PRACTICAL RESULTS FROM SHORT CIRCUIT TESTING OF LITHIUM BATTERIES IN TELECOM CIRCUITS

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Abstract

If a battery cannot trip a load breaker, a whole site can go dark because of a short circuit event. In secure telecoms often requiring high 9s reliability, this is not acceptable.

With the advent of lithium-ion batteries and their inherent battery management systems (BMS), it is important to understand their characteristics when applied in telecom circuitry.

Short circuit testing on lithium-ion batteries has been carried out to determine their ability to trip a load circuit breaker vs the battery breaker itself, vs the internal BMS.

This paper submits real experimental results showing oscilloscope traces of the short circuit current in various circuit arrangements. It would be very valuable for the industry to understand these reactions, speed of response of the circuit breakers, and to what level circuit breaker selectivity is possible (if at all), including the speed of response of the lithium-ion BMS module.

Introduction

Telecom circuitry is typically made up of rectifiers connected directly in parallel to both the battery and load circuits, as shown in the simplified diagram below:

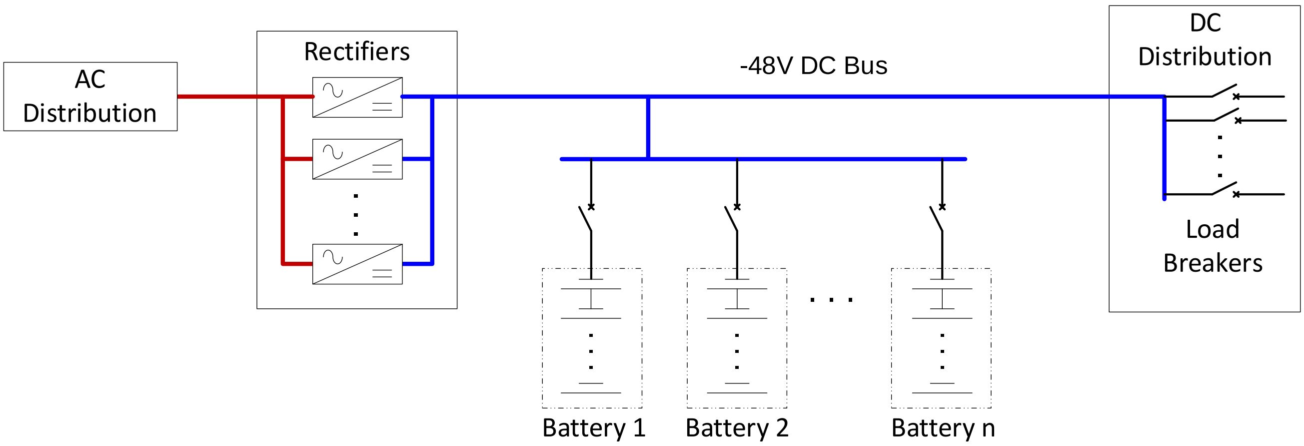

Figure 1. Typical Telecom Power Diagram with VRLA Batteries.

Note that with the battery breakers closed, there is a galvanic connection directly from the batteries to the loads. Also note that the battery circuit breaker is external to the battery, and selectivity between it and the load breakers can be configured at the overall system design stage.

The use of parallel rectifiers and batteries in this manner is fundamental to the security of the power system, and the achievement of "high 9s" availability.

With lithium-ion batteries, a BMS is introduced into the circuit, which is in series with the battery:

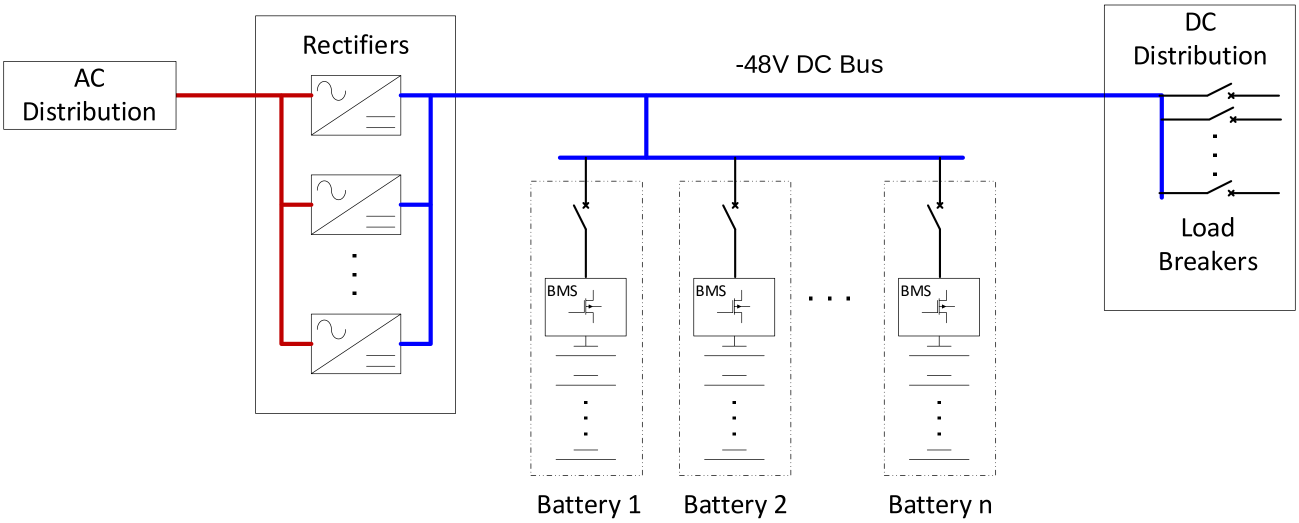

Figure 2. Typical Telecom Power Diagram with Lithium Batteries.

Note that the battery breaker is now normally wrapped up in the battery module itself. This is typically required for the battery to comply with UL 1973 or whatever other safety testing or installation standard might be required.

This now means there are two elements on the battery side of the system to consider: the battery breaker, and the BMS. As a side note, the BMS is interesting because now there is a silicon element in series between the battery and the load.

The purpose of this paper is not to assess the security/reliability of the system due to the introduction of this element (although this would be interesting) but is to examine the characteristics of fault currents during short circuit events at the load end.

We will begin with benchmarking a VRLA battery (the battery used is a 2 year old gel battery, with a name-plate capacity of 200 Ah (10 h rate). This will give us a trace of what the circuit breaker trip looks like with a 125 A miniature circuit breaker (MCB), since this is the same sized breaker that is in the lithium-ion battery, as well as a 63 A MCB which is the load breaker of choice for these tests.

We will then introduce the 5.12 kWh (100 Ah, nominal 51.2 V, 16 cell) $LiFePO_4$ battery, and examine the characteristics of its short circuit with varying load cable lengths. We will also check the cable length impact of the ability to discriminate between breakers that "official" have little selectivity gap.

Background

The batteries have been set up in a typical cell site (base transceiver station or BTS) arrangement with a power system at the top of the rack, and batteries distributed below.

Measurement Method

Although the testing is on dc circuits, the fault current is fast-moving (waveforms on the order of milliseconds or less), so current transformers (CTs) can be utilized to sense it. Scope probes attached to shunts might sound like an easy way to measure it, but the common-mode voltage discrepancies can cause numerous issues with accurate measurements – not to mention rather large currents through the earth probes. As a result, 1000:1 CTs were used.

Typical resistance for 100 Ah, nominal 51.2 V $LiFePO_4$ blocs is approximately 10 to 20 mΩ. Resultant prospective fault currents were then estimated to be on the order of 2.5 kA to 5 kA. A test was done with very short leads to verify this.

Circuit Breaker Background

Manufacturers rarely published trip curves with trip responses below 10 ms. However, EN 60898 gives a good indication of this. Preliminary testing determined that the breakers were tripping within 3 ms. This correlates well with experimental results where the breaking event finished within 3 ms at currents of 1.5 to 2 kA.

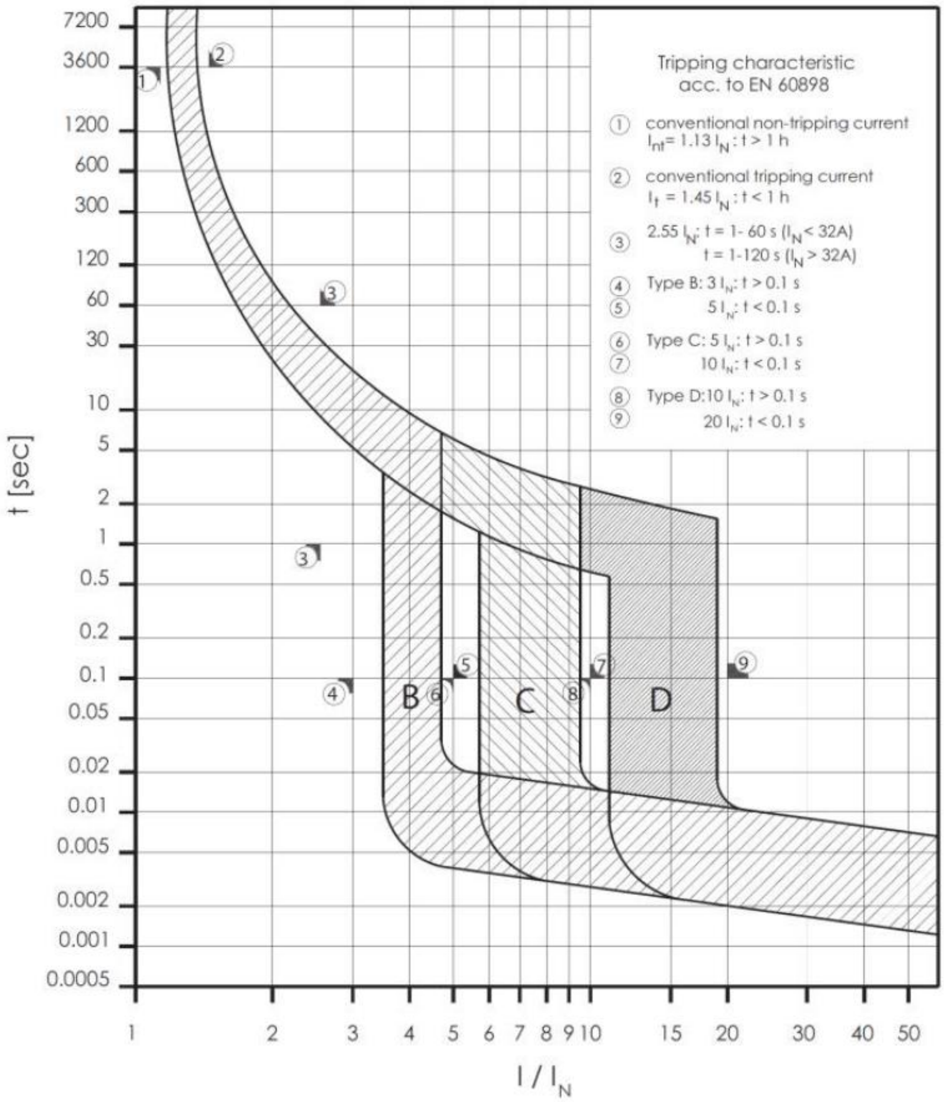

Figure 1. EN 60898 Circuit Breaker Trip Curves

Below is an overlay of a 63 A C-curve with a 125 A C-curve. Note that most 100 Ah 5.12 kWh $LiFePO_4$ batteries on the market have a 125 A breaker on their front panel. In most (but not all) international BTS site applications outside of North America 63 A is the largest DC Distribution breaker. Hence, discrimination between these two is desirable.

As can be seen in Figure 2, there is significant overlap in the instantaneous/magnetic trip region, which is where the battery short circuit current is. In theory then, it should not be possible to have predictable selectivity of the breakers. However, more batteries in parallel may serve to reduce the current contribution from each battery, thus increasing the probability of success. However, there will also be extra current from the parallel strings. Hence it will be prudent to also test batteries in parallel.

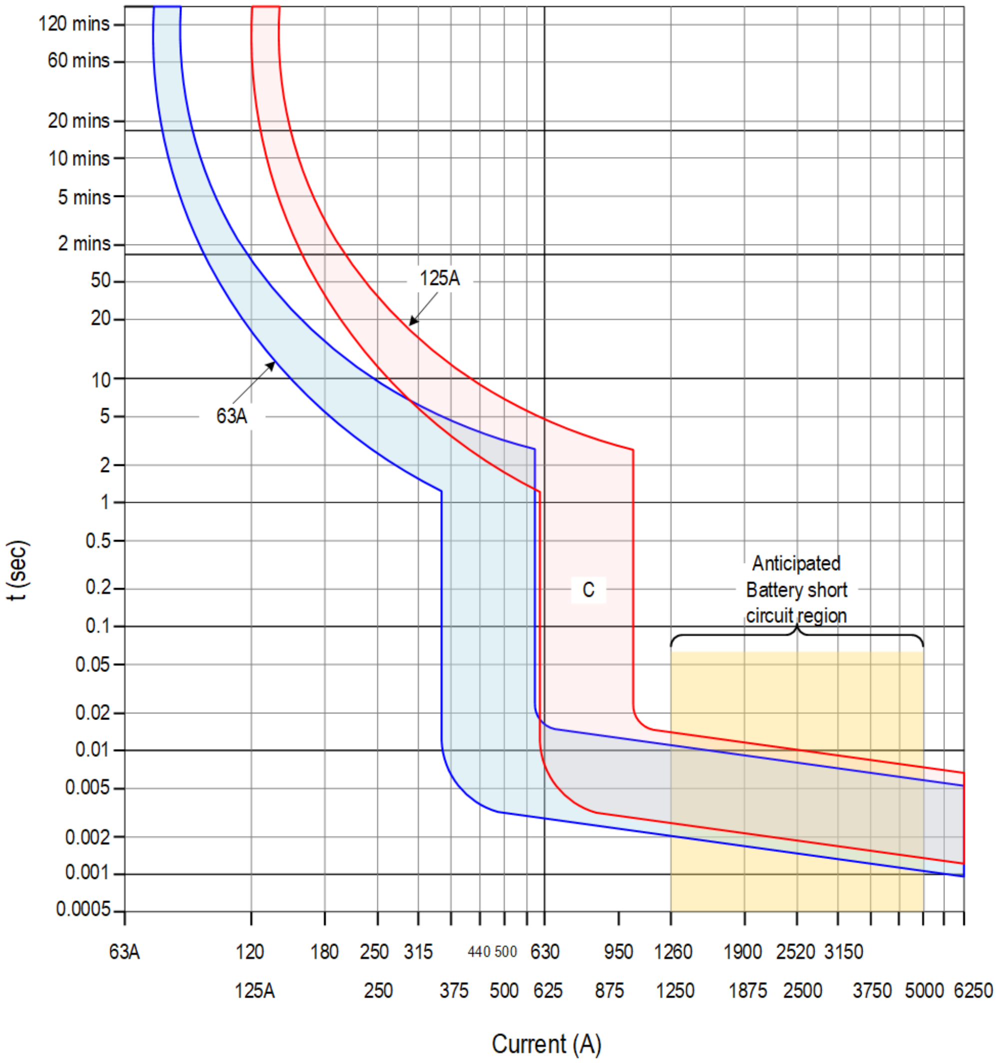

Figure 2. Circuit Breaker Trip Curves for 63 A and 125 A C-Curve Breakers

Note that circuit breaker manufacturer's data indicate that discrimination can only be guaranteed up to 1,000A when the upstream breaker is 125A and the downstream 63A (both C-curve) (Ref. 2). The testing performed here will verify whether there is any chance of predictable selectivity between the 125 A and 63 A breakers, with varying lengths of load cable introduced to examine any differences in predictability.

Furthermore, an examination of the contribution of current from parallel batteries would be helpful. This may mitigate the problem by lowering the current through the battery breaker, pulling it back further to its thermal region.

Role of the Lithium BMS

The BMS plays a significant role in the battery's capability to trip circuit breakers. Typical BMSs have an arrangement of FETs (field effect transistors) in series with the battery cells. These are usually the primary safety disconnect of the cells, followed by an in-line circuit breaker. Of course, FETs have a limited ability to withstand extremely high currents and the BMS manufacturers typically have many of them in parallel to lower the series on-resistance, increase reliability and also withstand the fault current in the event of a short circuit. An example can be seen in Figure 3.

If a BMS operates too quickly, then circuit breakers, wherever they are in the circuit, will not trip. Worse still, once one battery turns off, the other batteries will cascade. So, it is entirely possible that all of the BMSs in the connected batteries will turn off, resulting in the site going dark when there is no AC power (either from the electric utility or an engine-alternator).

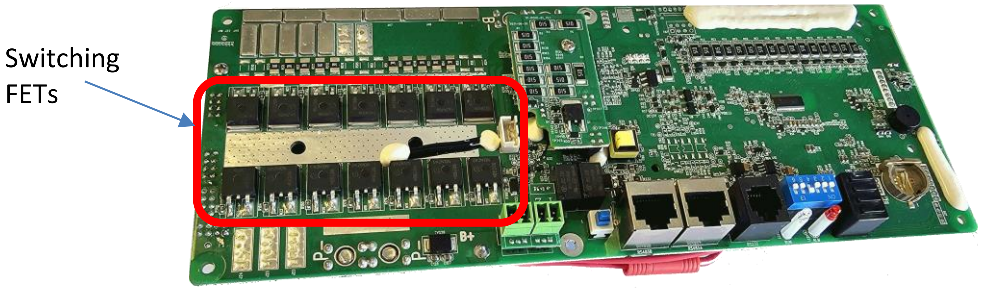

Figure 3. Generic Lithium-ion BMS Showing Multiple FET Arrangement

As a result, one of the first experiments would be to verify that the BMS does not trip out before the load breaker. As can be seen from the theoretical circuit breaker trip curves, the BMS needs to stay "on" for at least a couple of milliseconds.

Test Plan

The following is a broad outline of the planned experiments:

1. Benchmark circuit breaker operation with a VRLA battery.
2. Test the lithium-ion battery next to make sure the BMS does not trip too early.
3. Connect the circuit as per Figure 5 below and test to see if the load MCB (63 A) breaks before the battery MCB or BMS.
4. If both breakers trip, vary the length of load cable and re-check.
   Perform the tests with both short (≈ 3 m or 10 ft) and long 8 m (≈ 26 ft) circuit loops.
5. Benchmark the lithium-ion battery maximum short circuit current by shorting close to its terminals (this test is carried out near the end of the testing sequence in case it causes damage).
6. Connect 2 batteries in parallel and examine the short circuit current contribution of each.

Test Setup

A schematic of the test setup is shown in Figure 4

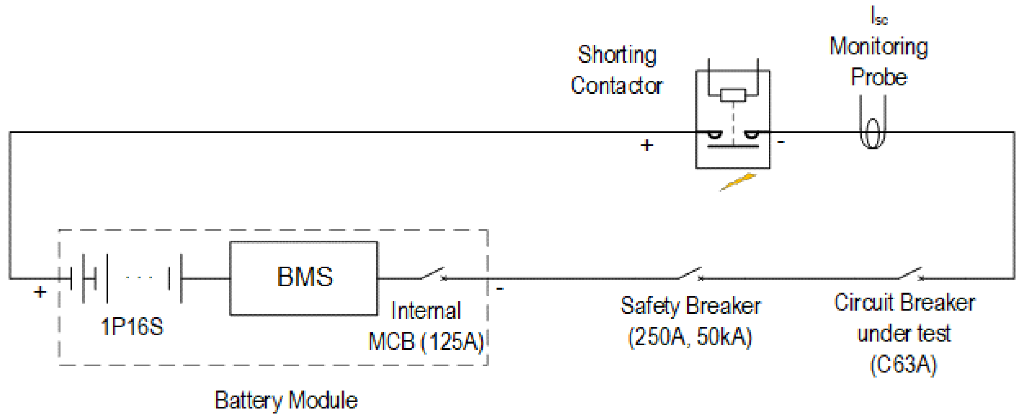

Figure 4. Schematic of Test Setup for Short Circuit Testing

The following is a single line diagram (SLD) pictorial of the test setup:

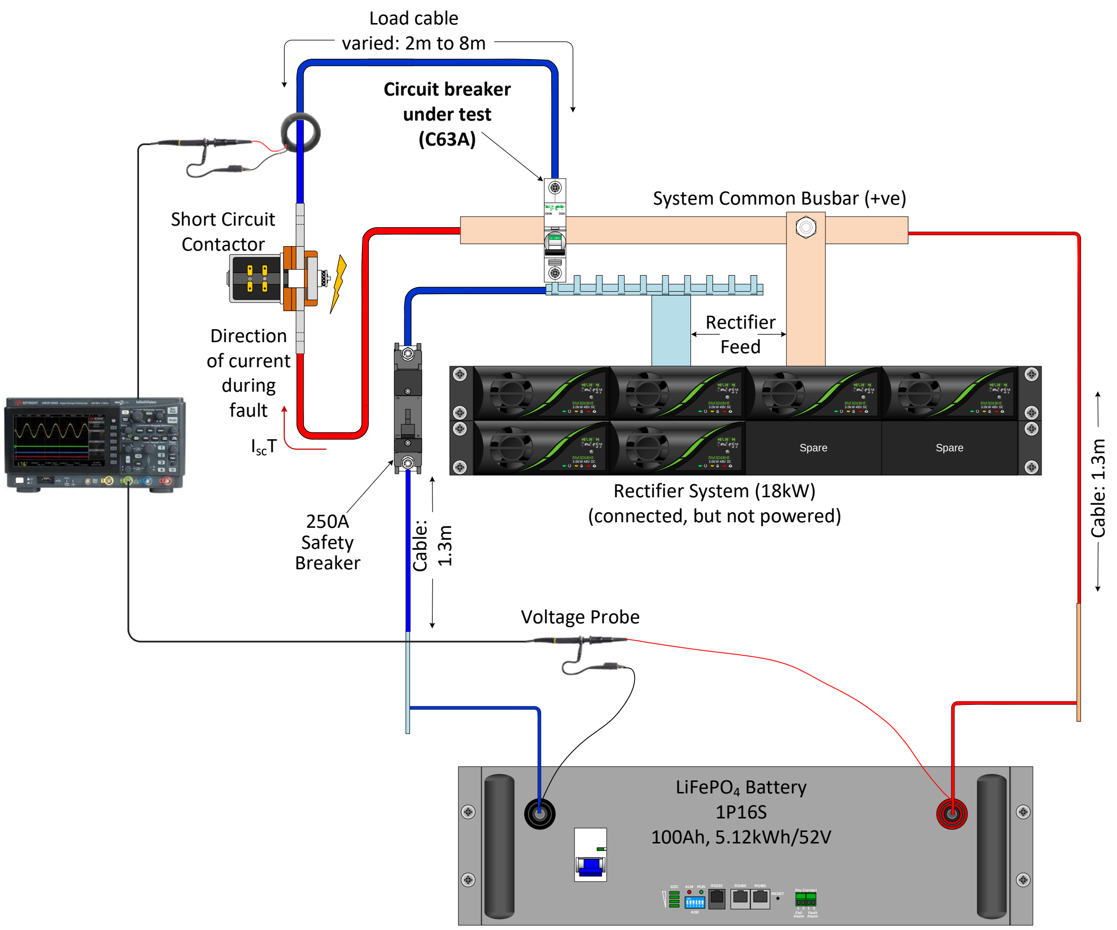

Figure 5. SLD Pictorial of Test Setup for Short Circuit Testing

Benchmarking Maximum Short Circuit Current

The test setup for quantifying the maximum battery short circuit current is shown below for both the VRLA battery and lithium-ion battery. The short circuit lead length was approximately 1.6 m (5'3") of 70 mm^2 (2/0 AWG) cable.

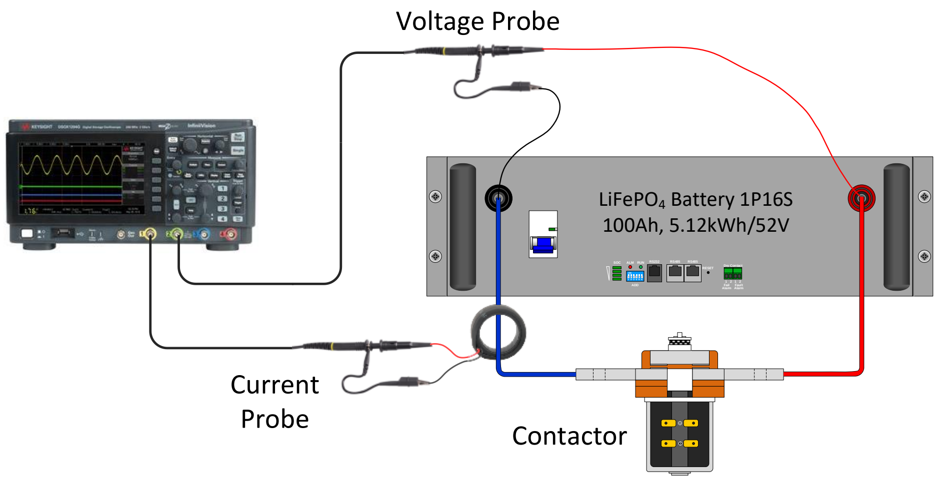

Figure 6. Proposed Test Setup for Verifying the Maximum Short Circuit Current of the Lithium-ion Battery.

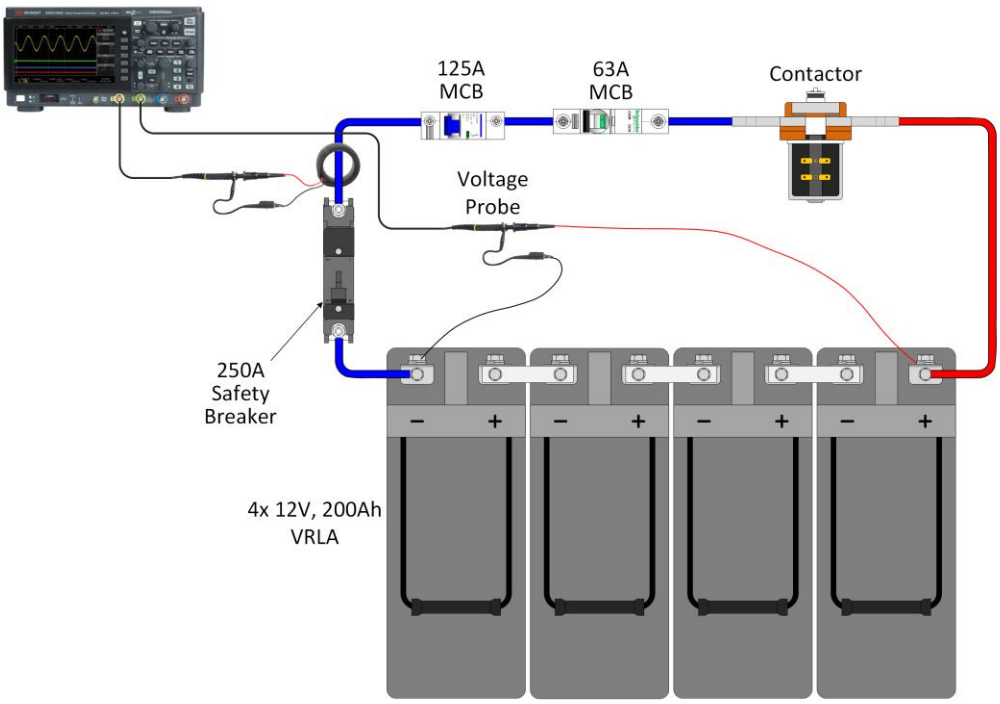

Figure 7. Proposed Test Setup for Verifying the Maximum Short Circuit Current of the VRLA Battery

Test Results

The following are the oscilloscope traces of the various tests. The scales and color keys are shown at the top of each trace.

VRLA Battery

The resultant short circuits with the setup as shown in Figures 6 and 7 are shown here:

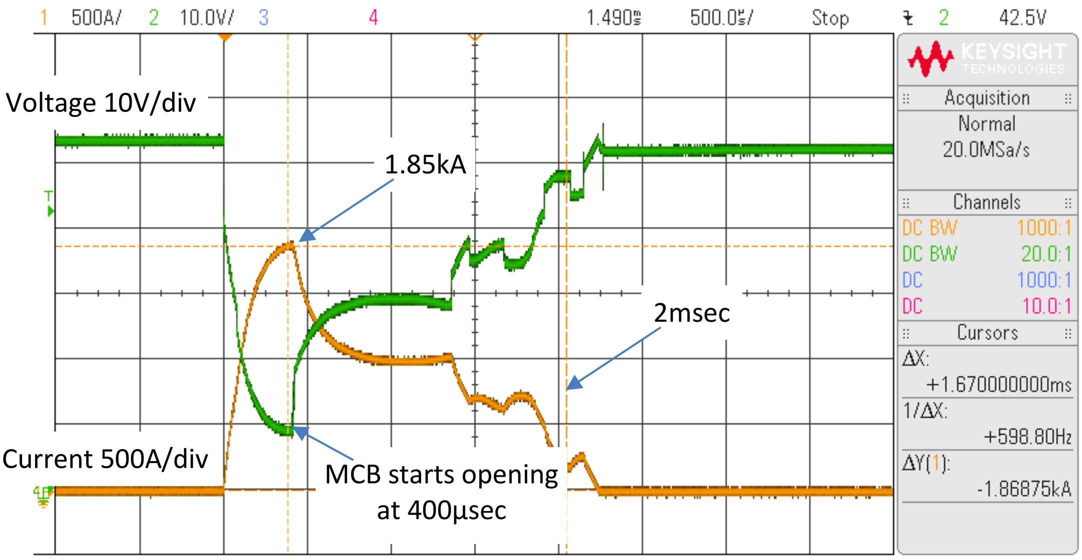

Figure 8. VRLA Battery Short Circuit; 63 A MCB Tripping

In this case, the 63 A MCB opened first, starting at about 400 µs. This test was repeated 5 times, and the results were similar each time.

The following trace was with the 125 A MCB alone. Note the much longer trip time (voltage only starting to rise at 3 ms), although onset of the trip was similar to the 63 A MCB.

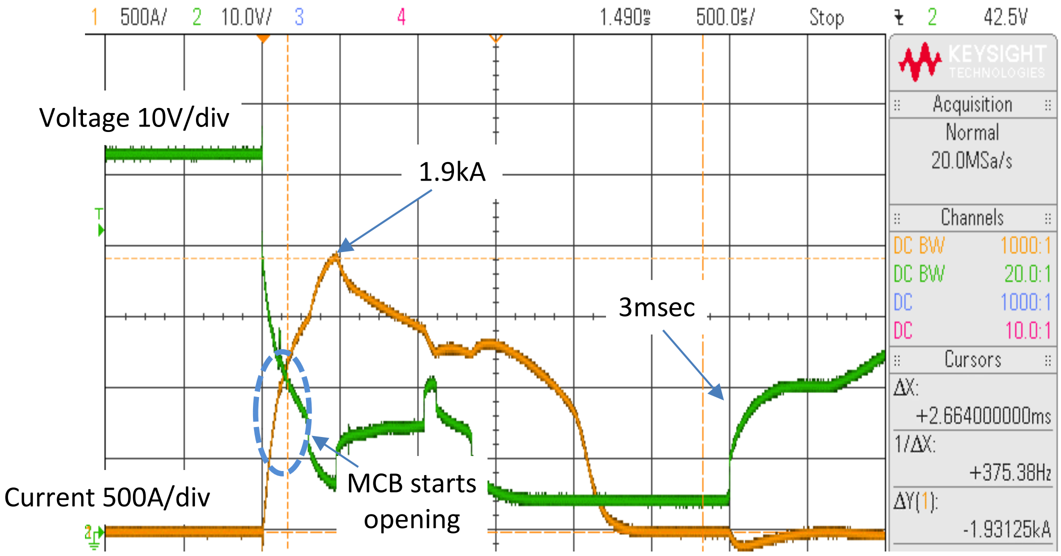

Figure 9. VRLA Battery Short Circuit; 125 A MCB Tripping

Verification of BMS Speed of Operation of Lithium Battery BMS

With the lithium battery, the first test was to verify whether the 63 A load MCB would open before either the BMS or battery MCB opened. Initial testing showed that the battery BMS always opened before any of the circuit breakers. At this point all testing ceased while the BMS was re-designed to be able to cope with an extended short-circuit time.

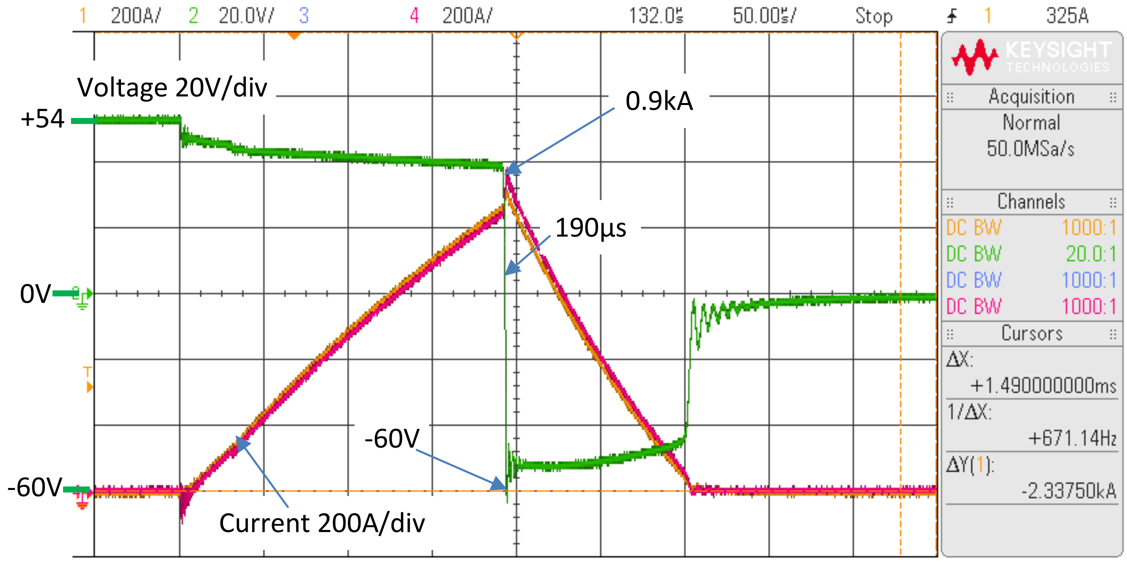

Figure 10. Scope Traces Showing BMS Operation Starting at 190 µs

As can be seen from the trace, the BMS started interrupting current at 190 µs. From the testing done with the VRLA batteries, this was never going to open any breaker. Furthermore, due to the rapid opening of the FETs the voltage kick-back due to circuit inductance was severe, with the ΔV of ≈ 100V in ≈ 2 µs.

In a lead-acid battery system, even if a load breaker failed to open for some reason, due to the plurality of batteries in parallel in a typical telecom BTS site, it would be unlikely that all of the breakers at the battery would open at the same time.

Unfortunately, with fast-acting BMS circuits, one of them opening will lead to a cascading effect where they all could open because no circuit breaker could act fast enough to clear the fault. The result if the AC is down at the time (i.e., no rectifiers on) is a possible site failure.

Effect of Rectifier Output Capacitance on Fault Current

In real telecom style systems rectifiers are always in circuit. For the purposes of this testing, we are interested in the fault characteristic when the AC has failed. The rectifier outputs are still connected, hence their capacitance will also discharge into a short. Fig. 11 shows the fault current from 6x 3kW rectifier modules that were connected, with only one powered to provide bus voltage.

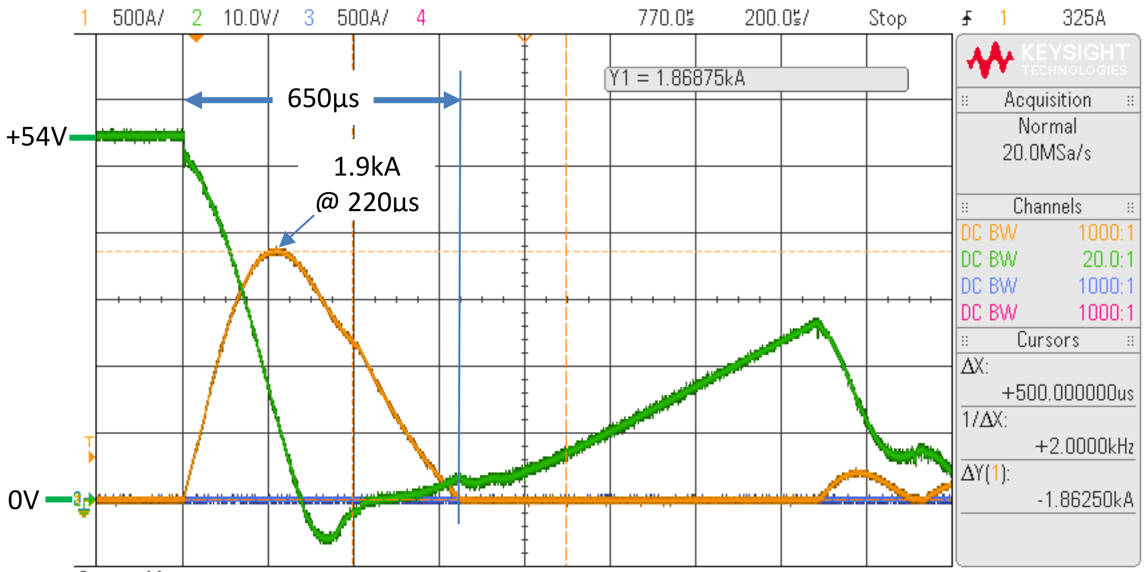

Figure 11. Rectifier Output Capacitance into Short Circuit.

As can be seen the fault current is significant. Of course, the fault current will increase or decrease depending on the number of modules connected. Note that this was insufficient to open the 63A load breaker.

Testing of Battery with Revised BMS

After re-design, the test was carried out again. This time the 63 A breaker reliably opened before either the BMS or battery breaker. Firstly, with a “loop” load cable length of 3 m (≈ 10 ft, 1.5 m hot and 1.5 m return). Unsurprisingly, both the 63 A load and 125 A battery breaker tripped, as shown below. It is interesting to see the time difference between the two. The 63 A breaker opened in just over 2 ms, while the 125 A breaker starts opening at about 4 ms. We assume this because the voltage trace is measured at the battery terminals, and for the voltage to return to 50 V, it is assumed to come from the battery.

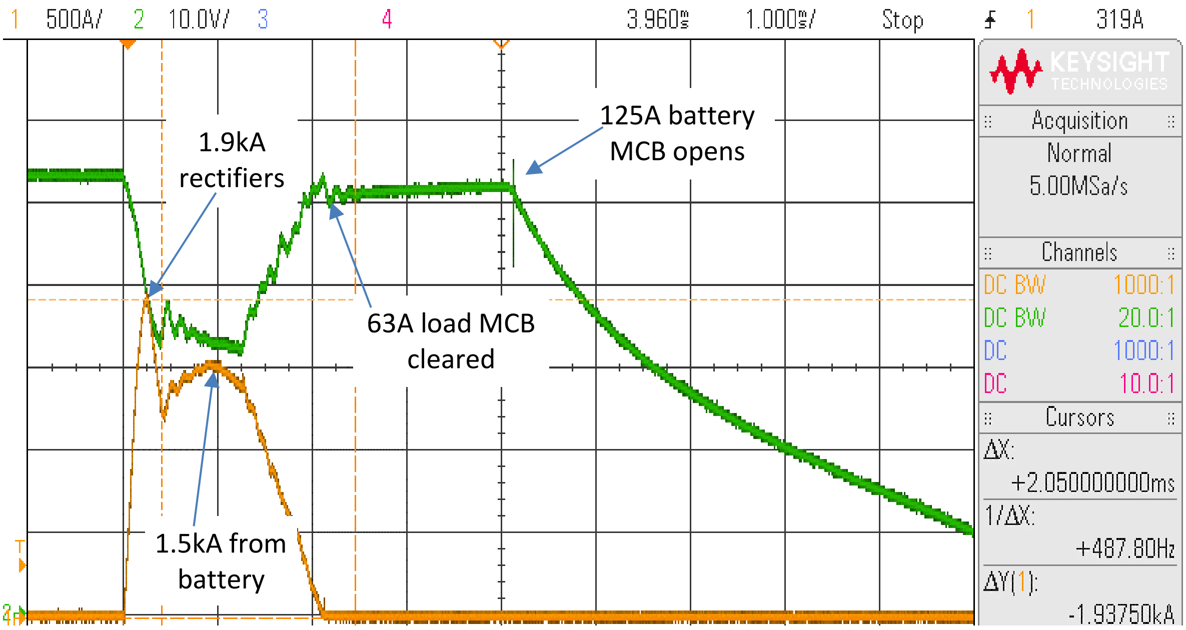

Figure 12. Scope Trace Showing both 125 A and 63 A MCBs opening, 3 m “loop” length load cabling.

The same test was performed with a 8 m (≈ 26 ft) length of load cable instead of the 3 m length. This time only the 63 A breaker opened.

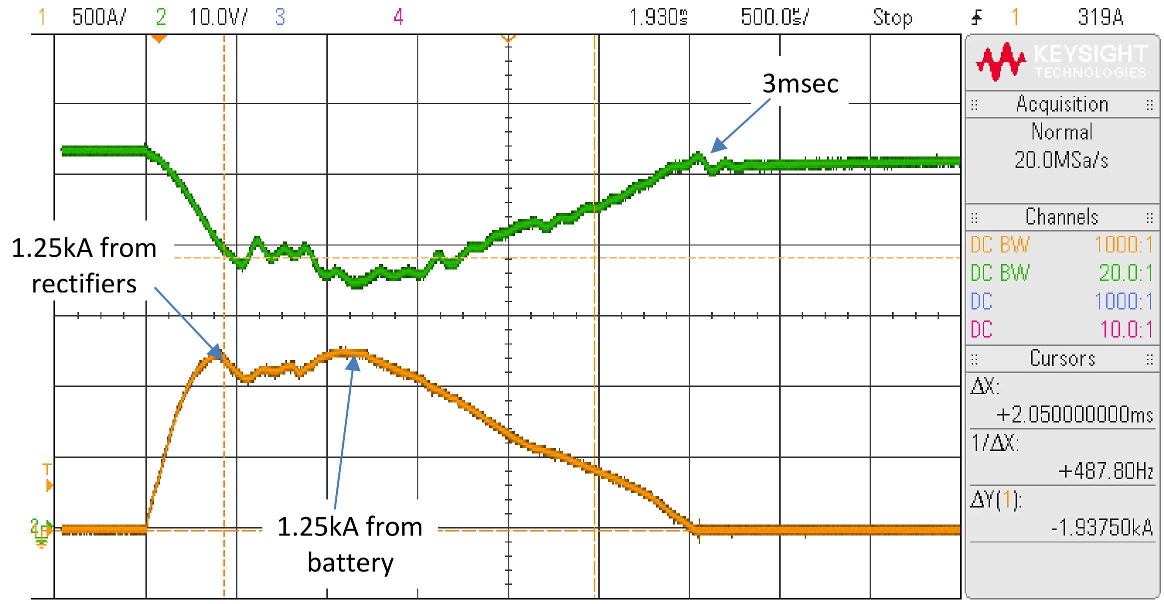

Figure 12. Scope Trace showing 63 A load MCB opening, 8 m load cable

This test was repeated ten times, with similar results each time. Only the 63 A MCB opened each time. Short circuit currents varied from about 1.0 to 1.3 kA. If we refer back to Figure 2, we could surmise that we are possibly only just entering the magnetic region of the 125 A breaker. However, according to the graph, there is still no theoretical guarantee of selectivity between the two.

A further test was carried out with the load cable reduced from 8 m to 5.5 m (17 ft). As expected, the short circuit current increased.

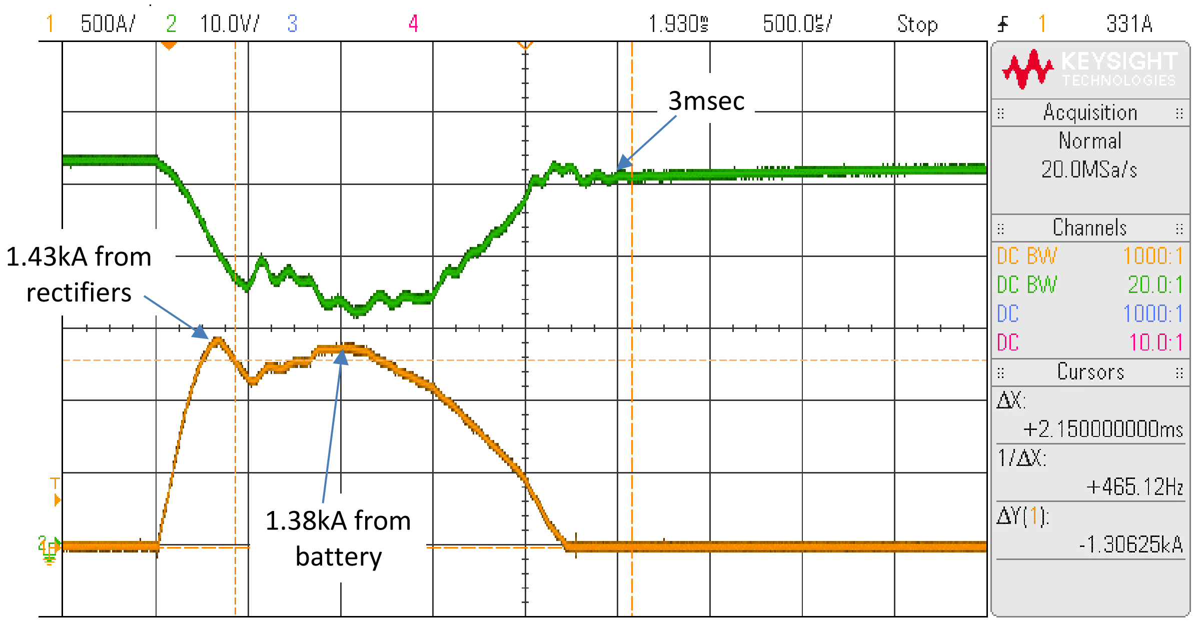

Figure 13. 'Scope trace showing 63A load MCB opening, 5.5m load cable.

A further 5 tests were carried out with this length of load cable, however, on two occasions, both the 125 A and 63 A breakers opened.

Benchmarking Lithium-ion Battery Terminal Short Circuit Current

At this point it was decided to benchmark the maximum short circuit current of the lithium-ion battery.

Lithium-ion batteries are purported to have much lower resistance when compared with their lead-acid cousins, hence we should see a higher short circuit current. This can be seen in their higher round-trip efficiency when compared to lead-acid. It is difficult to find accurate data, however, indications are that 10 mΩ might be reasonable for the Lithium-ion battery that was tested here. Individual cells can be as low as 0.3 mΩ each, giving a theoretical battery resistance of 5 mΩ. Adding connection, lead, BMS and circuit breaker resistance would add considerably to that. As a rough potential short circuit calculation, we could then take 53 V ÷ 0.01 Ω = 5.3 kA as a theoretical maximum.

The result was found to be 3.3 kA as shown in Figure 14. Battery SoC (state of charge) was 100%.

The 125 A circuit breaker tripped (and consistently so with repeated tests), comparing this to the VRLA short circuit, we can assume that the BMS was not interfering.

Approximately 10 seconds after the test, the battery circuit breaker was turned on and the battery functioned normally with no alarms. The test was repeated after 5 minutes, with no discernable change..

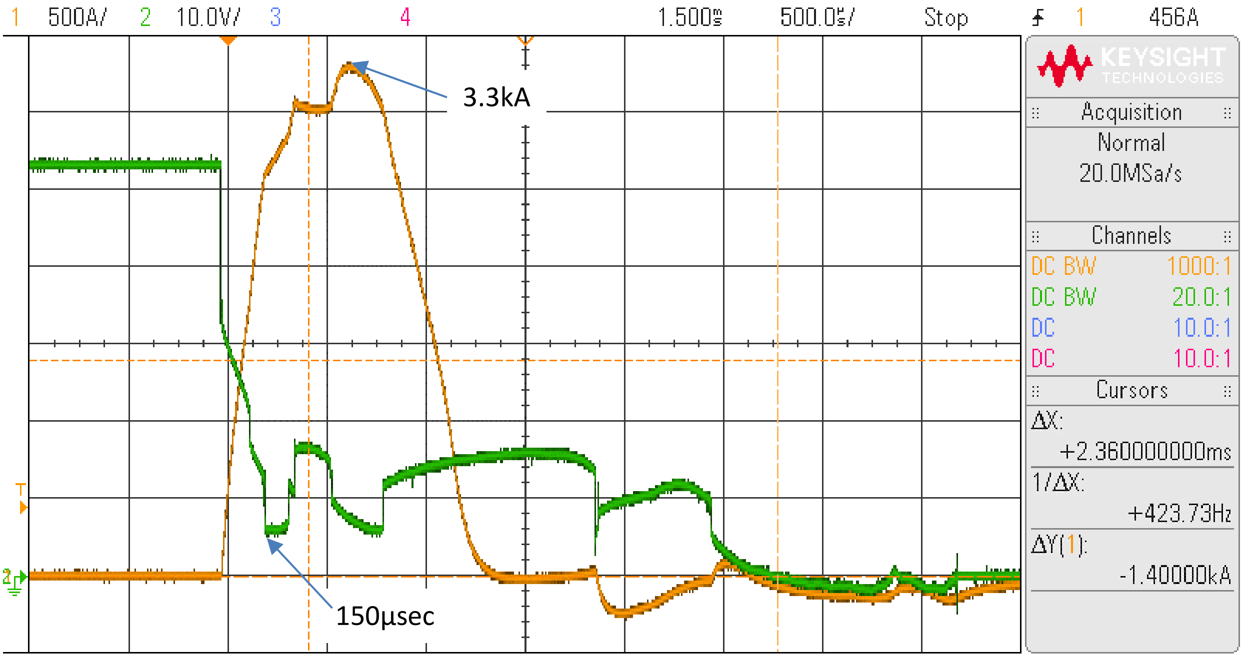

Figure 14. Result of Short Circuit Near Battery Terminals, no Rectifiers Slotted

Testing Batteries in Parallel

Figure 16 shows the test setup for quantifying the contribution of current from individual strings to the overall fault current. Of course, this will be very dependent on the specific layout and connections of the batteries, and this result will be largely dictated by the equivalent impedance (resistance) that the battery "looks into".

Two batteries were available for this testing. Future testing will have more batteries. One of the results of this will be to analyze total short circuit current to determine the required breaking capacity of the load circuit breakers. At present, many customers, when specifying circuit breaker interrupt capability, simply multiply the battery potential short circuit by the number of batteries. This can create expensive solutions (high breaking capacity breakers), and a needless waste of capital.

Figure 17 is the result of the test using the 3 m loop load cable. The blue and red traces are the individual battery currents, and the orange is the load current. Note that in this plot the time-base is 200 µs/div.

We can see from these results that the contribution of current from each battery is halved, greatly increasing the chance of discriminating between the 125A and 63A breaker. Recall that the manufacturer's data stated full discrimination up to 1,000 A.

In these tests (repeated 10 times), the 63 A breaker always tripped, the battery breakers never tripped.

An interesting area on the plot in Figure 17 is the region in the first 200us after the short. The rectifier capacitor current suppresses the battery current. This is to be expected as the voltage into the fault is the same, and the load resistance remains unchanged. Hence the contribution of current from the batteries is governed by ohms law and impedance seen by the batteries and ramps up relatively slowly.

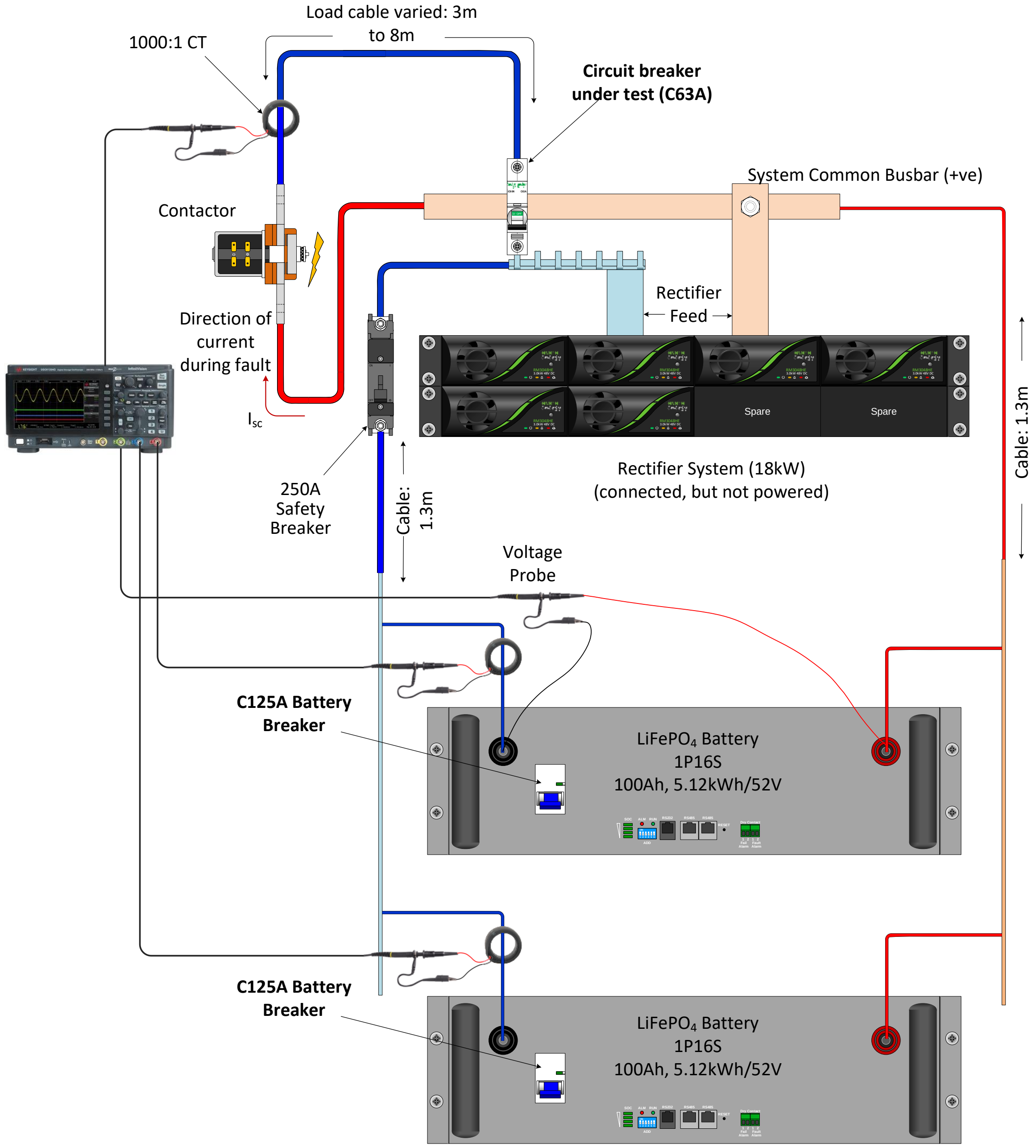

Figure 16. Proposed Test Setup for Verifying Current Contribution from Parallel Strings

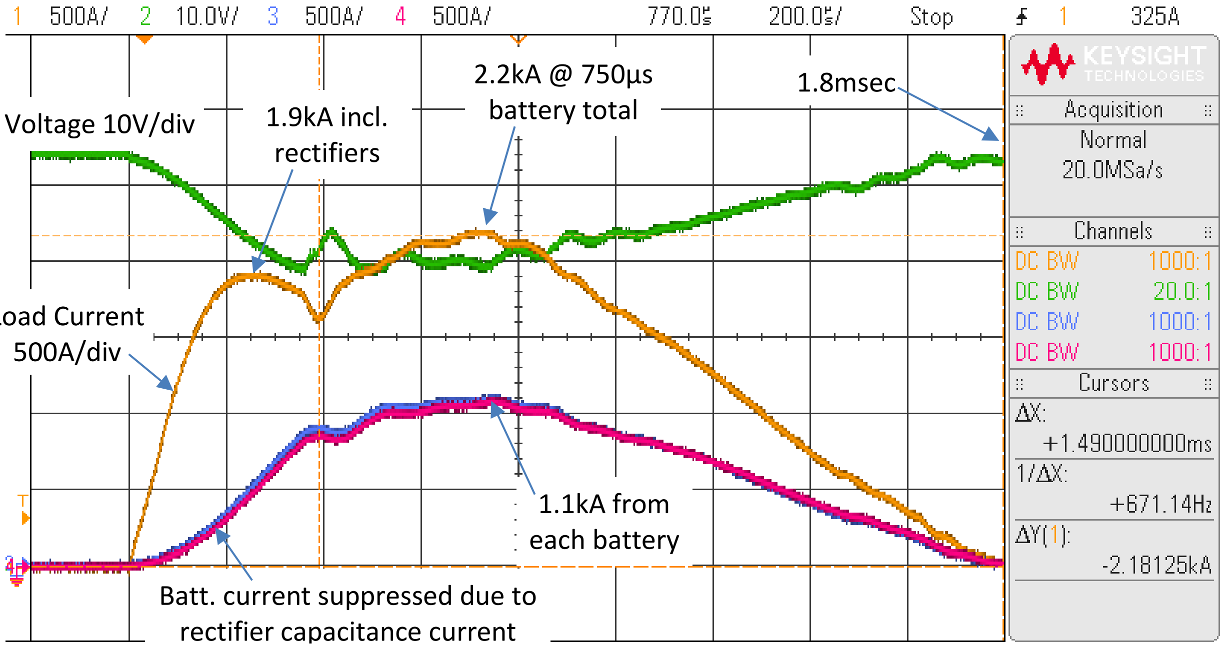

Figure 17. Result of Two Batteries in Parallel.

Figure 18 shows the effect of removing the rectifiers from the circuit. Understandably, the peak battery current is reached earlier than when the rectifiers are in-circuit (170µs (~23%) earlier).

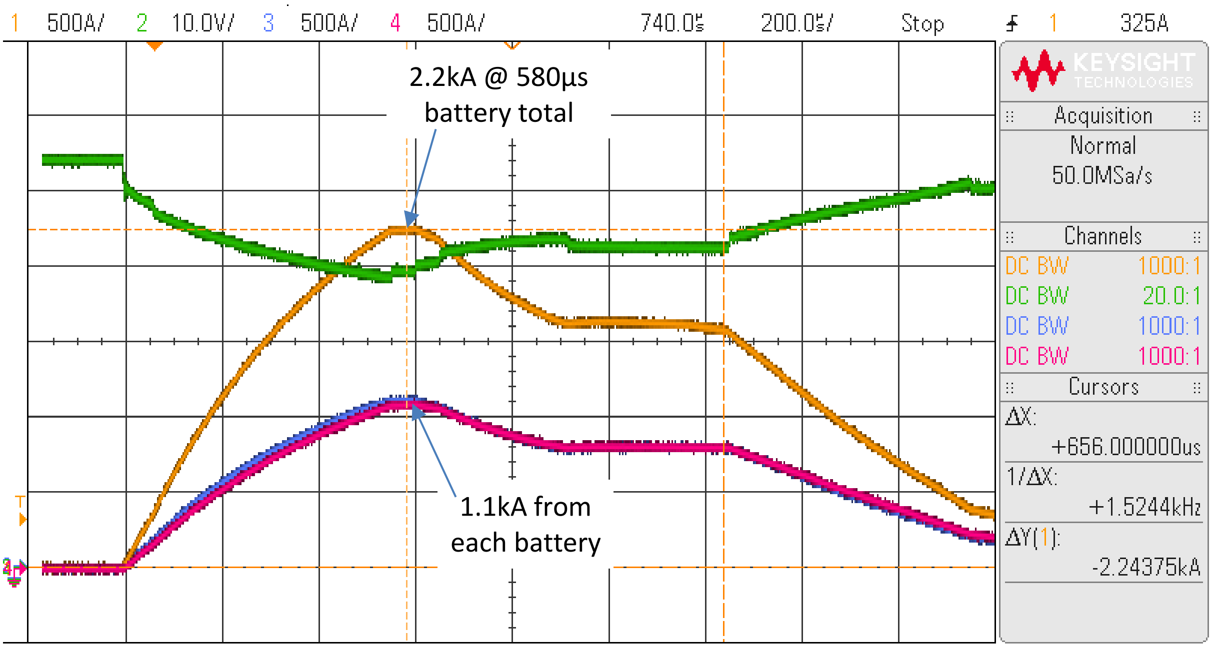

Figure 18. Result of Two Batteries in Parallel, no Rectifiers Connected.

It is important to note that the test in Figure 18 is the same as that performed in Figure 12, where the maximum battery current was seen to be 1.5 kA. In this test, each battery contributed 1.1 kA (total 2.2 kA). So, the total fault current due to two batteries is 1.47 (let's say ≈ 1.5) times the single battery.

It is the intention of the author to test variations of this with more (and different) batteries, different system wiring, and different circuit breaker arrangements. The intention is to see if there are any "rules of thumb" that can be used in the industry when considering breaking capacity ratings of circuit breakers.

Summary

It is hoped that the results presented here provide some "base" ground-work with respect to understanding the magnitude of actual short circuit currents – in particular with respect to using lithium-ion batteries.

The lithium-ion battery BMS is a crucial element in battery system security. A fast-acting BMS could cause havoc if a short circuit were to occur during an AC outage.

Not surprisingly, we have demonstrated that the selectivity between the 125 A and 63 A circuit breakers is indeterminate. However, with longer load cabling (≈ 8 m, or 26 ft), it appears that the 63 A breaker consistently trips before the 125 A breaker. Reducing the load cable to 5.5 m (17 ft) was enough of a reduction to make selectivity indeterminate once again.

Furthermore, parallel strings of batteries do not mean the fault current increases by the number of batteries connected. Individual battery fault current contribution is reduced, putting the 125 A MCB more into its thermal operating region, creating selectivity between the 125 A and 63 A MCBs.

We can see that, when in their magnetic operating region, the circuit breakers clear rapidly, starting to open in under 0.5 milliseconds, with the fault normally cleared within 3 milliseconds.

We can also see that, although lithium-ion batteries supply higher currents, circuit resistance can pull them back to similar currents that we see from VRLA batteries. As found during these experiments, the action of the BMS is crucial to the security of a telco system (or any secure power system of similar architecture). Once the BMS is taken out of play, conventional circuit breaker selectivity can be used. However, with the battery breaker built-in to the battery module, the user is unable to increase its size, making guaranteed selectivity difficult. However, parallel strings may help mitigate this issue.

Conclusions

There are potentially many critical power systems using batteries with BMSs that may not perform as expected when a load short event occurs.

It is critical to understand the short circuit characteristics of complex battery packs.

Understanding the effect of cable length and parallel batteries is helpful in network design to mitigate potential failure modes.

References and Acknowledgements

As this paper is largely experimental, there are few papers or articles to reference. I would like to acknowledge and thank Andrew McDougall here at Enatel for technical advice, and his help in building the test CTs. Also, thanks are due to Ajay Singh at Enatel for his help in setting up the experiments.
I would also like to thank Greg Dendle at Telstra for his proof-reading and technical advice.

1. EN 60898; Circuit Breaker Trip Curves.
2. Schneider Electric; 2019 - Selectivity, Cascading and Coordination Guide, P. A53