Battery Model for Over-Current Protection Simulation of DC Distribution Systems

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SUMMARY

This paper describes an electrical model of a battery that can accurately simulate characteristic battery behaviour during over-current instances. The battery model can be coupled with other distribution component models to simulate the protection performance in telecommunications DC distribution systems.

INTRODUCTION

The reliability and safety of a telecommunications DC power system is significantly affected by the performance of storage, distribution and protection devices. Voltage excursions caused by an over-current instance can cause electronic equipment malfunction due to over-voltage, and disrupt service due to under-voltage. Any requirement to directly protect either a battery string, or the primary distribution, with an over-current protection device immediately raises the issue of discrimination with other downstream protection devices. The issue of battery protection has received scant attention in the literature to date [1].

The design and analysis of over-current protection for telecommunication DC power systems can be greatly assisted by the use of a computer-aided simulation tool. However, a simulation can only be as accurate as the component models and element values used to represent the real world. The 1993 INTELEC included a paper [2] describing the development of a fuse and circuit-breaker model, introducing advanced modelling techniques to accurately represent complex non-linear device characteristics.

The rapid advancement of both computing power and analogue circuit simulation programs derived from SPICE software provides a user-friendly environment for over-current protection design and analysis. This is advantageous as telecommunications power distribution systems are often large and complex, and developing an equivalent circuit model for a power system is not a trivial task.

In this paper the non-linear and complex behaviour of a battery during discharge is modelled using the *Analog Behavioural Modelling* functions available with MicroSim's PSpice simulation software. Short circuit tests are conducted on a valve-regulated and flooded lead-acid battery to validate the model.

BATTERY MODEL

Lead-acid battery electrical characteristics during discharge can be modelled over a large range of operating conditions by a model comprising a variable voltage source in series with a variable resistance [3,4], as shown in Figure 1. The battery voltage during discharge, E, is then equal to the open circuit voltage, V_{oc}, minus the I×R drop across the internal resistance, R, due to the current, I:

$$E = V_{oc} - I \times R \qquad (1)$$

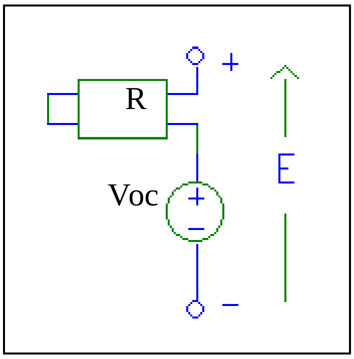

Figure 1. Battery Equivalent Circuit Model

Both the open circuit voltage V_{oc} and the internal resistance R vary during discharge. The internal resistance can be described as the sum of:

- a resistance R1 due to grid, group bar and lug material, which is constant,

$$R1 = A1 \qquad (2)$$

- a resistance R2 due to the electrolyte, which varies as a function of the remaining battery capacity C,

$$R2 = A2 / C \qquad (3)$$

- a resistance R3 due to the plate surface sulfation, which varies as a function of the remaining battery capacity C,

$$R3 = A3(1\text{-}C) \qquad (4)$$

A Nernstian relationship can be used to derive the variation of open circuit voltage V_{oc} as a function of the remaining capacity C,

$$V_{oc} = A4 + A5 \times \text{Log } C \qquad (5)$$

The capacity remaining in the battery varies as a function of the discharge current I and can be described using the Peukert relationship,

$$C = A6 \times I^{A7} \qquad (6)$$

Equations (2)-(5) describing the variation of R and V_{oc} during discharge are consistent with an electrochemical explanation of the capacity loss phenomenon, however they assume steady state, homogeneous conditions at a constant temperature. For a battery operating at high current levels over a long time duration, dynamic variations in R and V_{oc} are to be expected. Also, it is recognised that equations (3)-(5) are first-order approximations of the non-linear behaviour of capacity depletion associated with battery discharge.

The battery model used to model equations (1)-(6) is shown in Figure 2 and comprises:

- a voltage source V_b, which is used to sense battery current. This source acts like an ideal current sensing shunt, where V_b=0V.
- a variable current source G_b, which sources a current proportional to the battery current. The transfer characteristic of this source is controllable, and is used to model the effect that discharge current has on remaining battery capacity, described by (6).
- a capacitor C_b, whose voltage represents the normalised available capacity remaining in the battery. The capacitor has a voltage of 1V when the battery state-of-charge (SOC) is 100%, and a voltage of 0V when the battery SOC is 0%.
- a variable voltage source E_{Vb}, which sources a voltage equal to the battery open circuit voltage. The transfer characteristic of this source is controllable, and is used to model the Nernstian relationship (5).
- a variable voltage source E_{Rb}, which sources a voltage that is proportional to the current flowing through itself, hence it represents a resistance element. The resistance characteristic of this source is controllable, and is used to model the internal battery resistance described by (2), (3) and (4).

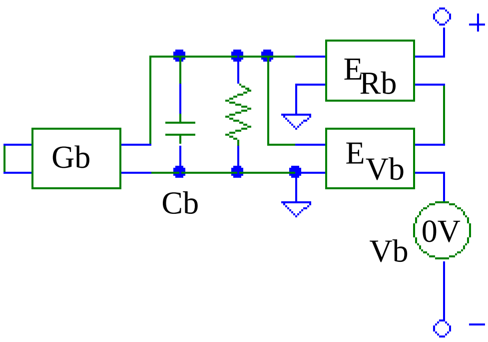

Figure 2. Battery Simulation Model

The model functions by sensing the current through V_b and varying the effective voltage of E_{Vb} and resistance of E_{Rb} to simulate long duration capacity-loss effects.

Ambient temperature and temperature rise effects can be included in the model where required. Ambient temperature can be introduced as a constant parameter, for example to modify the Peukert expression [5]; and temperature rise effects can be introduced using a time dependant variable, for example to modify electrolyte resistance during long duration discharge.

The very short response time characteristic of the electrodes (plates) due to interface chemistry has yet to be modelled in this work.

PARAMETER ESTIMATION

Parameters A1-A7 are typically empirically derived as they relate to physical battery criteria, such as plate surface area, effective active material volume. These parameters differ significantly between batteries of different design, although similar battery technologies designed for particular applications can be expected to have some typical parameter values, such as the exponential parameter A7 in the Peukert relationship.

MODEL VALIDATION

Measured voltage and current waveforms during over-current operation of both a valve-regulated and a flooded lead/acid battery cell were used to validate the model.

An over-current test circuit was constructed using a 3kA rated contactor, a 50mV 500A current shunt and bus bar interconnects. Current and voltage waveform measurements were taken using a digital oscilloscope. Test circuit inductance was measured at 0.57µH with the valve-regulated cell, and 0.65µH with the flooded cell. Forced air cooling of the current shunt was used during long duration tests. A nominal 300Ah (C_{10}@25°C) valve-regulated cell and a nominal 500Ah (C_{10}@25°C) flooded cell were used in the tests.

A schematic of the simulated test circuit is shown in Figure 3. Measured and simulated voltage and current waveforms for a long duration over-current discharge are shown in Figure 4 for the valve regulated cell, and in Figure 5 for the flooded cell. Representative battery model parameter values for A1-A7 and C_b were used in the simulations, and are given in Table 1. Simulation results show good agreement with measured results, with some variation occurring in the flooded cell results at long duration, due most likely to temperature rise affects. Measured temperatures in the flooded cell after 10 minutes discharge rose to 49°C for the electrolyte, 53°C for the positive group bar and 59°C at the top of the positive post.

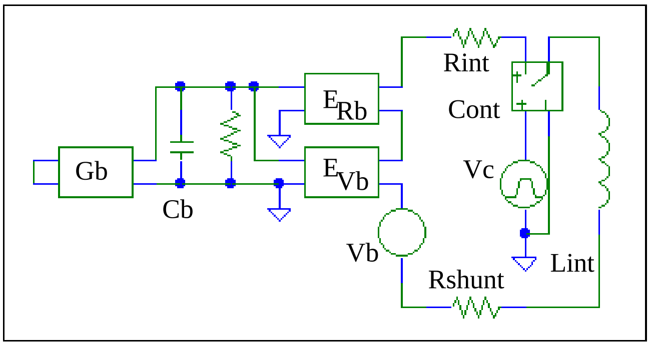

Figure 3. Test Circuit Schematic

Measured and simulated voltage and current waveforms during the first few milliseconds of an over-current discharge are shown in Figure 6 for the valve regulated cell, and in Figure 7 for the flooded cell. The measured results show the effects of the contactor contacts closing in the first 2-3 milliseconds. The contactor has a leading contact (used for arc quenching) which makes contact about 1½ ms before the main contacts close. The contacts are spring loaded, causing minimal contact bounce disturbance. Simulated results of the rise time characteristic, caused by circuit inductance, show good agreement with measured results.

CONCLUSION

In summary, this paper describes a new battery model that accurately simulates characteristic battery behaviour during over-current instances. The battery model can be coupled with other distribution component models to simulate the protection performance in telecommunications DC distribution systems [6].

Acknowledgements

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References

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	A1	A2	A3	A4	A5	A6	A7	Cb
300Ah Valve-Regulated Cell	327μΩ	165μΩ	2μΩ	2.06V	41mV	300	1.16	1080kF
500Ah Flooded Cell	79μΩ	250μΩ	150μΩ	2.06V	20mV	1200	1.27	2160kF

Table 1. Simulation model parameter values.

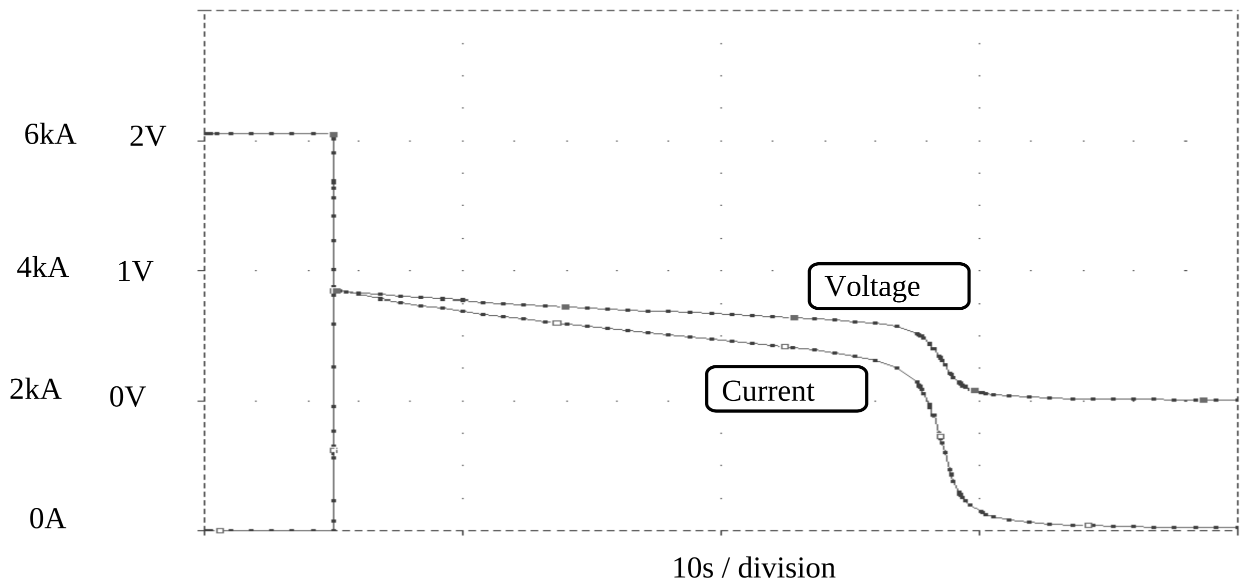

Figure 4a. Simulated voltage and current waveforms for the valve-regulated cell - long duration.

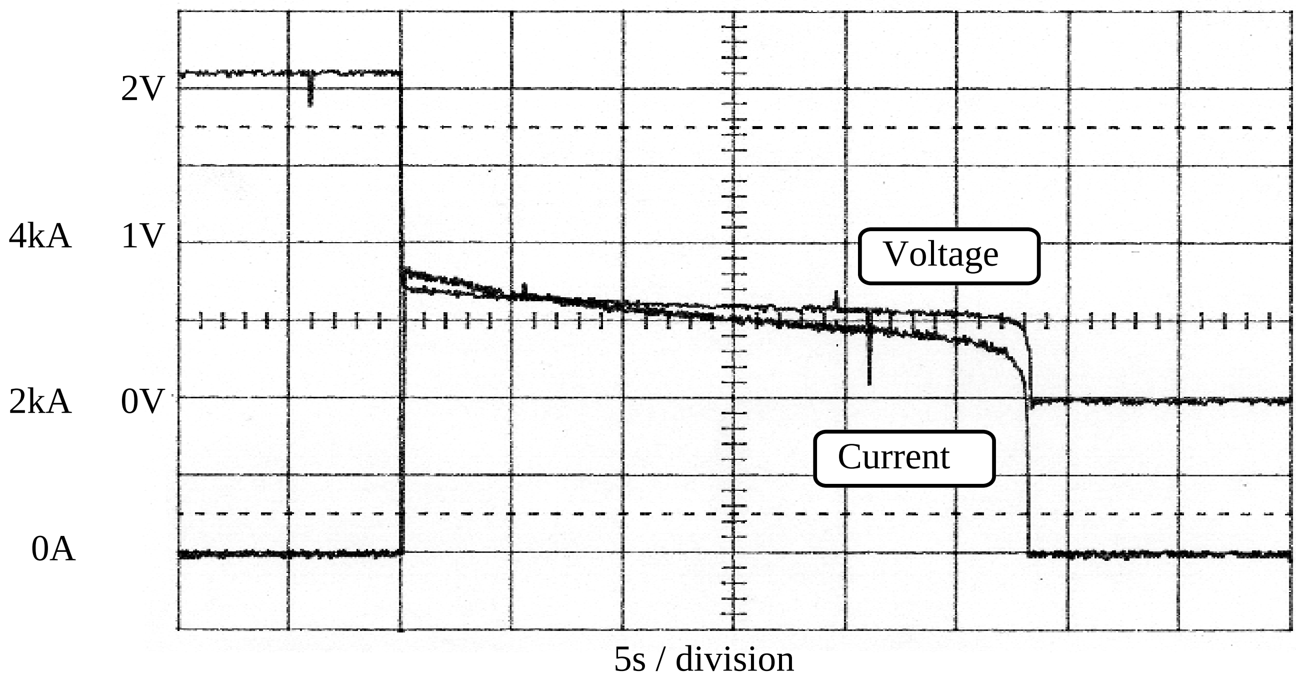

Figure 4b. Measured voltage and current waveforms for the valve-regulated cell - long duration.

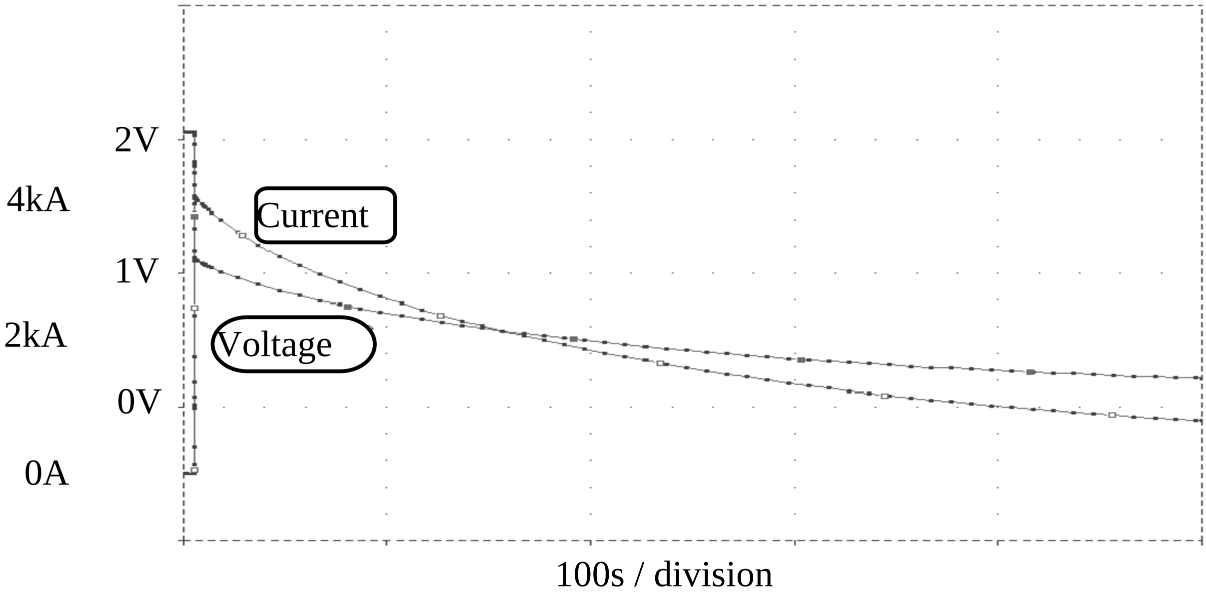

Figure 5a. Simulated voltage and current waveforms for the flooded cell - long duration.

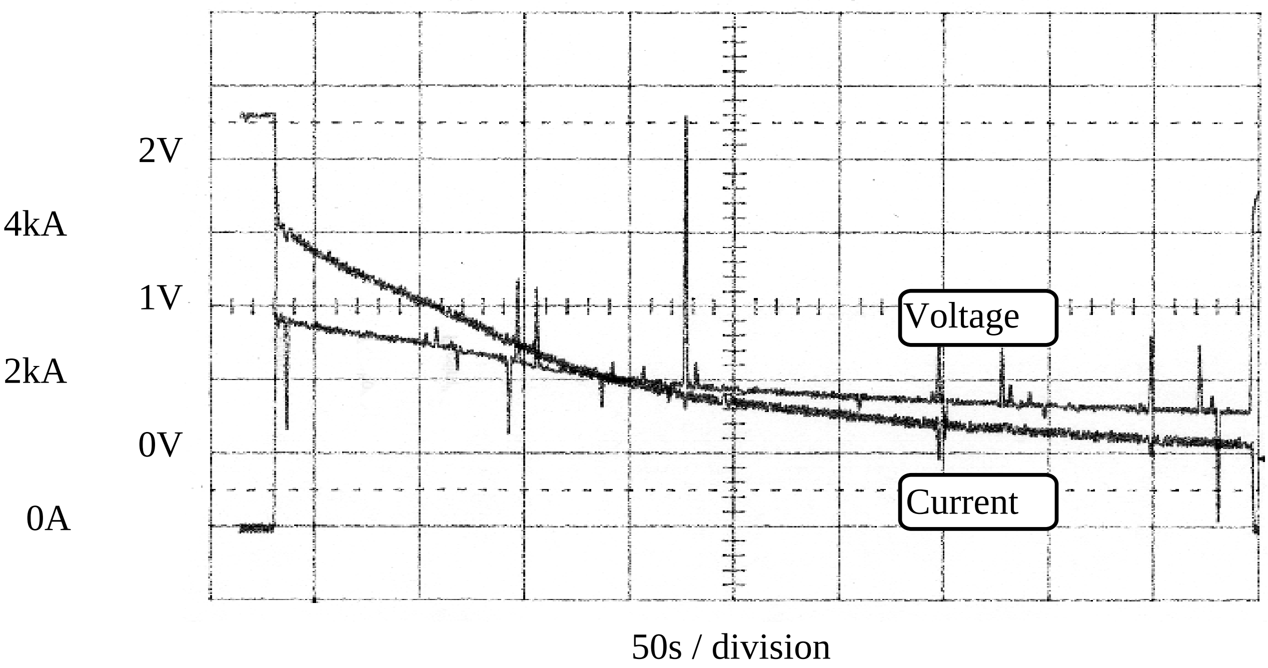

Figure 5b. Measured voltage and current waveforms for the flooded cell - long duration.

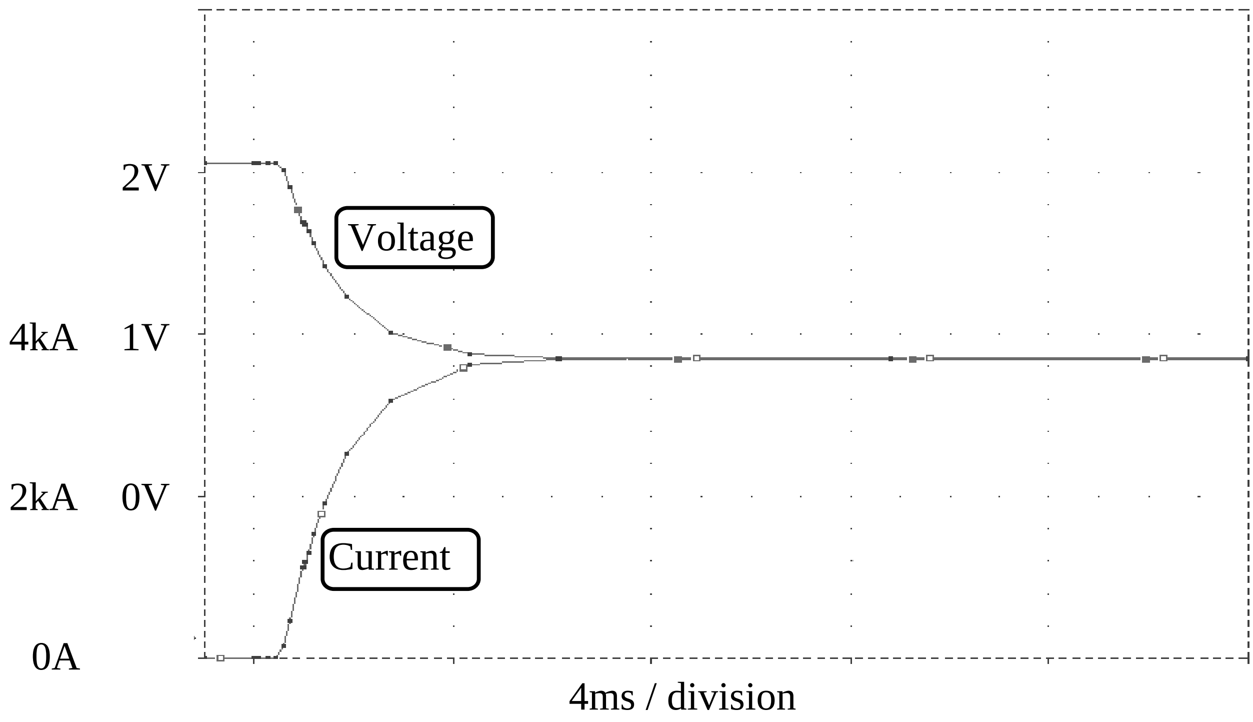

Figure 6a. Simulated voltage and current waveforms for the valve-regulated cell - short duration.

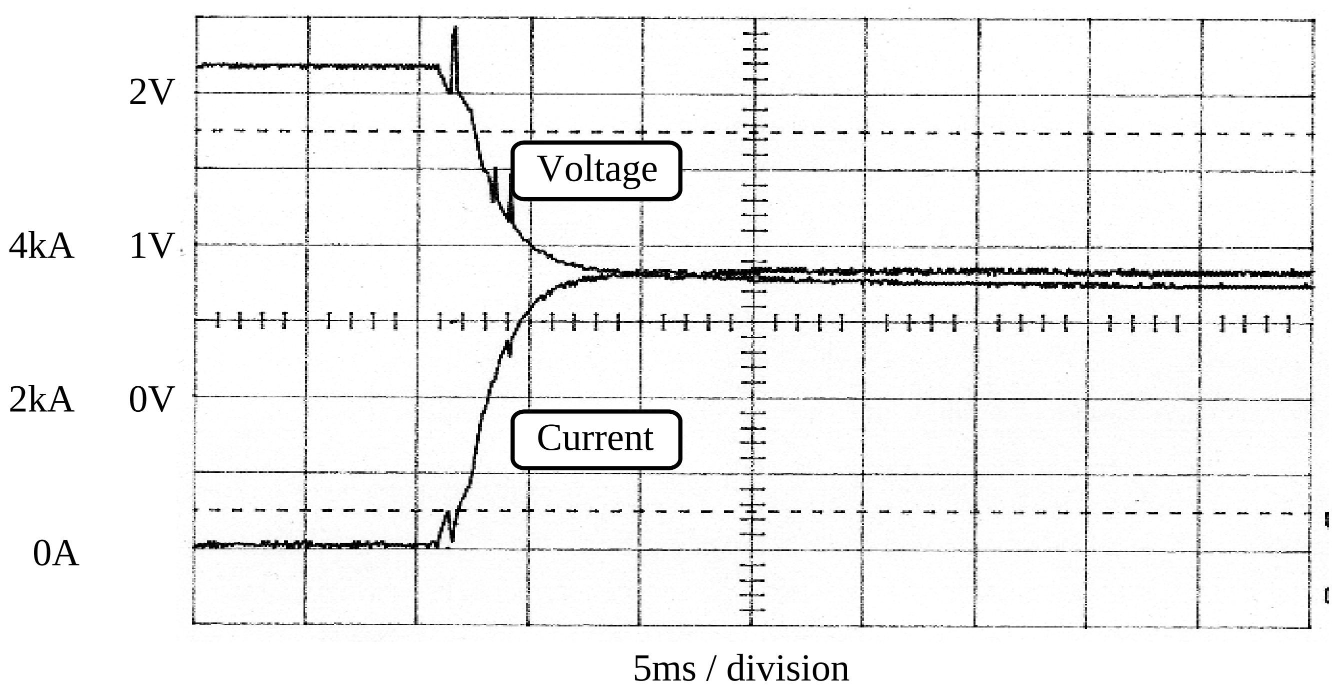

Figure 6b. Measured voltage and current waveforms for the valve-regulated cell - short duration.

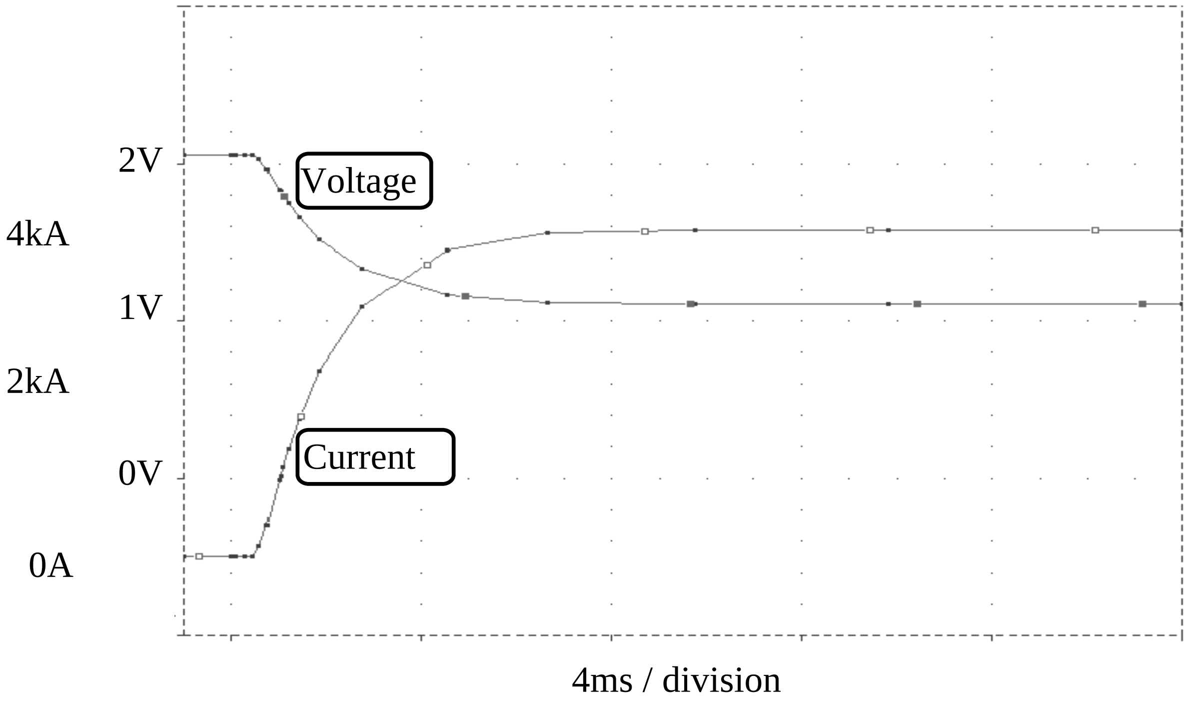

Figure 7a. Simulated voltage and current waveforms for flooded cell - short duration. (Note that the y axes for the simulated voltage and current waveforms are different than in the measured waveforms)

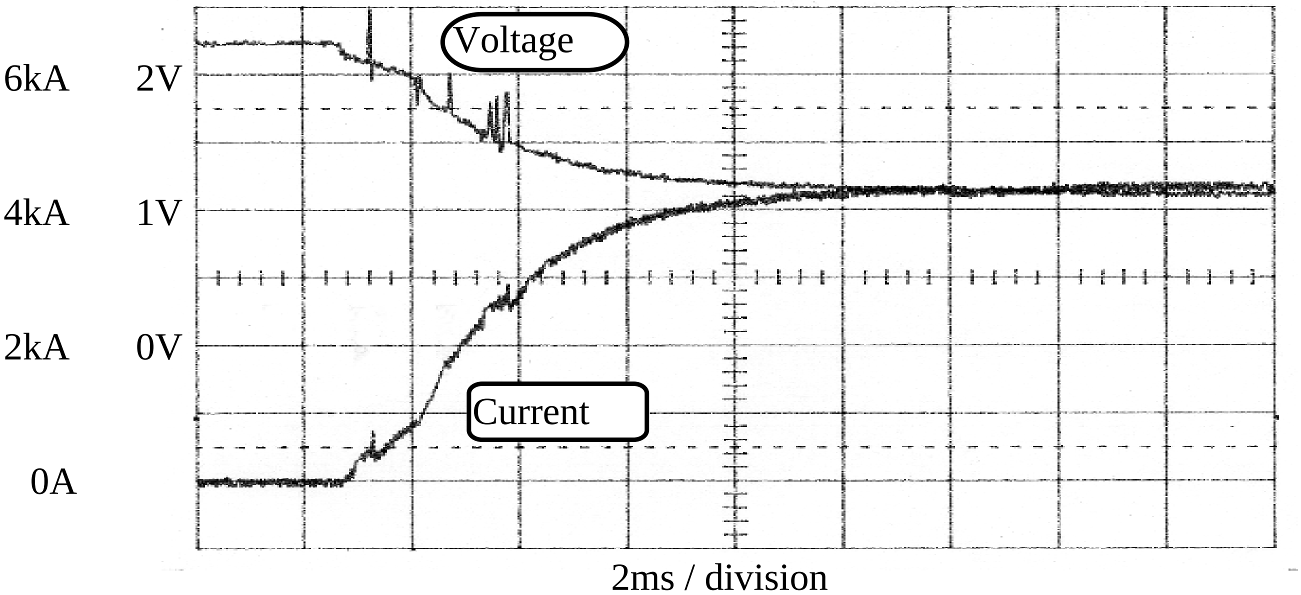

Figure 7b. Measured voltage and current waveforms for flooded cell - short duration.