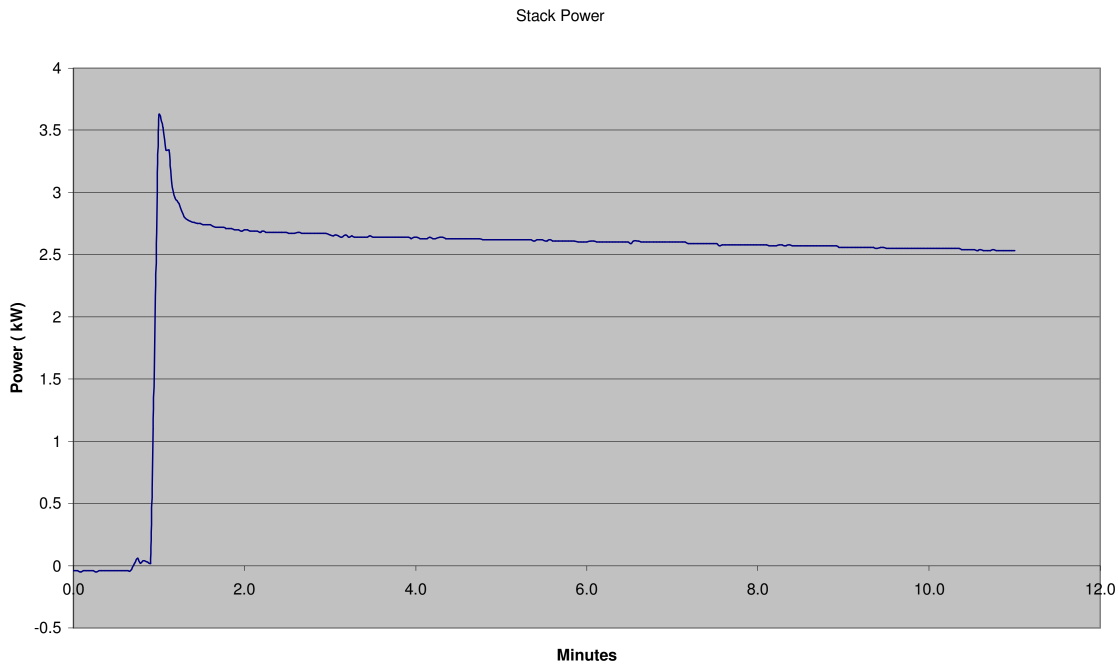


Figure 50. Cold start capacitive load, 2kW 0.8Lead. Stack Power Vs time

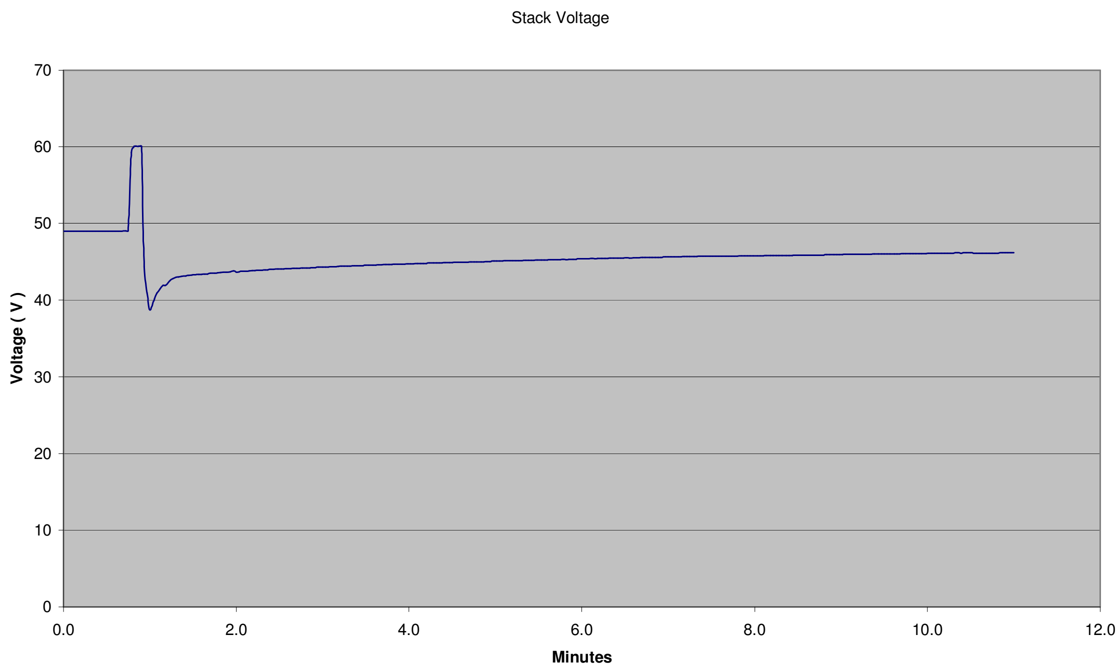


Figure 51. Cold start capacitive load, 2kW 0.8Lead. Stack Voltage Vs time

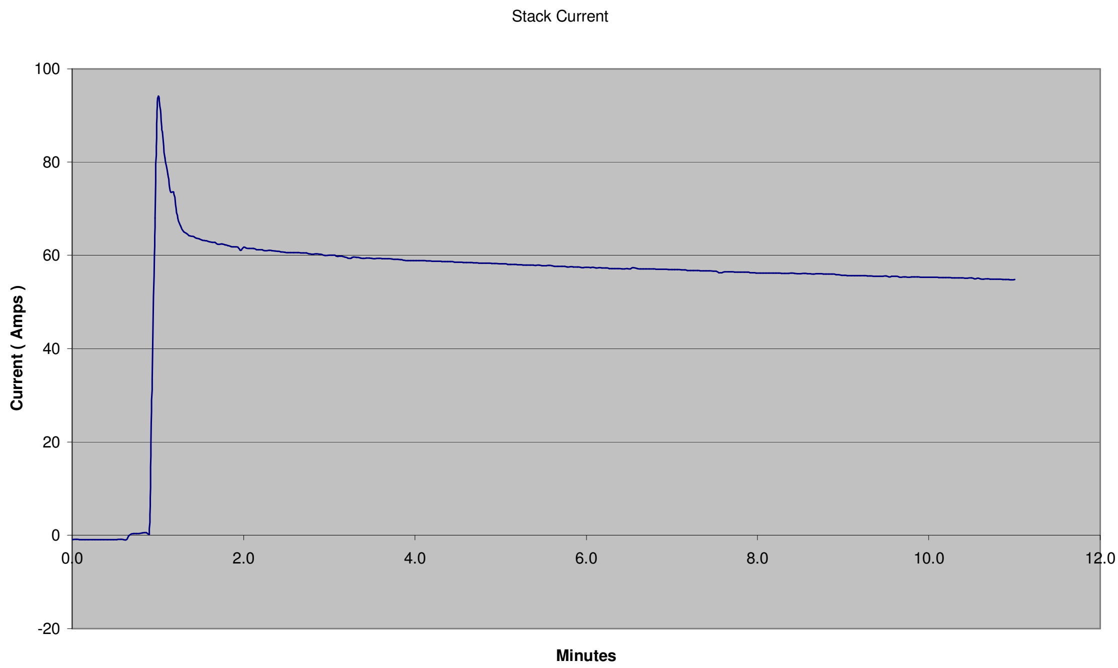


Figure 52. Cold start capacitive load, 2kW 0.8Lead. Stack current Vs time

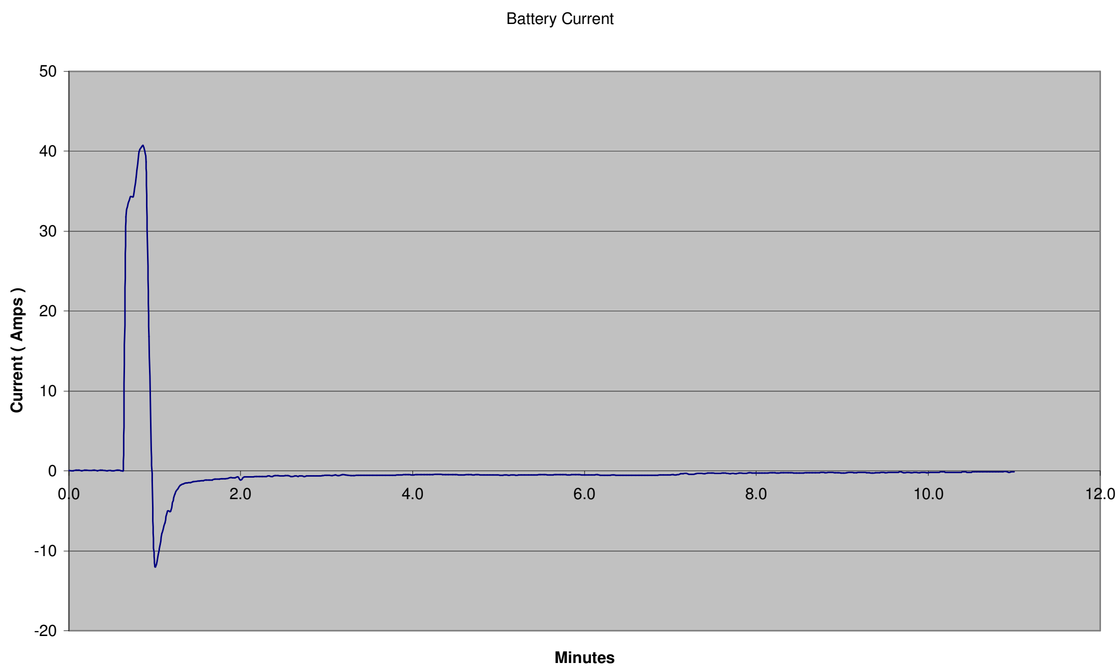


Figure 53. Cold start capacitive load, 2kW 0.8Lead. Battery Current Vs time

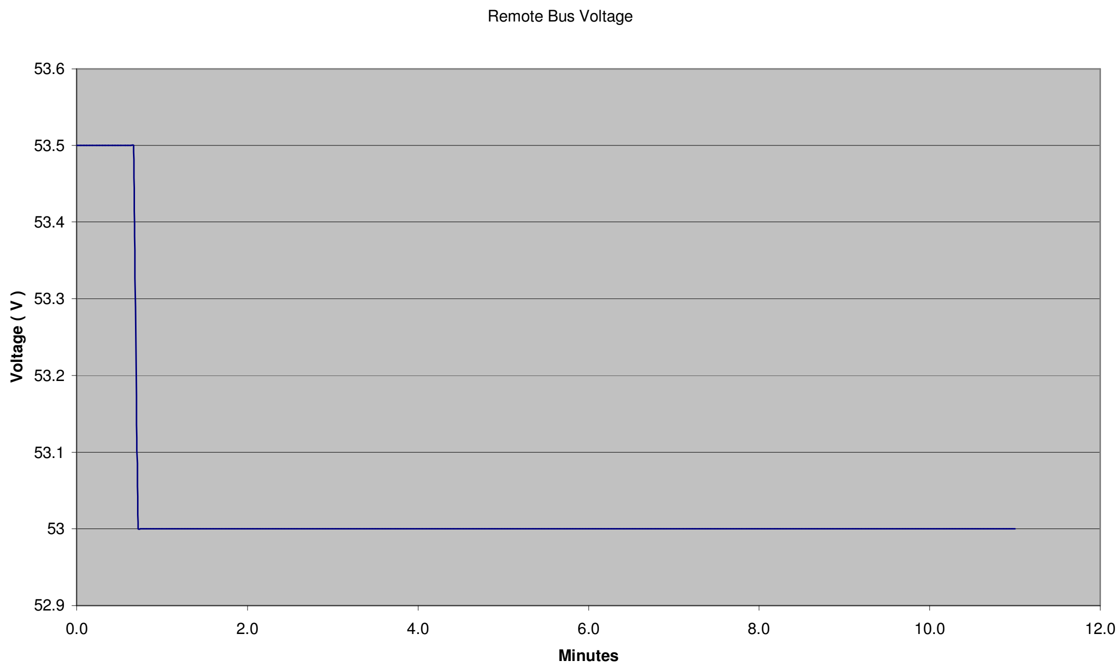


Figure 54. Cold start capacitive load, 2kW 0.8Lead. Battery Voltage Vs time

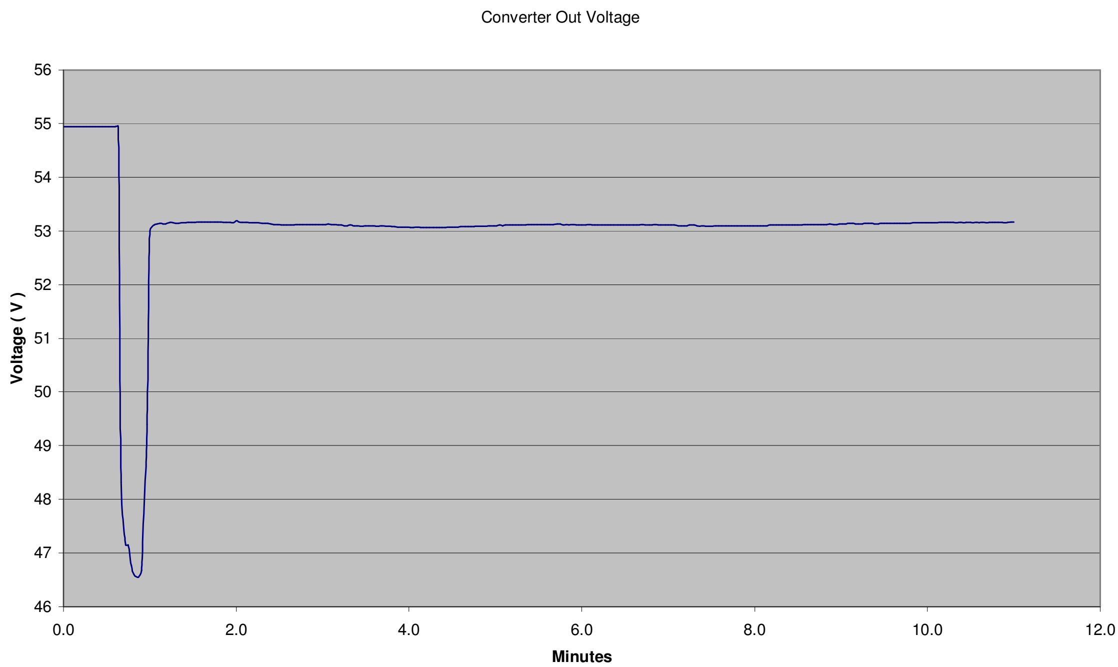


Figure 55. Cold start capacitive load, 2kW 0.8Lead. Converter Voltage Vs time

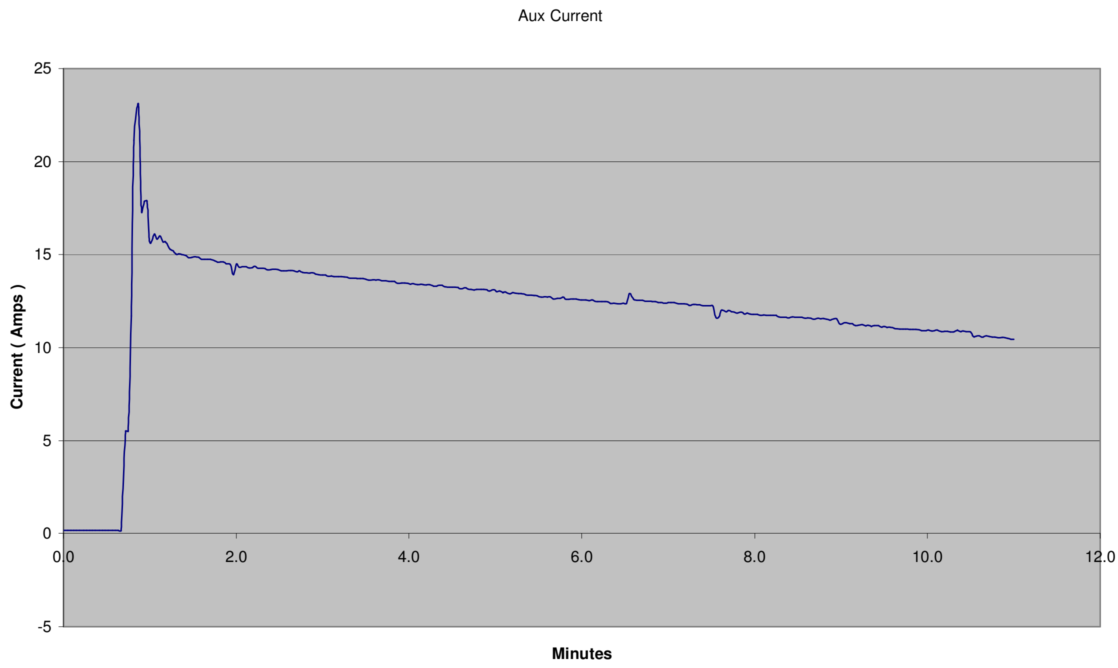


Figure 56. Cold start capacitive load, 2kW 0.8Lead. Converter Current Vs time

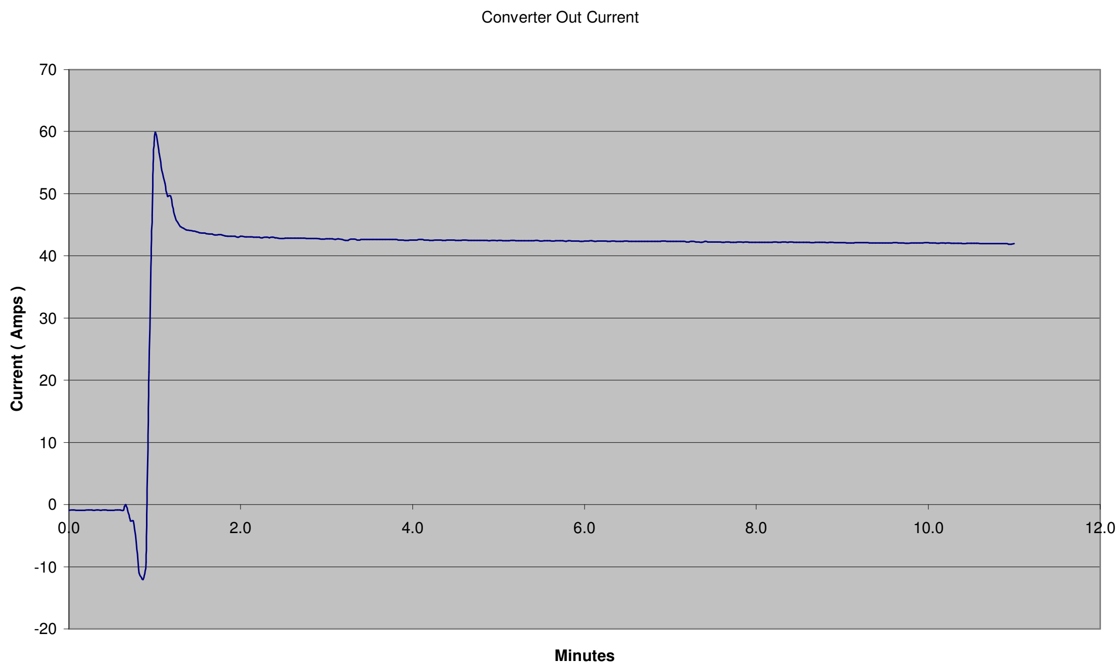


Figure 57. Cold start capacitive load, 2kW 0.8Lead Auxiliary Current Vs time

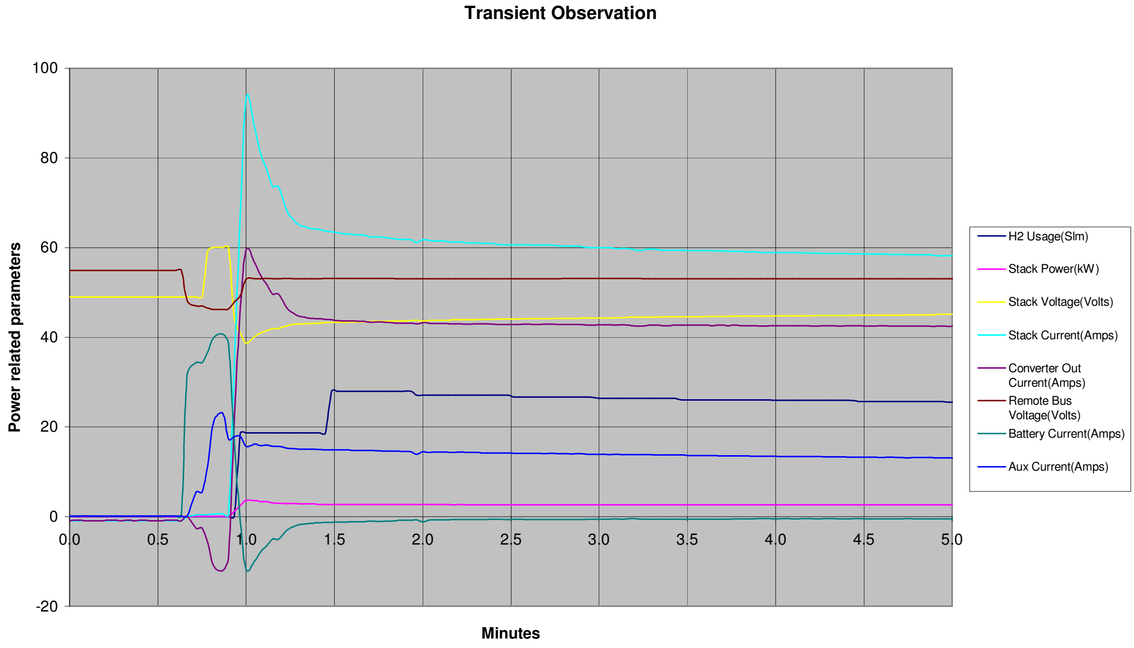


Figure 58. Cold start capacitive load, 2kW 0.8Lead. Transient Parameters Vs time

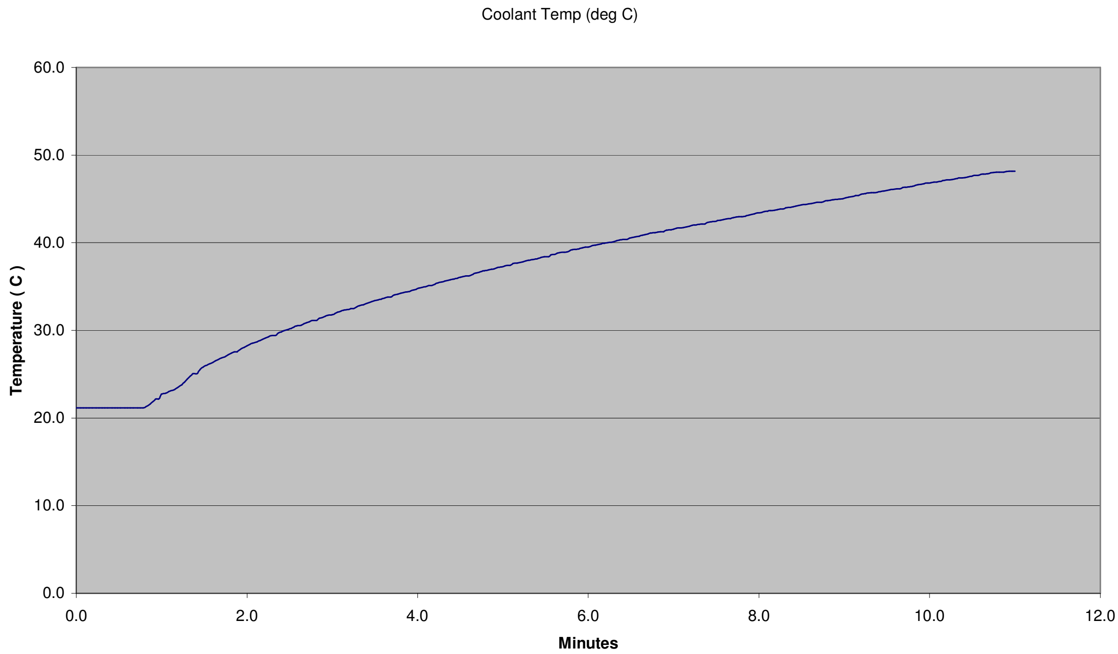


Figure 59. Cold start capacitive load, 2kW 0.8Lead. Coolant Temperature Vs time

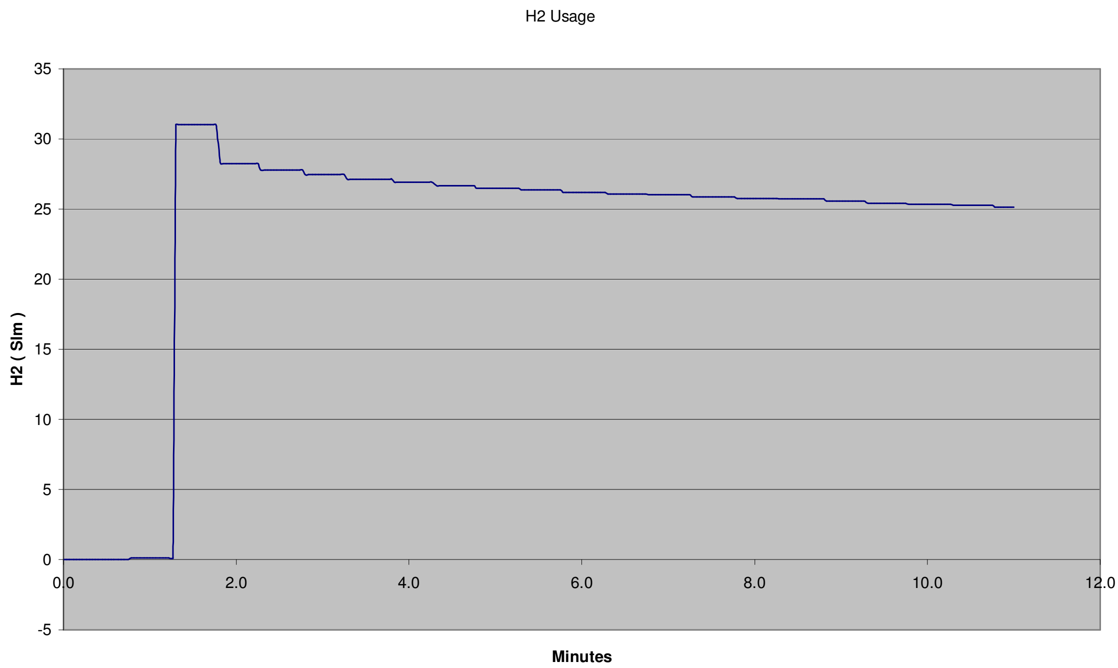


Figure 60. Cold start capacitive load, 2kW 0.5LeadHydrogen usage Vs time

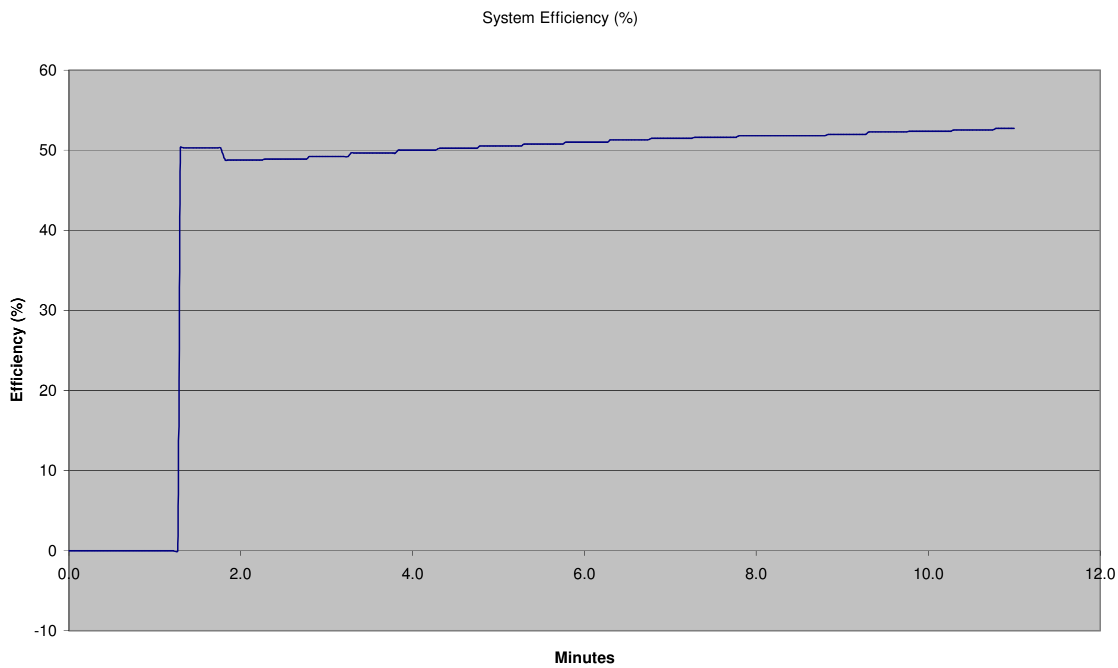


Figure 61. Cold start capacitive load, 2kW 0.8Lead. System Efficiency Vs time

10.1.4 Cold Start Capacitive load 2kW 0.5 Lead (Refer section 3.2.2)

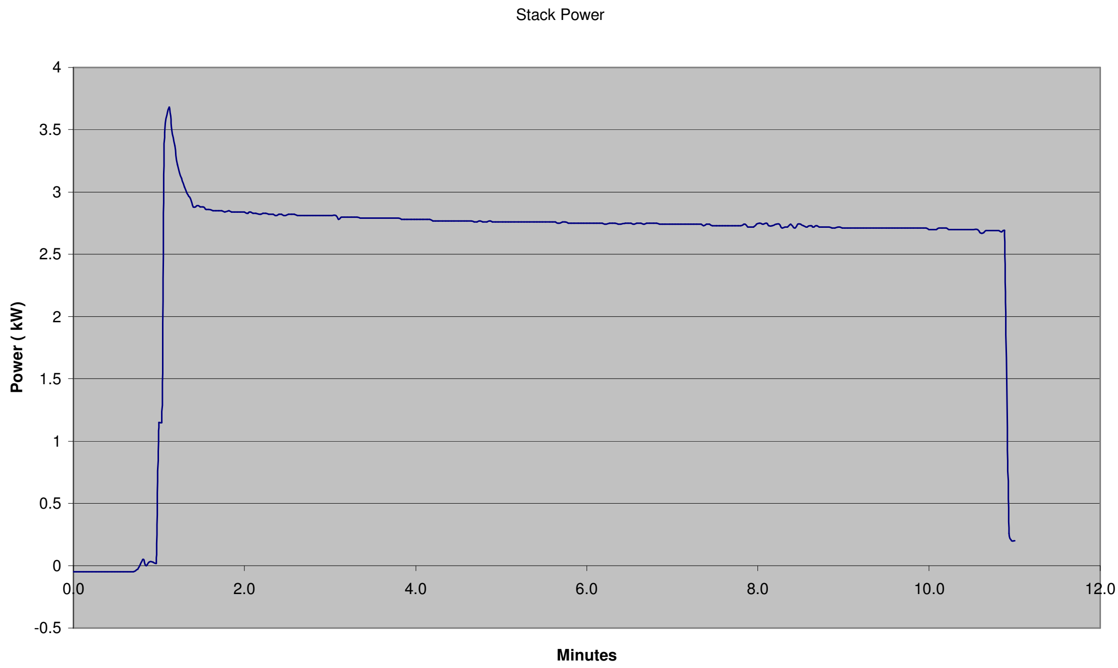


Figure 62. Cold start capacitive load, 2kW 0.5Lead. Stack Power Vs time

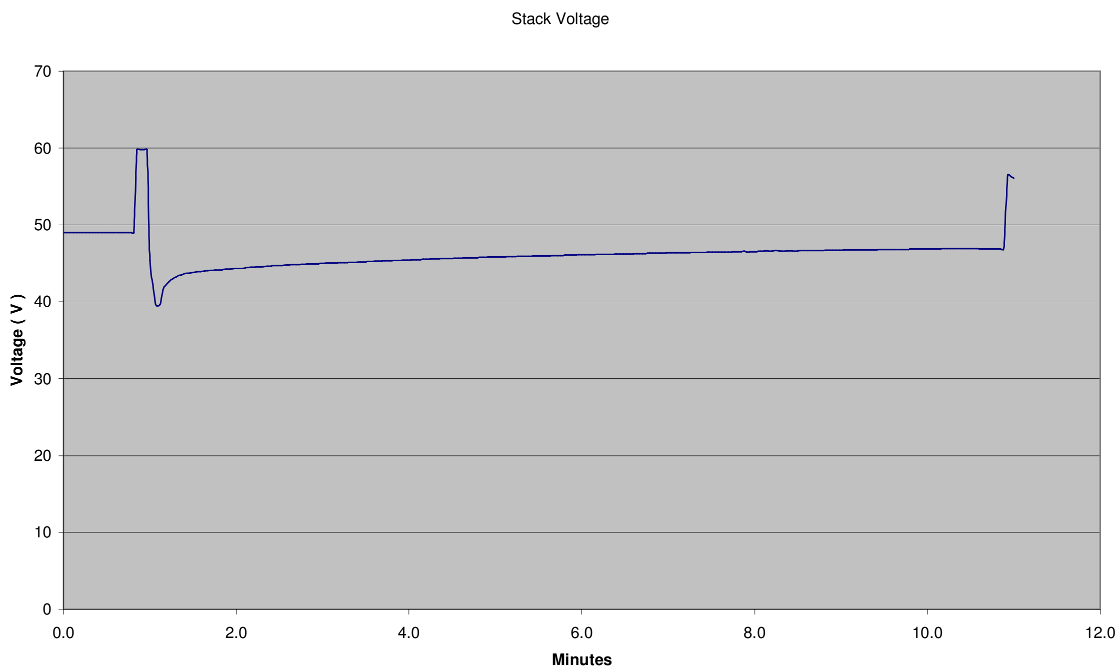


Figure 63. Cold start capacitive load, 2kW 0.5Lead. Stack Voltage Vs time

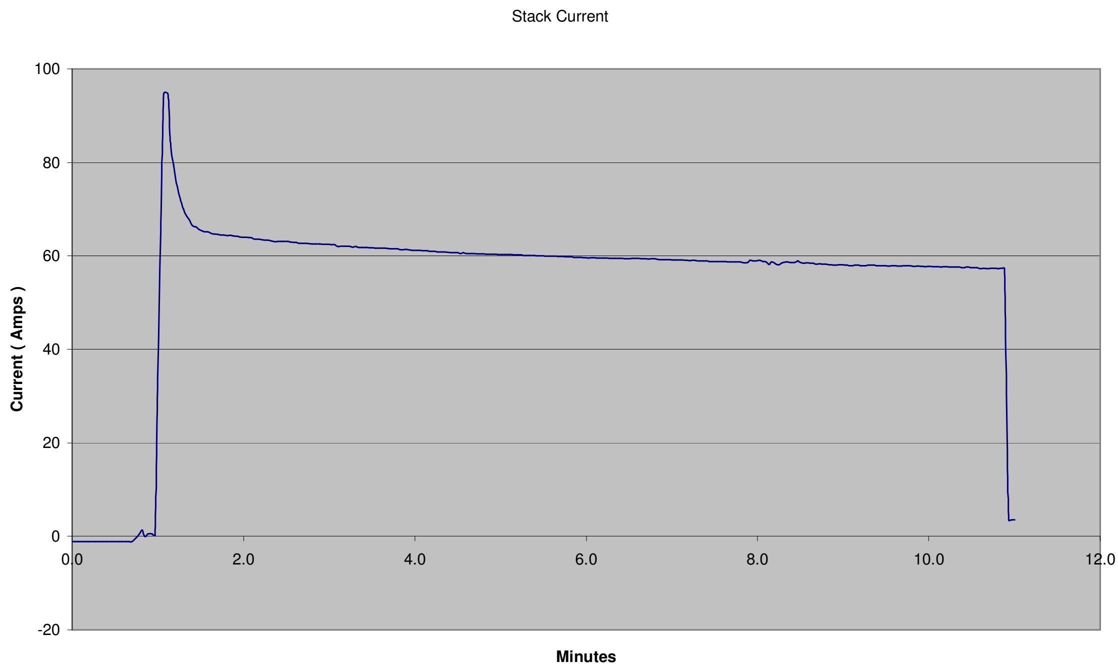


Figure 64. Cold start capacitive load, 2kW 0.5Lead. Stack current Vs time

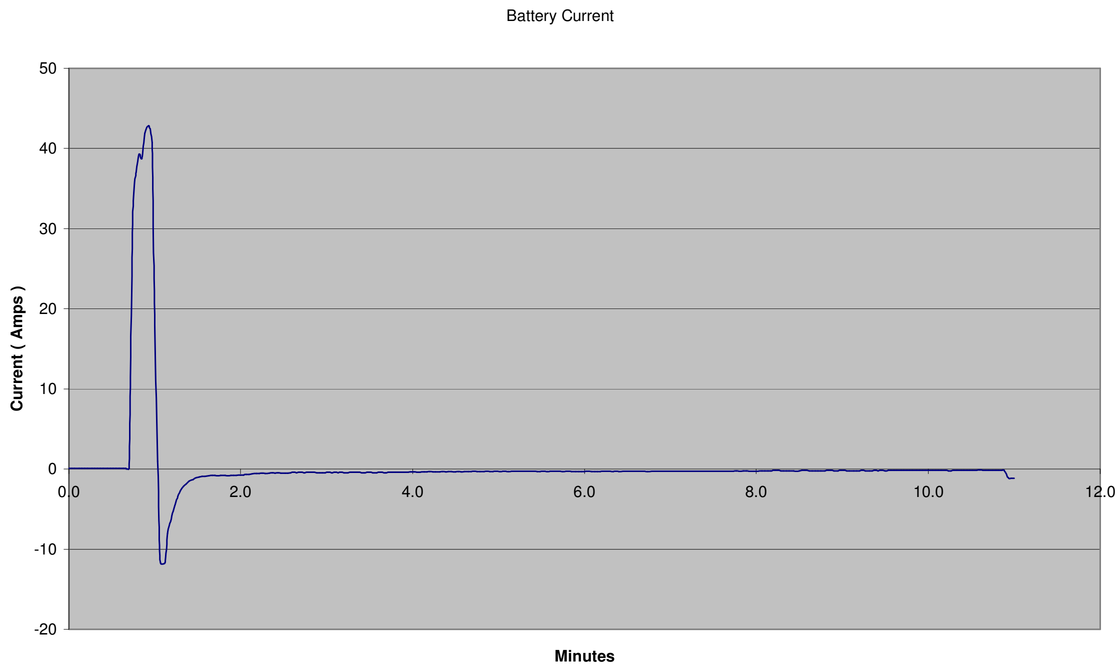


Figure 65. Cold start capacitive load, 2kW 0.5Lead. Battery Current Vs time

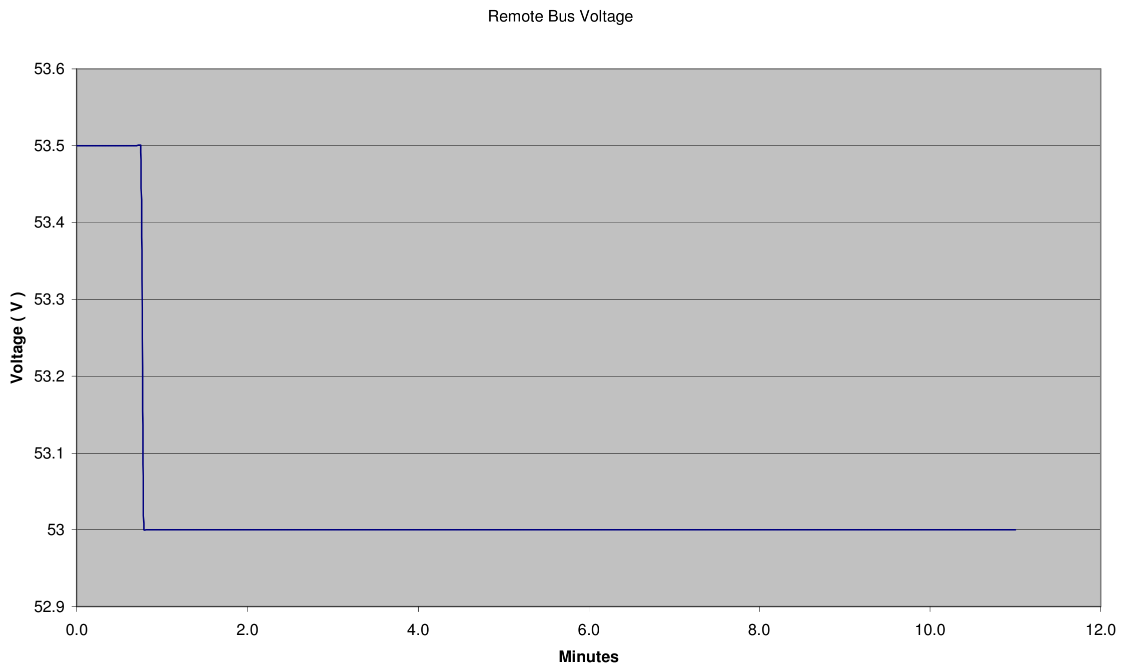


Figure 66. Cold start capacitive load, 2kW 0.5Lead. Battery Voltage Vs time

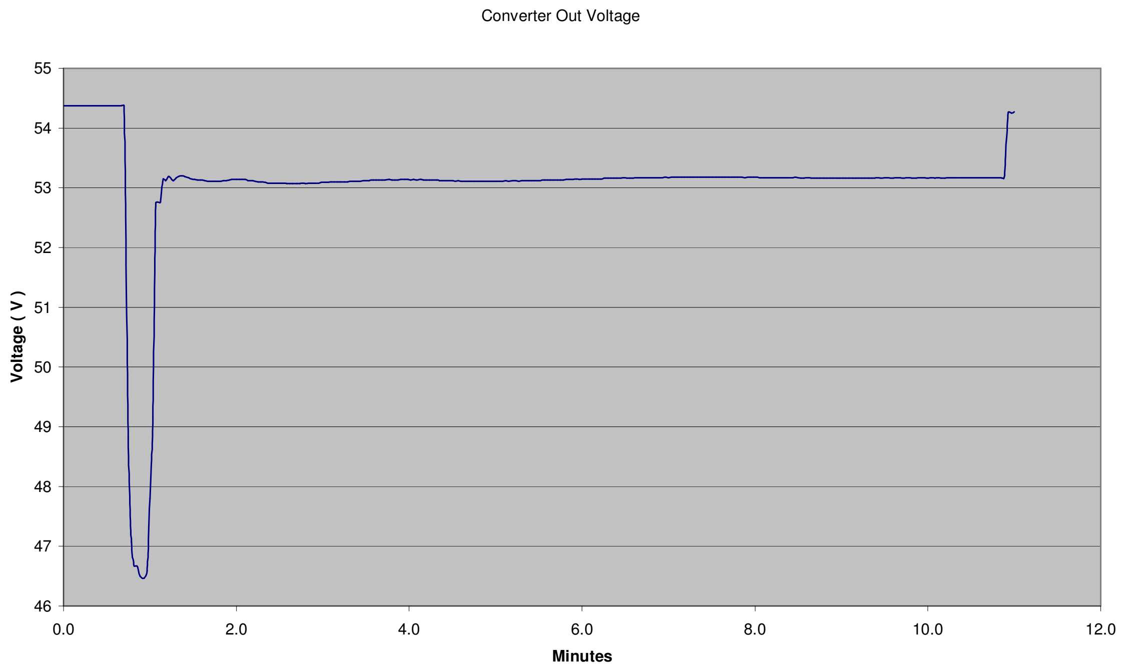


Figure 67. Cold start capacitive load, 2kW 0.5Lead. Converter Voltage Vs time

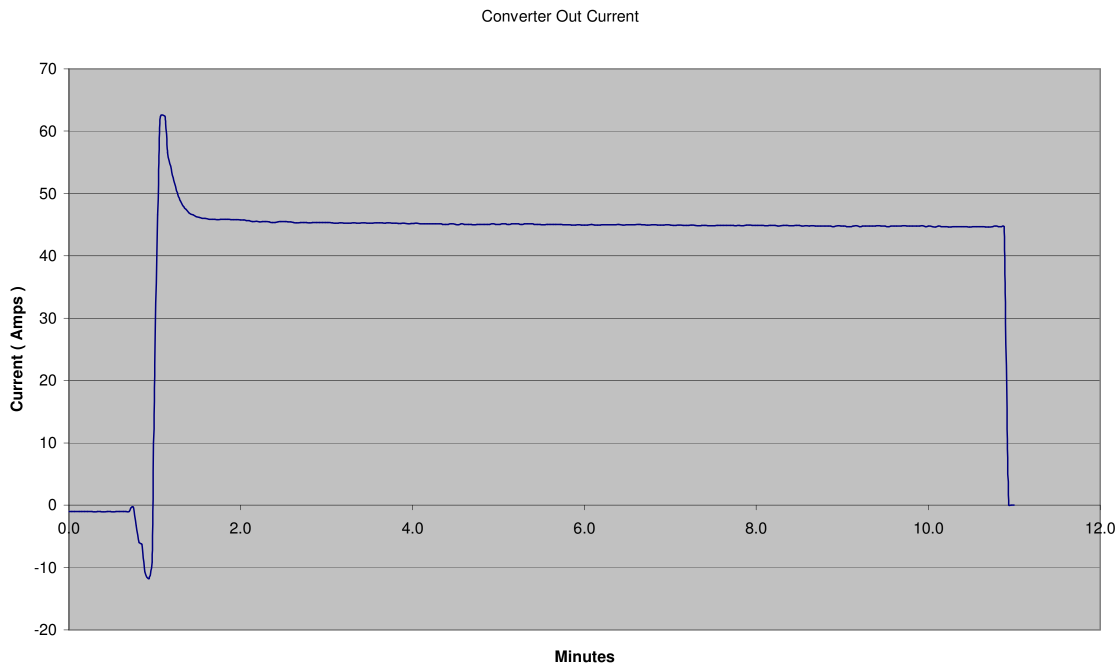


Figure 68. Cold start capacitive load, 2kW 0.5Lead. Converter Current Vs time

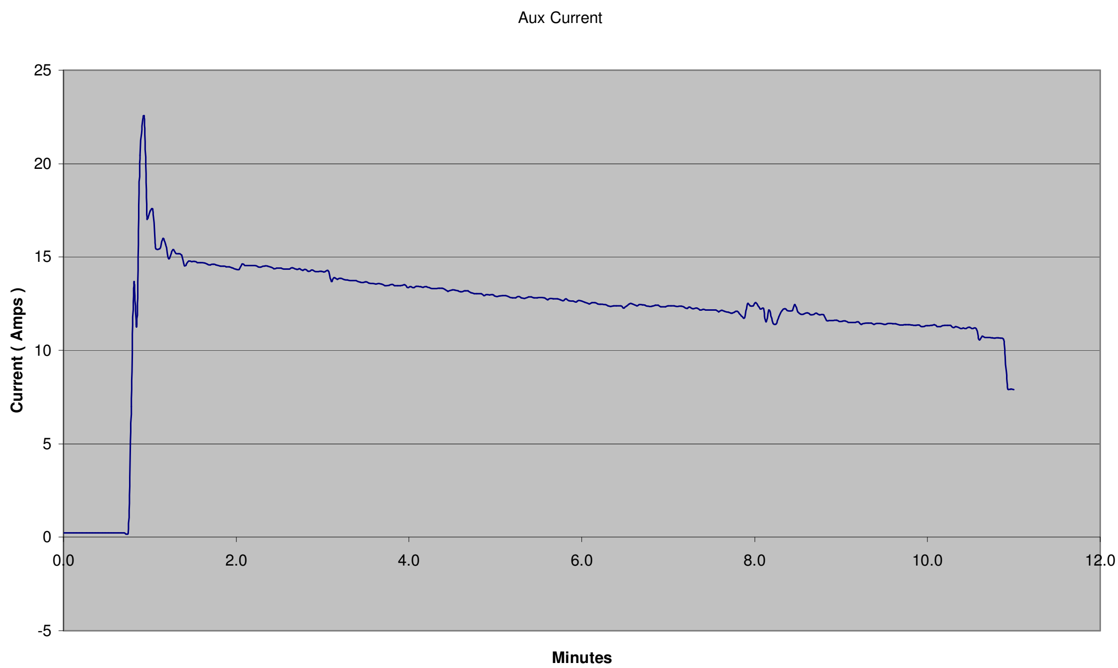


Figure 69. Cold start capacitive load, 2kW 0.5Lead Auxiliary Current Vs time

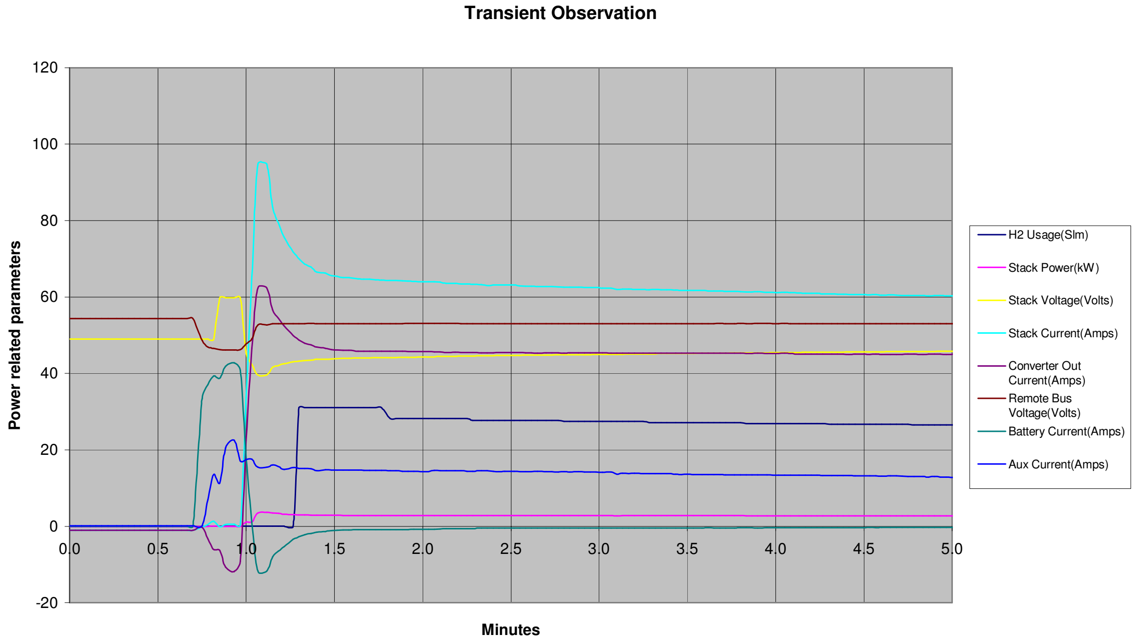


Figure 70. Cold start capacitive load, 2kW 0.5Lead. Transient Parameters Vs time

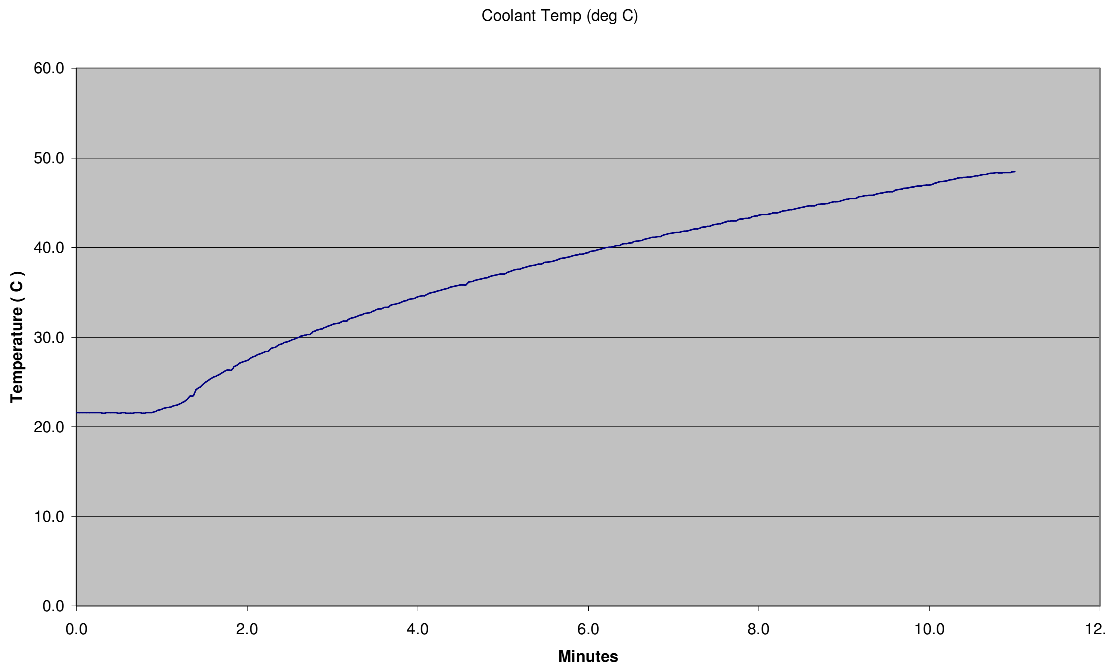


Figure 71. Cold start capacitive load, 2kW 0.5Lead. Coolant Temperature Vs time

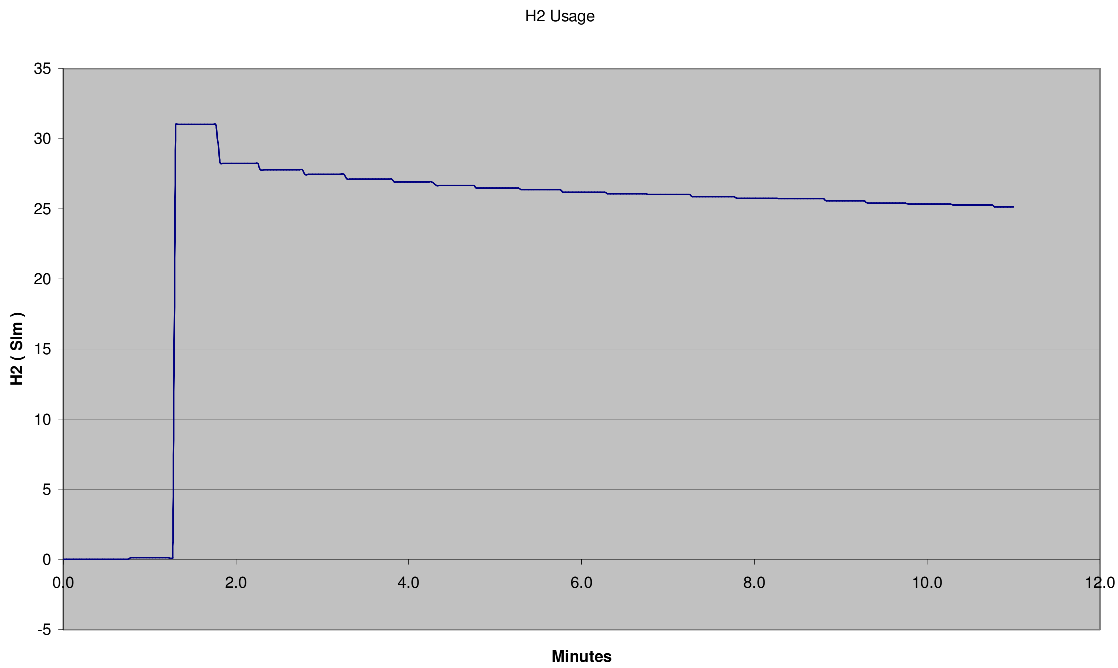


Figure 72. Cold start capacitive load, 2kW 0.5LeadHydrogen usage Vs time

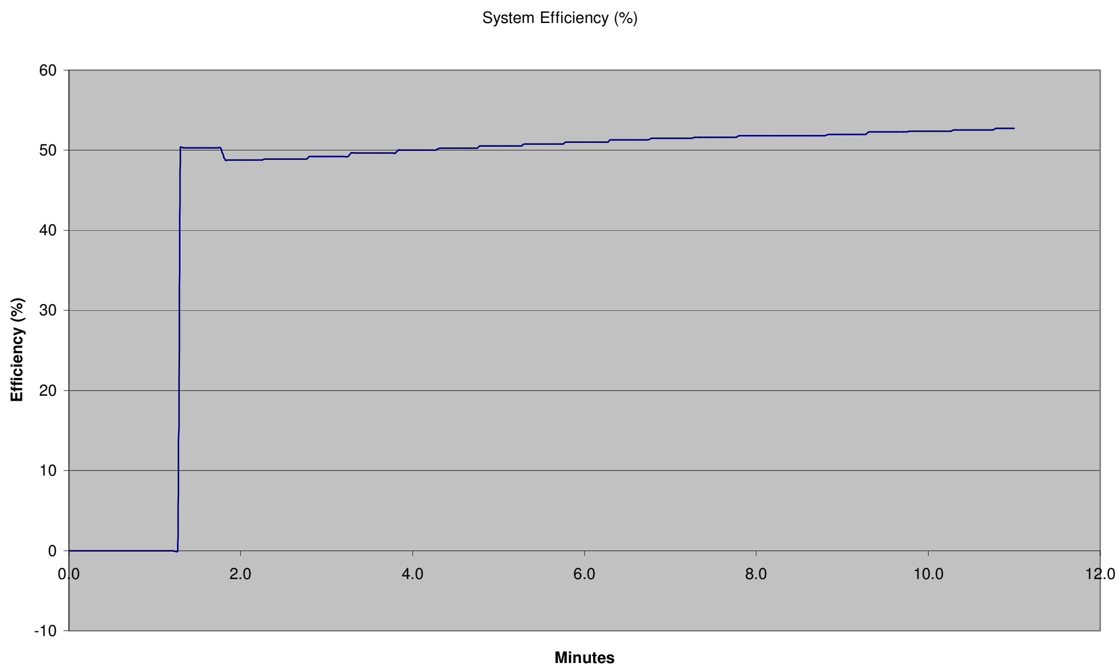


Figure 73. Cold start capacitive load, 2kW 0.5Lead. System Efficiency Vs time

10.1.5 Cold start capacitive load 4 kW 0.8 Lead (Refer section 3.2.2)

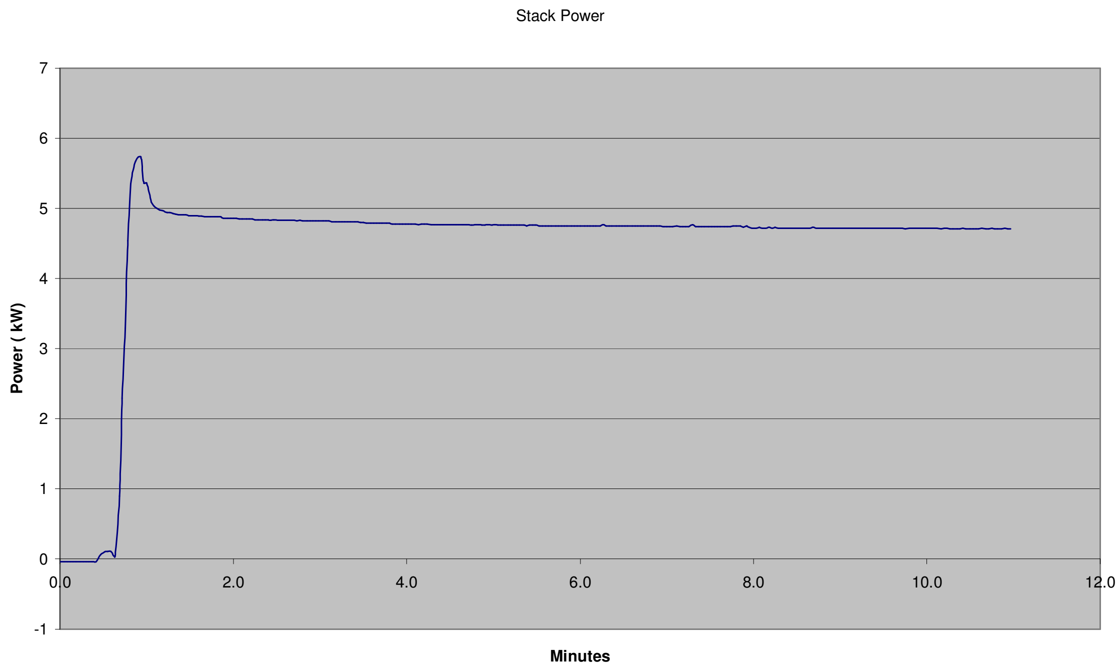


Figure 74. Cold start capacitive load, 4kW 0.8Lead. Stack Power Vs time

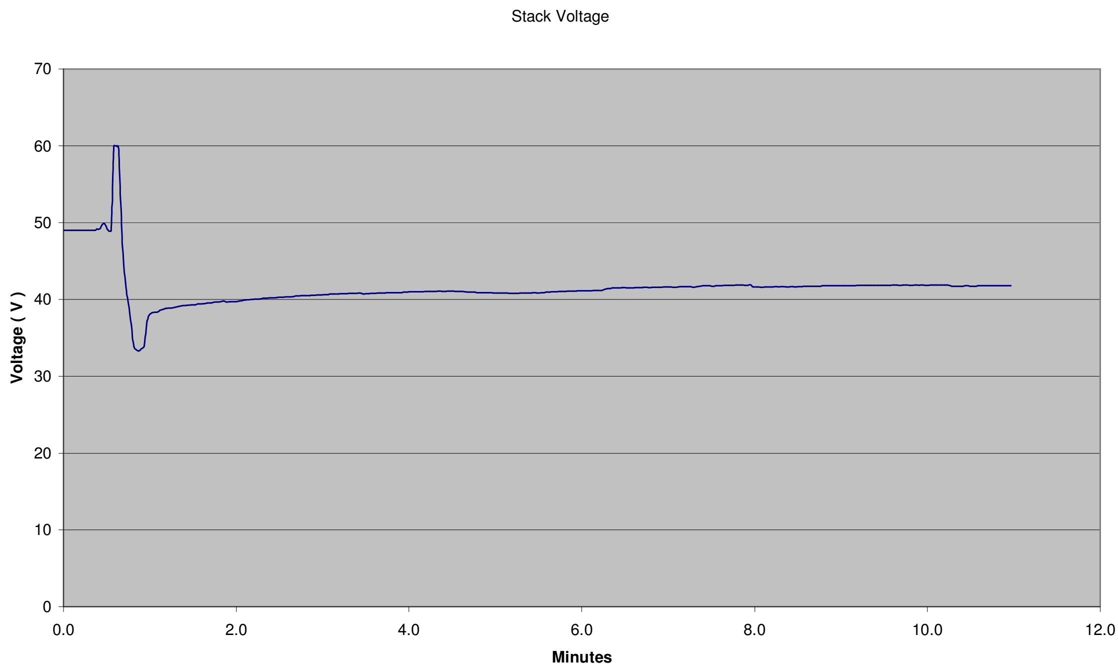


Figure 75. Cold start capacitive load, 4kW 0.8Lead. Stack Voltage Vs time

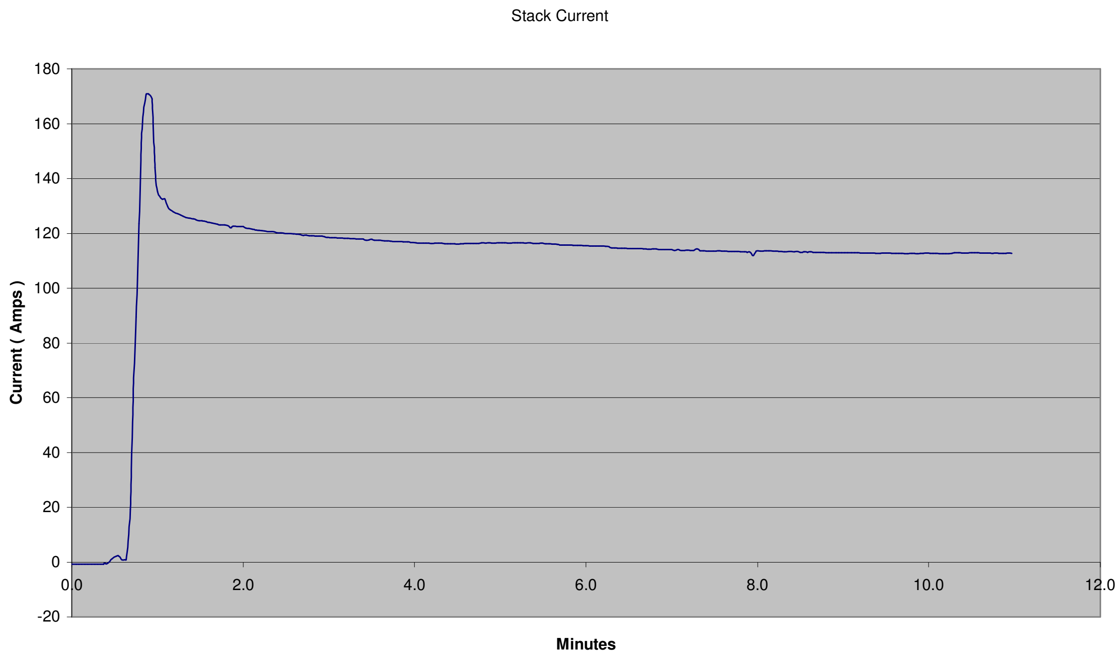


Figure 76. Cold start capacitive load, 4kW 0.8Lead. Stack current Vs time

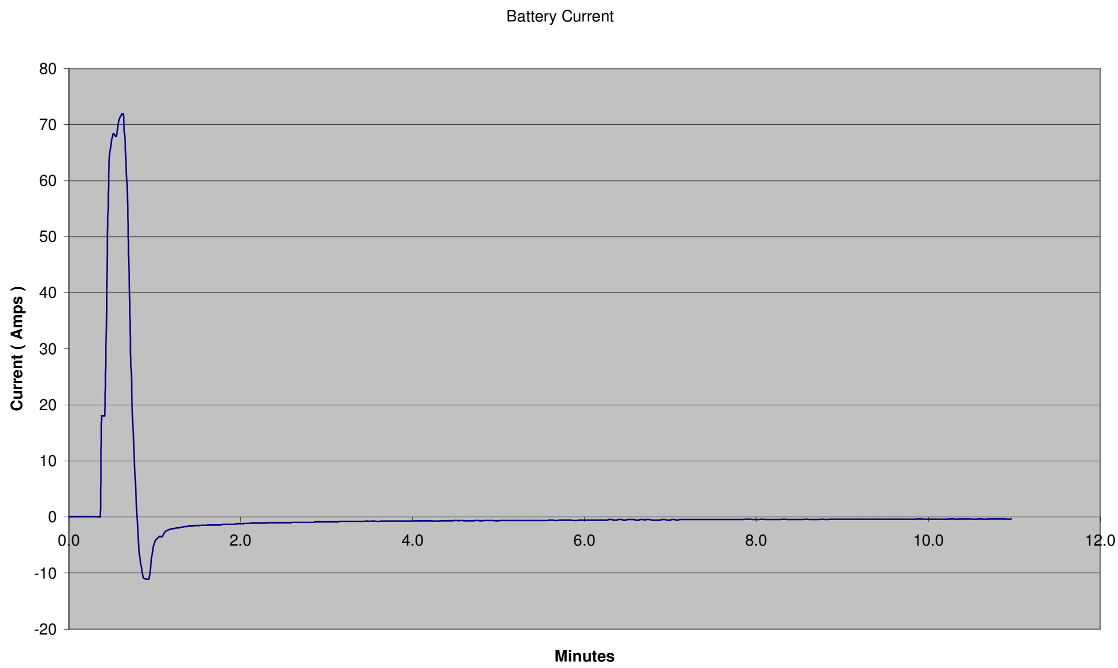


Figure 77. Cold start capacitive load, 4kW 0.8Lead. Battery Current Vs time

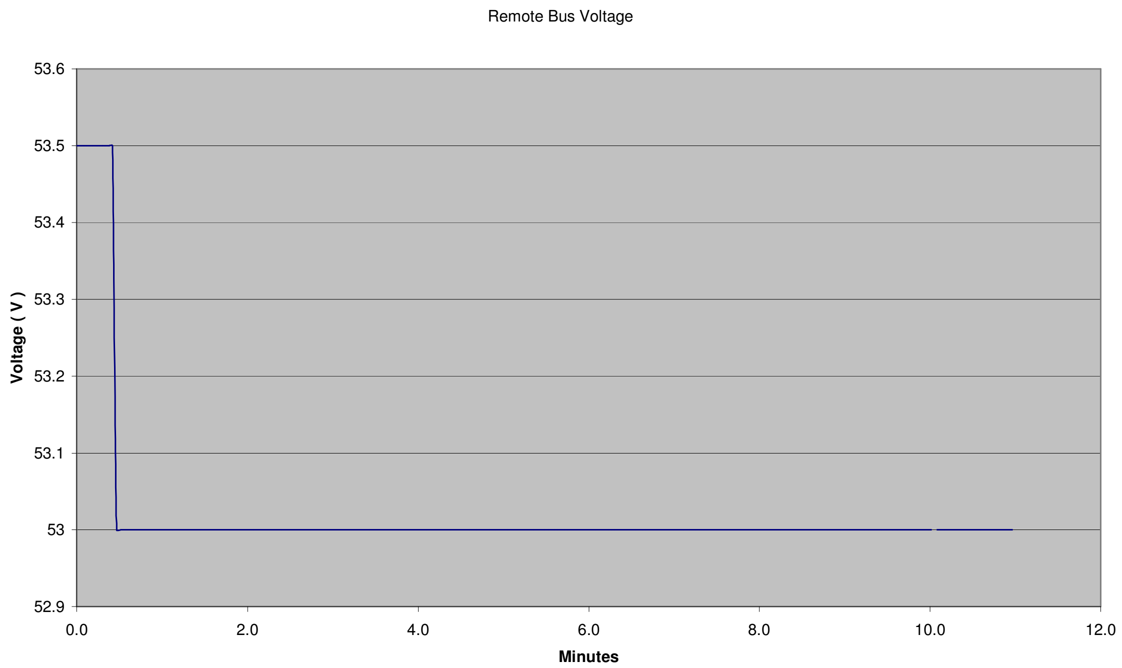


Figure 78. Cold start capacitive load, 4kW 0.8Lead. Battery Voltage Vs time

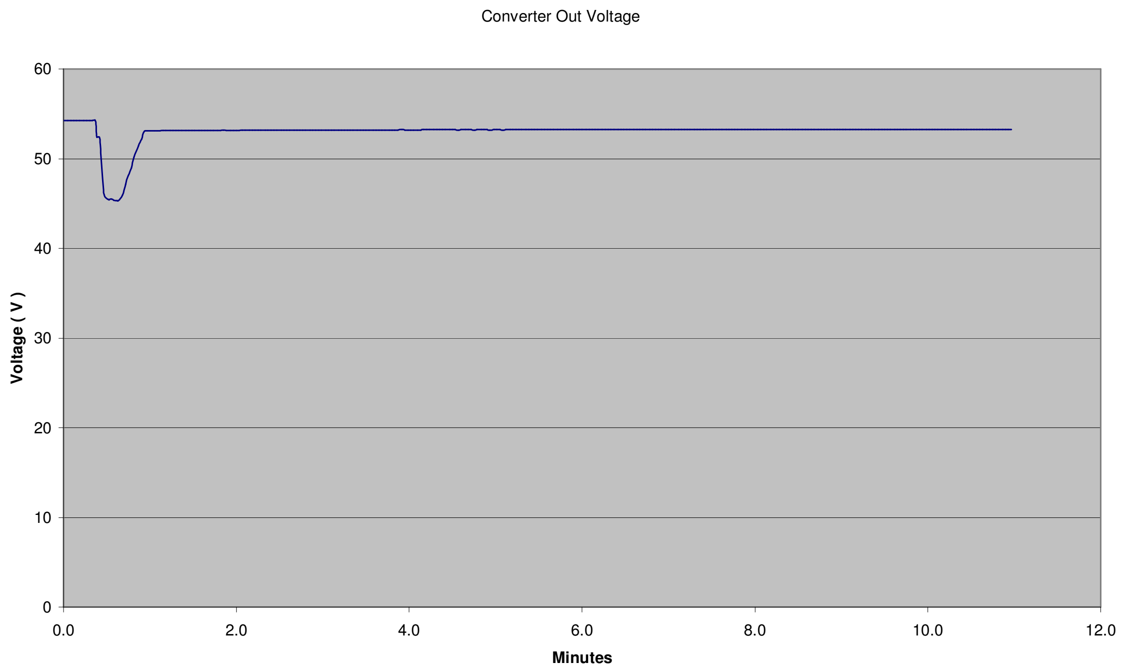


Figure 79. Cold start capacitive load, 4kW 0.8Lead. Converter Voltage Vs time

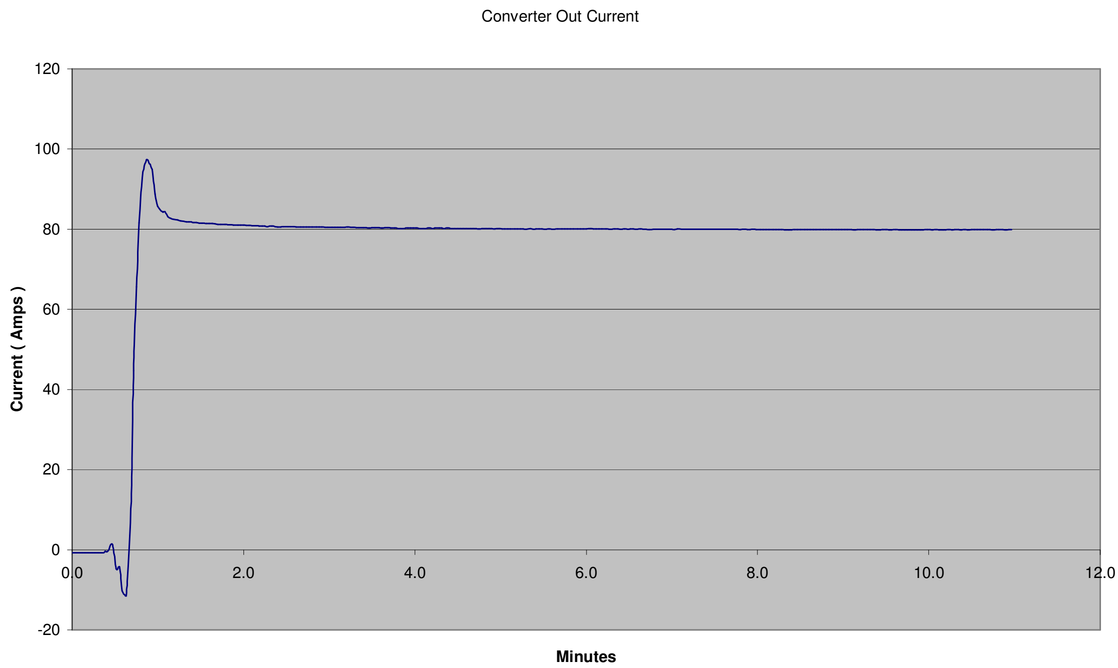


Figure 80. Cold start capacitive load, 4kW 0.8Lead. Converter Current Vs time

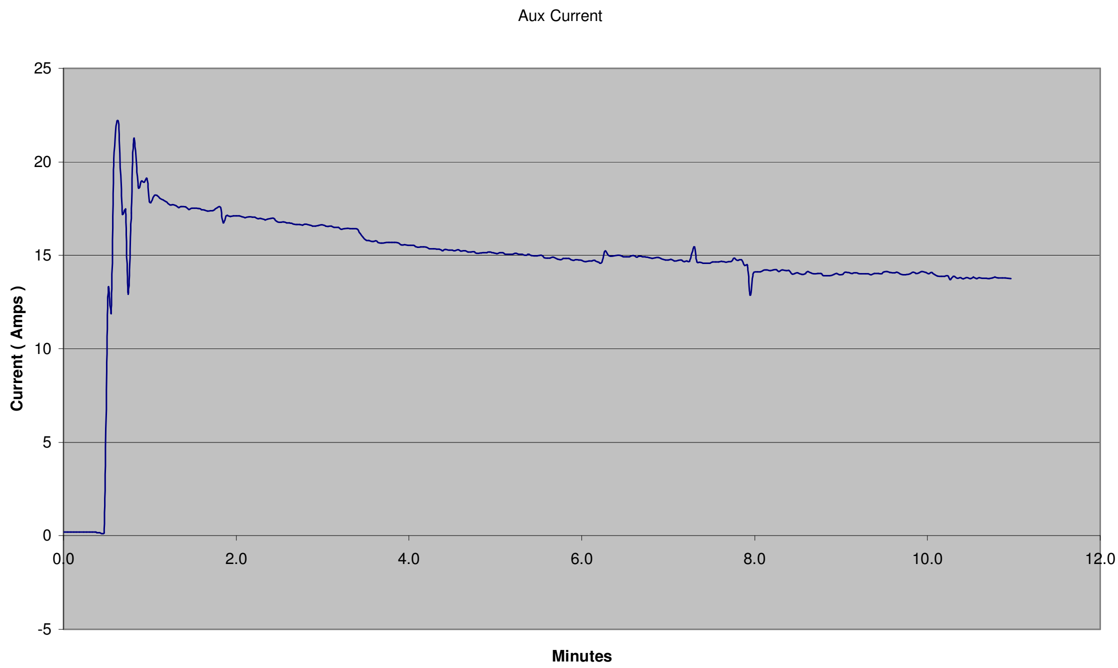


Figure 81. Cold start capacitive load, 4kW 0.8Lead Auxiliary Current Vs time

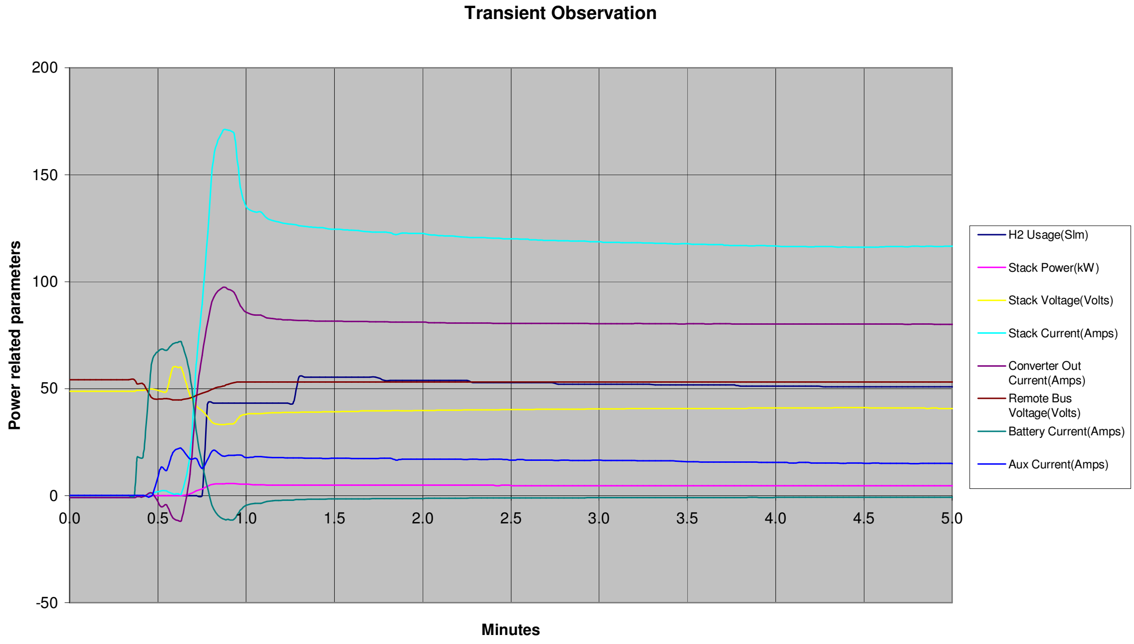


Figure 82. Cold start capacitive load, 4kW 0.8Lead. Transient Parameters Vs time

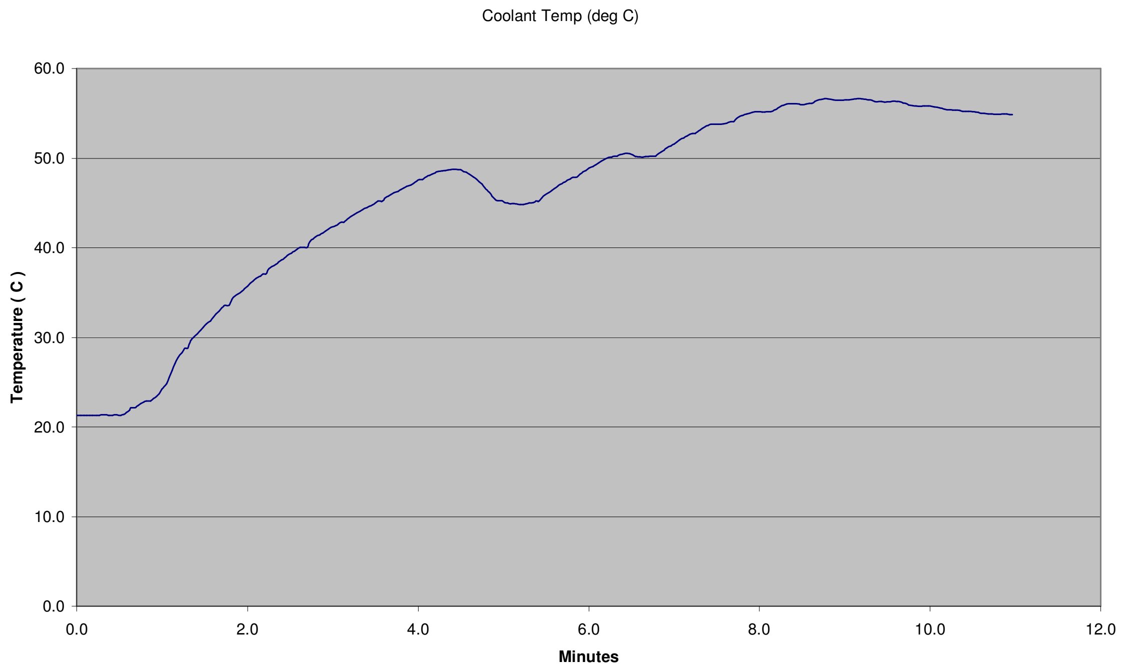


Figure 83. Cold start capacitive load, 4kW 0.8Lead. Coolant Temperature Vs time

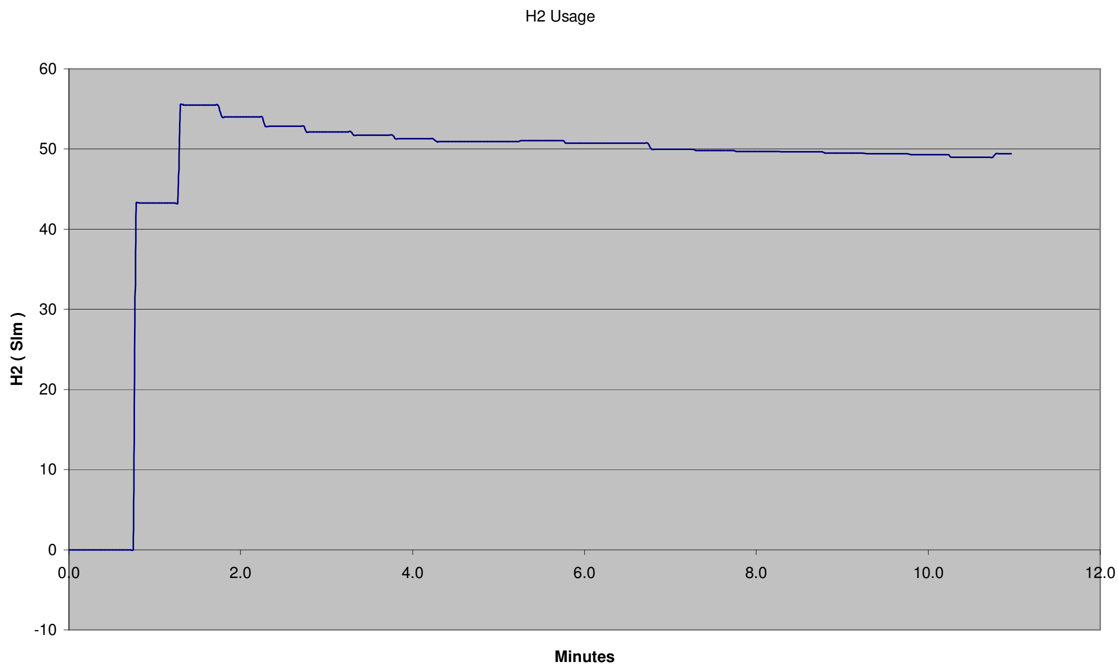


Figure 84. Cold start capacitive load, 4kW 0.8LeadHydrogen usage Vs time

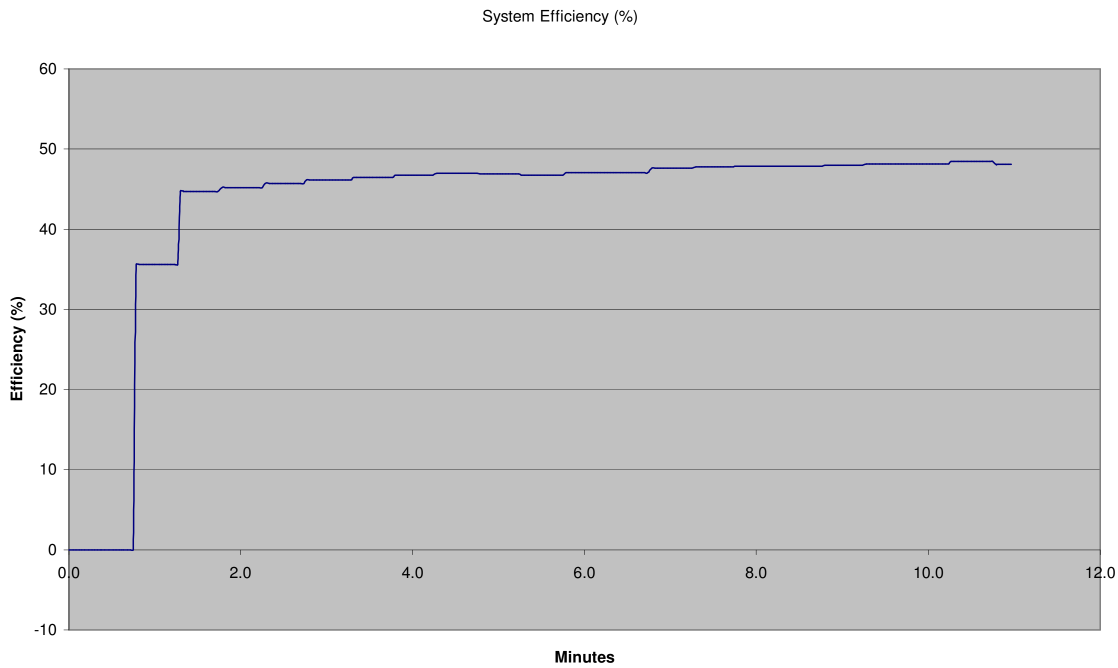


Figure 85. Cold start capacitive load, 4kW 0.8Lead. System Efficiency Vs time

10.1.6 Soak tests graphs. (Refer section 3.2.5)

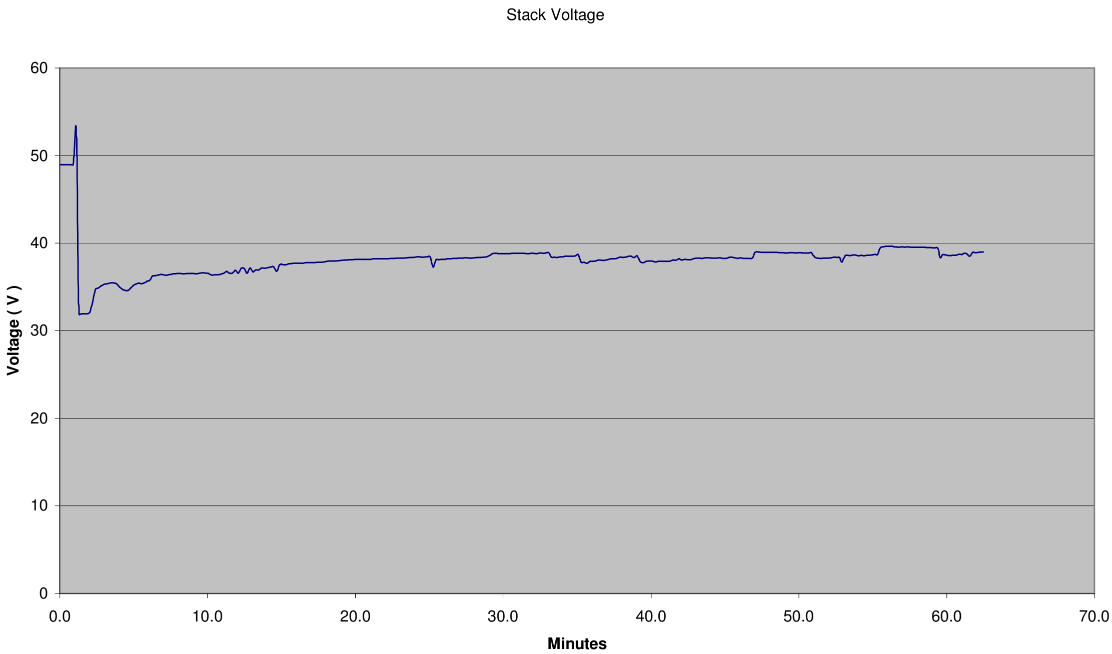


Figure 86. Soak test - Run 1, Stack voltage Vs time

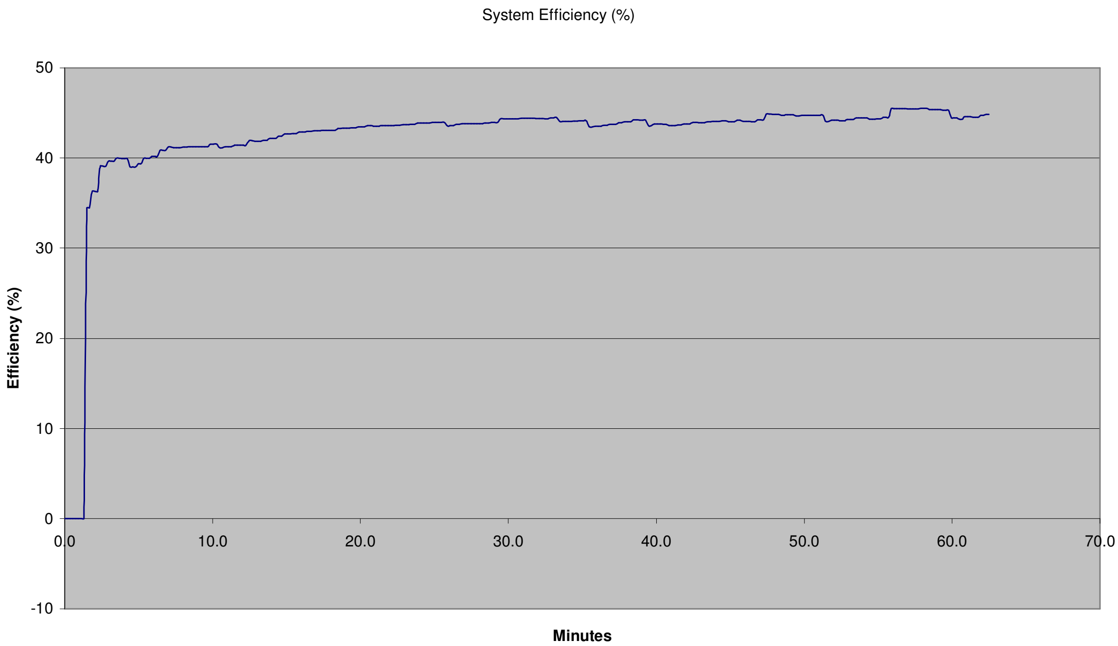


Figure 87. Soak test – Run 1, System efficiency Vs time

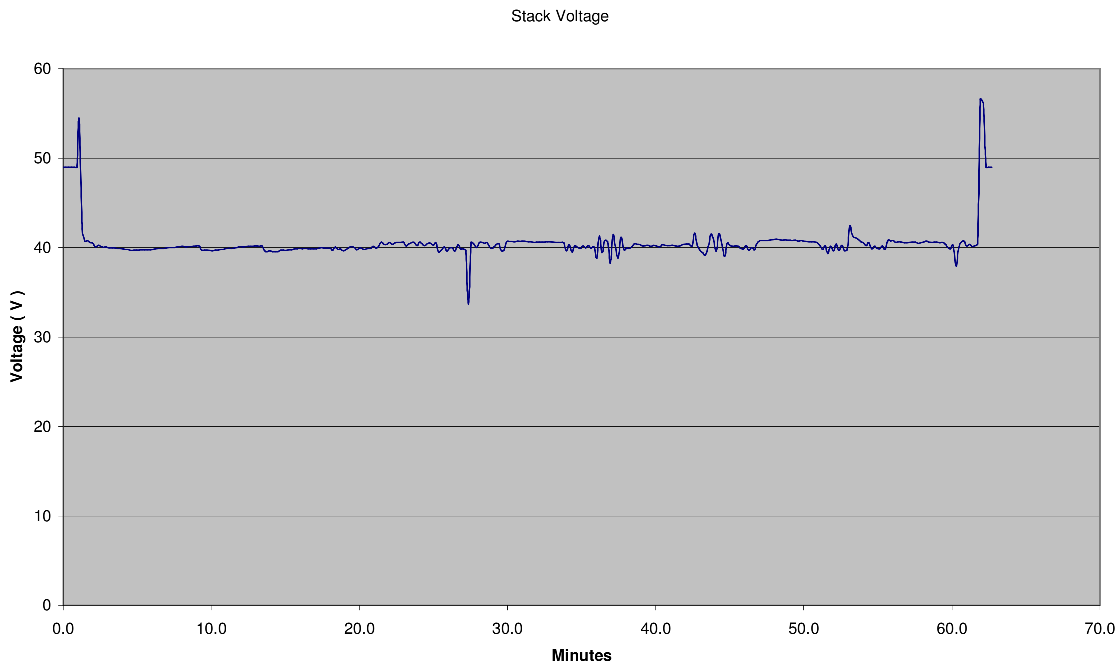


Figure 88. Soak test- Run 2. Stack voltage Vs time

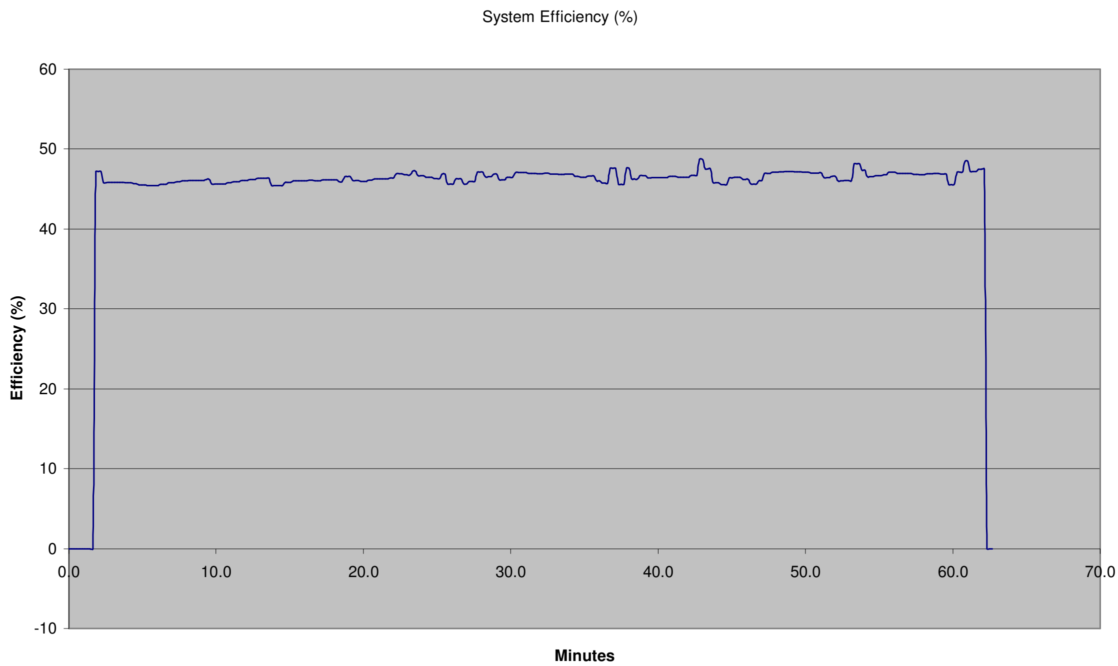


Figure 89. Soak test – Run 2. System efficiency Vs time.

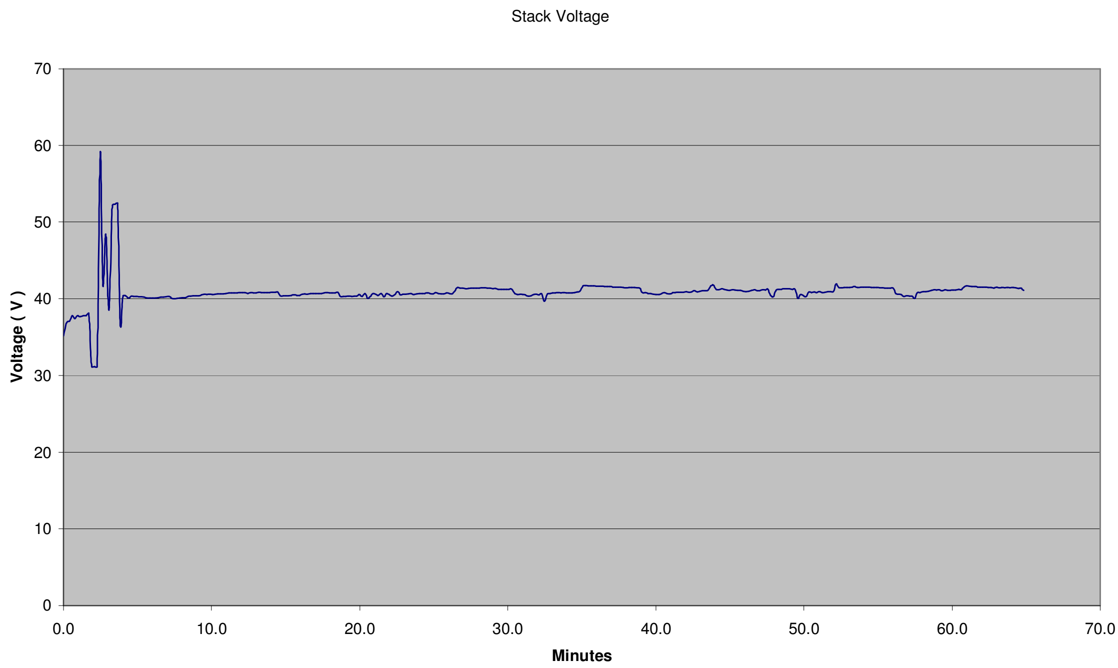


Figure 90. Soak test – Run 3, Stack voltage Vs time

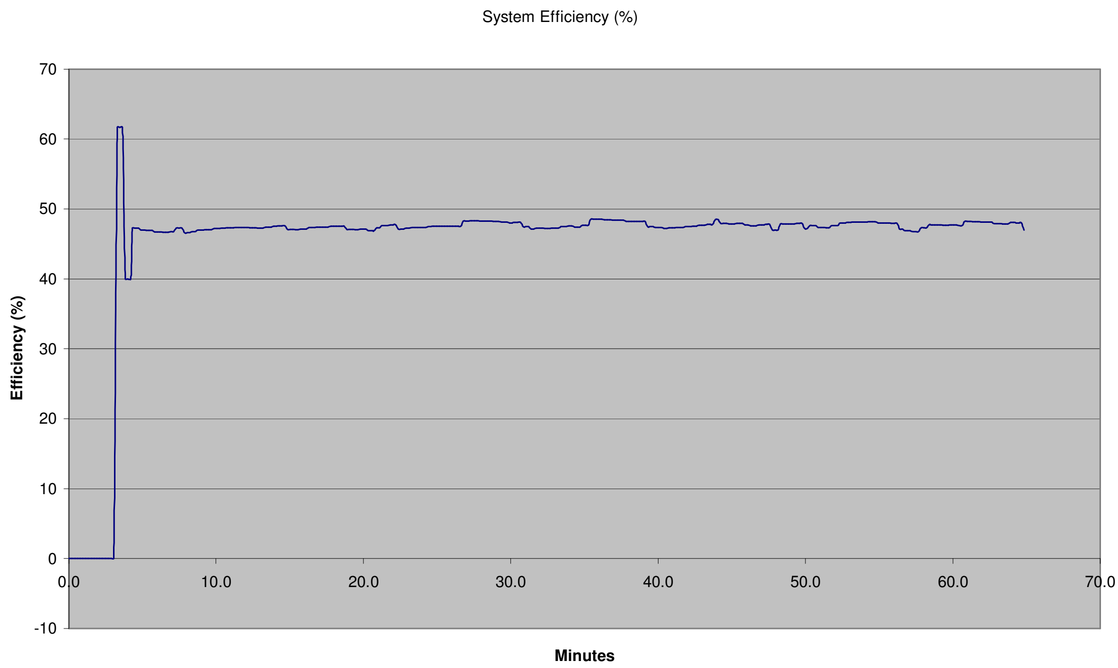


Figure 91 Soak test- run three – System efficiency Vs time.

10.1.7 Load switching graphs. (Refer section 3.4)

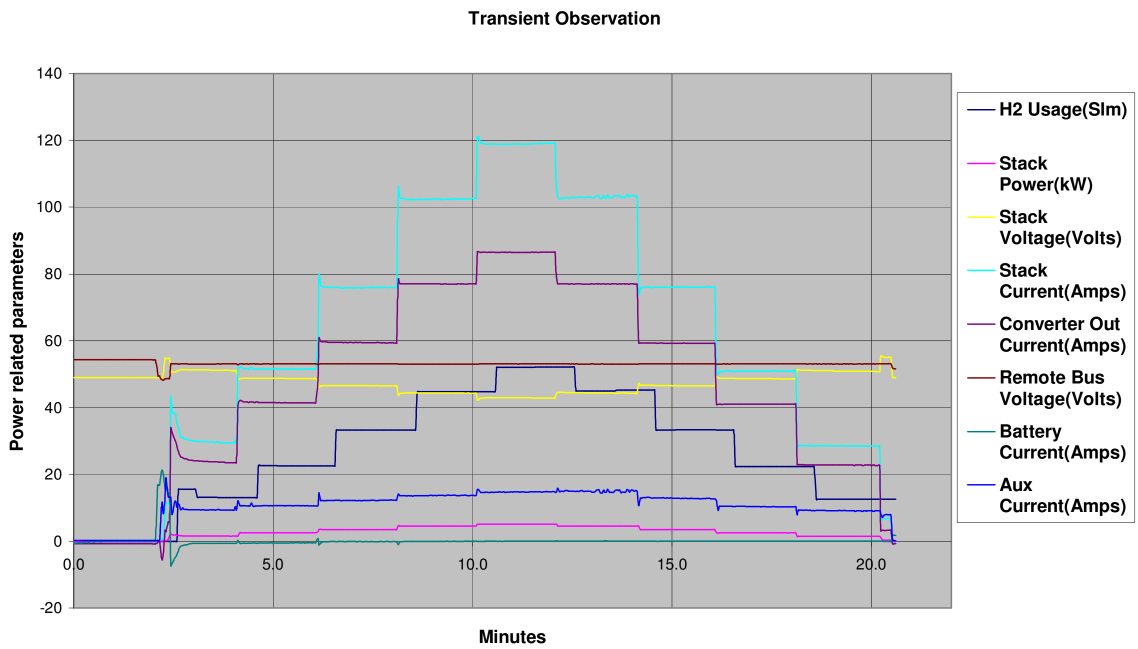


Figure 92. Transient parameters in 1kW switching load

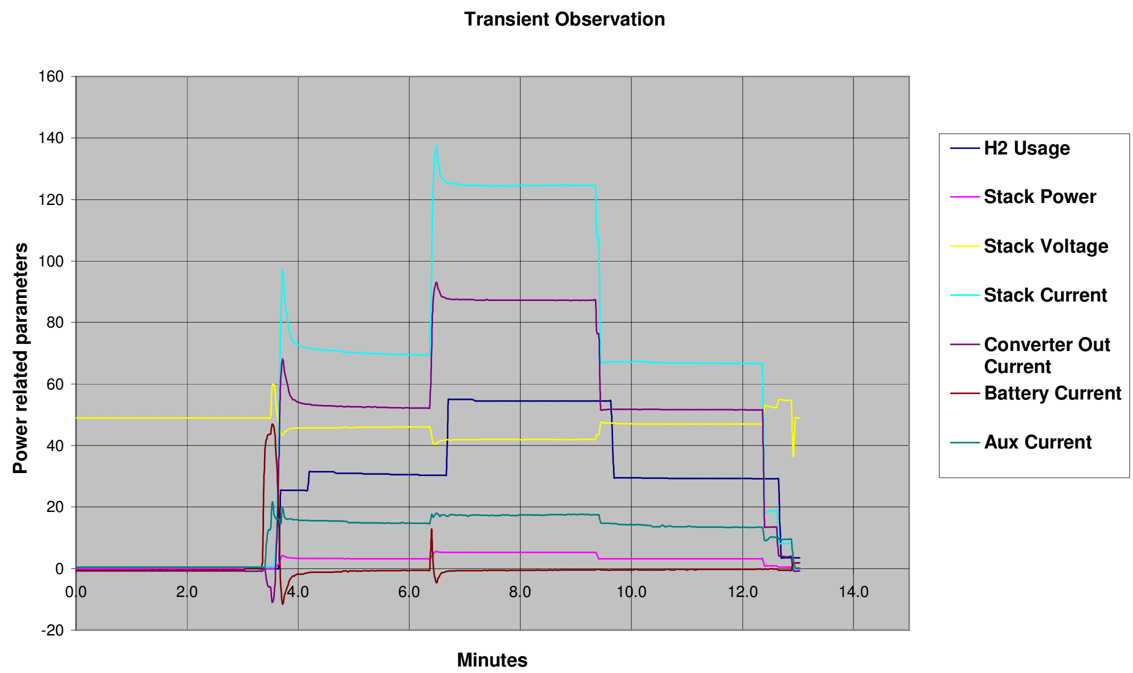


Figure 93. Transient parameters at 2kW switching load

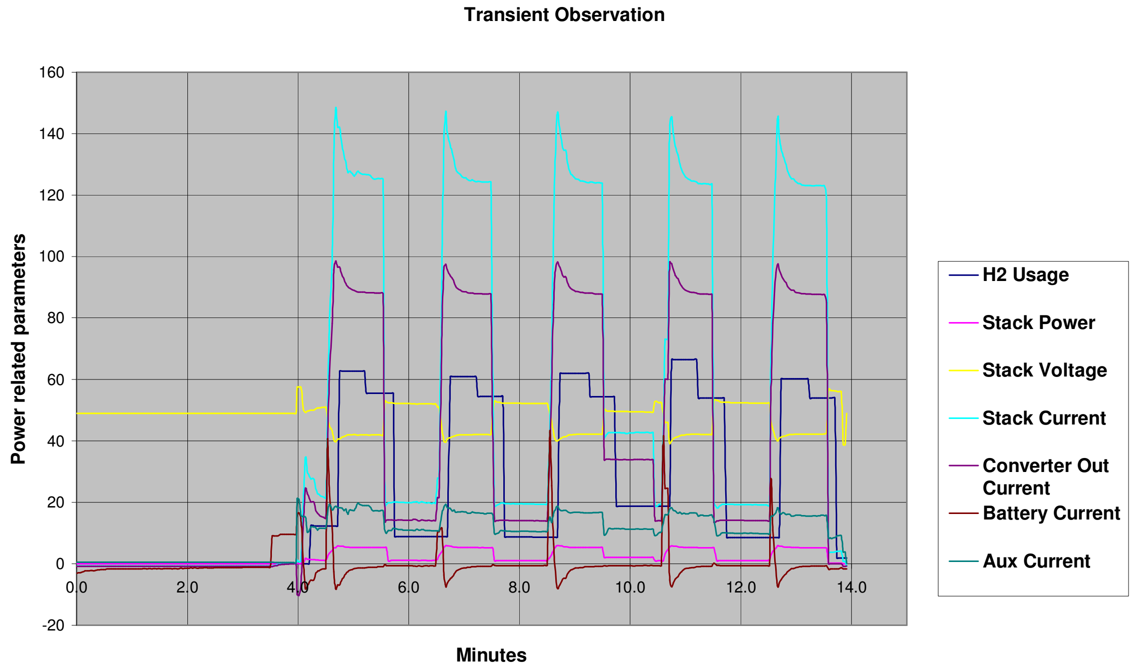


Figure 94. Transient parameters 0.5kW – 4.5kW alternate switching

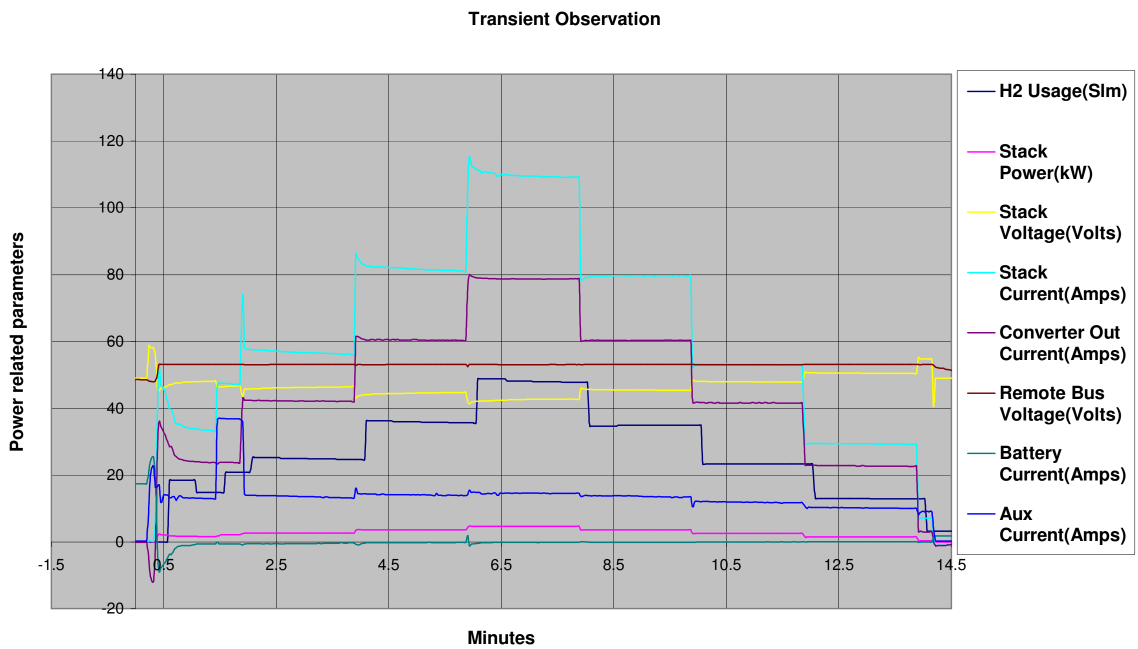


Figure 95. Transient parameters at 1kW, 0.8 Lead Load switching

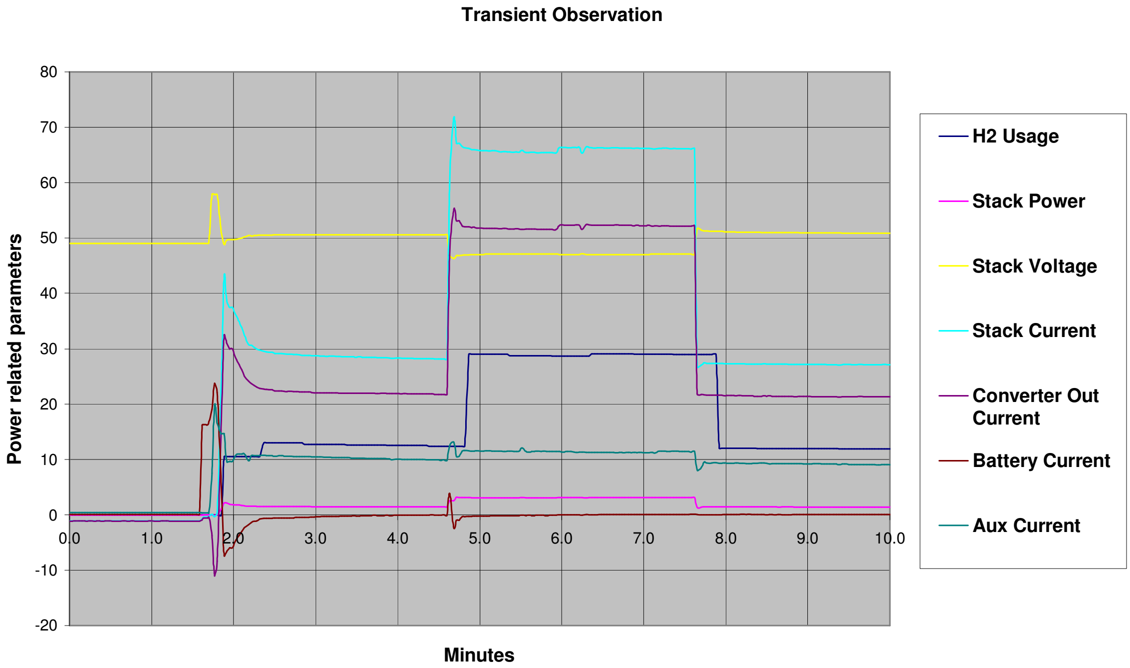


Figure 96. Transient parameters at 2.5kW 0.5Lead switching load

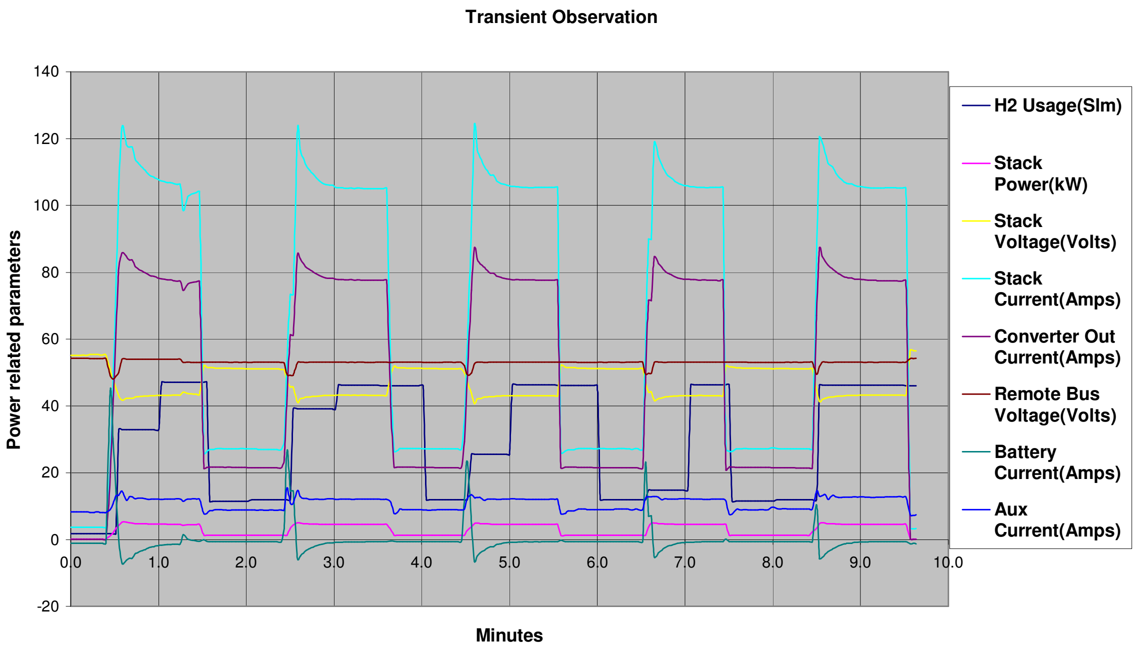


Figure 97. Transient parameters at 4kW 0.8Lead Switching loads