Challenges for testing labs of the future generation of DC fuse links for battery applications

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***Abstract*—Market demand for DC fuse links for battery applications is growing. This presents both a significant opportunity and an enormous challenge for manufacturers, standards organizations, and of course testing laboratories. This study reviews the situation with regard to standards and compares the most viable scenarios in the testing of interrupt ratings for fuse links in testing laboratories. The setups under consideration are from regular three-phase rectifiers, capacitor bank add-ons, to the most equivalent source – a Li-Ion battery system. The data analyzed for this study were generated from SPICE simulations with corresponding models, manufacturer datasheets, or actual laboratory measurements when available.**

***Keywords*—Batteries, electric energy storage systems, fuse links, standards, testing.**

I. INTRODUCTION

The world's transition to a low-carbon economy is a long-term project [1]. Part of this "Energy Transition" [2] is the instituting of smart electrical grids with home-to-grid scale energy storage systems and sustainable transportation based on renewable energy. Nowadays, the mode of energy storage with the greatest approval is the use of batteries. The main applications of this mode are electric vehicles (EVs), hybrid electric vehicles (HEVs), and battery electrical (energy) storage systems (BESS). Unfortunately, any application is only as clean as the source from whence its electricity originates – but this subject is beyond the scope of the current paper.

Overcurrent protection devices for battery applications are, as with their usage, manufactured and tested based on various standards – with the exception of those that are IEC; this is because IEC 60269-7 is still a SC 32B project [3], with a forecasted publication date of June 2020. The widely known and used fuse links for electric vehicles, hybrid electric vehicles, and battery electrical storage systems have rated voltages up to 1000 V, current ratings up to 600 A, and, mostly, interrupt ratings of 20 kA. Demands on the market are growing, with rated voltages of 1500 V and interrupt ratings up to 100 kA, but at the same time the system time constant is being lowered to 1 ms or less. The development of standard test methods has to not only take into account the efficacy of products based on their intended use, compatibility and inter-operability, but also the feasibility of testing them in laboratories.

II. STANDARDS

Fuse links for EV and HEV applications are new to the market. They can be viewed as a crossover between automotive fuse links and low voltage fuse links, with sets of standards for both carrying specific demands which have developed over time. Thus, automotive fuse links need to be, for instance, vibration and cyclic-load tested, whilst low voltage links should cover, for instance, higher rated voltages, currents, and interrupt ratings. Most of these tests are also necessary for fuse links in BESS applications.

Manufacturers can, of course, themselves provide solutions that are fully focused on accommodating each Original Equipment Manufacturer (OEM) requirement, but products will then lack compatibility and interoperability.

A. Manufacturers' referenced standards

DC fuse links for battery applications are nowadays referenced as products to be conform with a long list of national and international standards. Examples from manufacturers' fuse link datasheets include the following:

- Designed to JASO D622 and ISO 8820-8
- Manufactured under an IATF 16949 quality system for compliance with automotive requirements
- IEC/EN 60269-2, IEC/EN 60269-6, UL 284-4
- IEC 896 Stationary lead-acid batteries - General requirements and methods of test
- IEC/EN 60269

- UL 2579, UL 248-1
- In accordance with IEC SC 32B standardisation work
- IEC 60269-7.

The 2006 Japanese Automotive Standards Organization (JASO) D622 addresses battery DC fuses at a rated current of 400 A or less, a rated voltage of 450 V, and a breaking capacity of 2000 A. The now seven-year-old International Organization for Standardization (ISO) 8820-8:2012 has the same electric limitation as JASO D622; its replacement is at the final draft stage, but lacks notable changes.

International Automotive Task Force (IATF) 16949:2016 is one of the automotive industry's most widely used international standards regarding the Quality Management System (QMS).

International Electrotechnical Commission / European Standard (IEC/EN) 60269-2:2013:2013+AMD1:2016 covers AC as well as DC fuse links for use by authorized persons. Rated DC voltages are as high as 1500 V, rated currents 1250 A or even 4800 A, and breaking capacities range from 25 kA to 100 kA. Supplementary requirements for fuse links for the protection of solar photovoltaic (PV) energy systems are found in IEC/EN 60269-6. The UL 284-4 is a nonexistent standard.

The original standard IEC 896 from 1988 is now re-written into IEC 60896 parts 11, 21 and 22 from 2002 to 2004 with requirements and methods of testing for stationary lead-acid batteries only.

The outline of investigation UL 2579 applies to DC fuses for photovoltaic systems rated up to 1500 V. UL 248-1 is a standard for AC and/or DC low-voltage fuses rated 1000 V or less.

All above referenced standards exclusively cover automotive fuse links or low voltage (including PV) fuse links or have nothing directly in common with fuse links.

B. IEC standard 60269-7

The last two manufacturers' descriptions are referencing subcommittee SC 32B (low-voltage fuses) project task PT 60269-7 (fuse links for the protection of batteries); the project task has the goal of creating a standard for the protection of batteries, and the requirements, test procedures, and applications of such fuses. The project is currently at the draft stage of preparation of compilation of comments on committee (PCC).

Test requirements in the latest committee draft (32B/684/CD) highlight some significant challenges for testing laboratories – particularly where the desired time constant for the rated breaking capacity tests is the shortest. A quick summary of the more interesting test requirements from the draft are presented below.

- The scope and object are fuse links with a nominal voltage of up to 1500 V DC - but this may be higher.
- Rated currents are as in IEC 60269-1, with the addition of 8 which are higher than 1250 A - from 1400A to 3150 A.
- Conventional times for rated currents higher than 400 A are as long as 4 hours.
- Verification of rated currents is subject to 100 test cycles, after which characteristics shall not change.
- The minimum value of rated breaking capacity required by IEC60269-7 is 30 kA.
- The test mean value of recovery voltage is 100% (−0% +5%) rated voltage, with the tolerance including ripple.
- Time constants $\tau(I_1)$ and $\tau(I_2) = 1$–3 ms, $\tau(I_5) \leq 1$ ms.
- In some practical applications, time-constant values may be found which are shorter than those indicated in the test and which may result in a more favourable fuse performance.

III. POSSIBLE LABORATORY SETUPS FOR TESTING OF INTERRUPT RATINGS FOR FUSE LINKS

Given the growing demand for future-generation DC fuse links from users in the EV, HEV and BESS industry, manufacturers are searching for locations providing test support for their products' development. The most called-for test requirements are at the IEC 60269-7 limits – a DC test voltage up to 1500 V, prospective current of 100 kA, and time constant of 1 ms. This setup is currently not feasible in its entirety, since the current and time constant requirements are for now mutually exclusive. To satisfy demand, laboratories can either upgrade their current DC testing equipment or construct an entirely new testing line.

A. Three-phase rectifiers

Using rectifiers after low voltage high power transformers is the most usual way of conducting a DC power test. The above-mentioned test requirements can thus evolve from a totally theoretical to a practical setup. The current and power factor ($cos\varphi$) of the transformer setup is calculated at the combined switch and rectifier point on the low voltage side; thus, it combines all the influences of the grid, transformer and power lines.

- A 74.2 kA transformer setup with *cos*φ = 0.95 and with no load on the DC side (zero length short) could, in theory, be just sufficient to satisfy all the test requirements, including the time constant τ = 1 ms, if we compare Fig. 1's traces *a* and *ref*. The real-world *cos*φ are, at this level of current, much lower.
- A 74.2 kA transformer setup with a more realistic *cos*φ = 0.14, and again, with no load on the DC side, equally satisfies the current requirements, but fails regarding the time constant, with τ = 2.1 ms We are also confronted, in this scenario, with extreme test current transients, reaching as high as I_{OL} = 173 kA and as low as I_{UL} = 57 kA, both visible in Fig. 1 trace *b*. The only solution is the employment of transformer setups with higher current capabilities and additional loads on the DC side.
- A more powerful 230 kA and *cos*φ = 0.14 transformer setup with a pure resistor load on the DC side again satisfies requirements, with a trace similar to trace *a*. However, stray/loop inductances on the DC side are not negligible, so, again, this is simply a theoretical setup.
- Europe's most powerful testing laboratories, to our knowledge, have around 250 kA transformers, with equivalent speculative power factors. Adding in the simulation, a cumulative DC-side inductance of just L_{DC} = 30 µH raises the time constant to τ = 3.0 ms. The trace *c* slope is therefore more gentle than any of the others, although laboratories are presently not reaching even this trace. By way of comparison, the 30 µH inductance represents a *l* = 23 m-long power line theoretical self-inductance, or, the more practical and illustrative inductance of a loop with a *d* = 9.5 m diameter. The inductance is unavoidably collected by the self/parasitic inductance of resistor loads, including loads on the primary side, and the often long but necessary distances between the switch/rectifier and test field.
- With the aid of new low-inductance resistor loads and distance minimization on the DC side, the inductance can be lowered – for example, to L_{DC} = 8.2 µH (equal to a *d* = 3.2 m loop diameter inductance). Such optimization could lower the time constant to τ = 1.5 ms, as illustrated in Fig. 1 trace *e*.
- With the aid of a 500 kA and *cos*φ = 0.14 transformer setup combined with the previous optimization, we can finally, in practice, satisfy all test requirements, as Fig. 1 trace *e* is most satisfactory in approaching our reference for the time being.

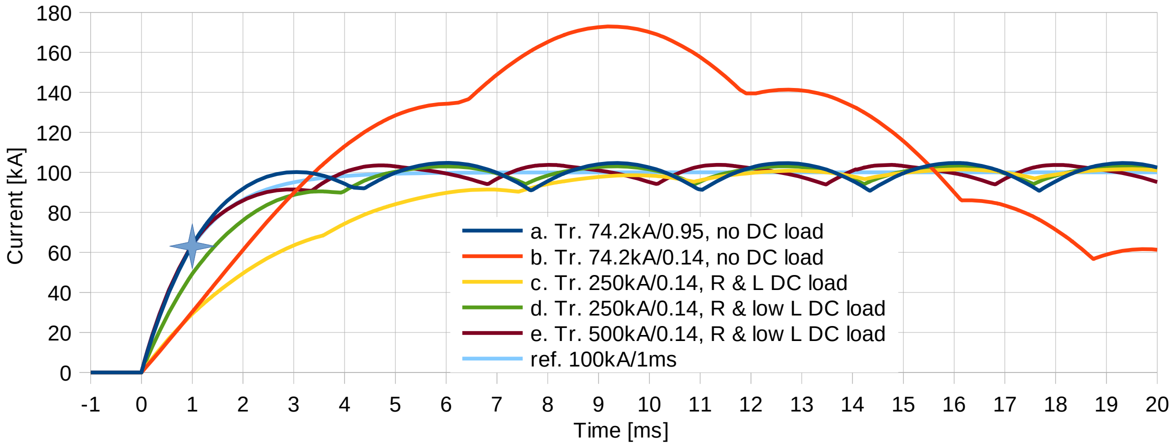

Figure 1. Current traces with different transformer-rectifier-load setups

Upgrading current DC testing equipment based on high-power transformers and rectifiers obviously implies a complete change of the equipment's main parts.

B. Battery systems

The most equivalent source for testing DC fuse links for battery applications is indubitably a battery system. The test environment is, irrespective of the chosen battery technology, the closest to the world in which these fuse links will be employed. One of the most pressing challenges is, again, to not exceed the time constant of τ = 1 ms. The cumulative inductance for the test should be L_{DC} = 15 µH, as the inductance of a *d* = 5.5 m diameter loop. Using battery arrangements, as seen in large battery rooms, is therefore not suitable. The battery system density must be as high as that found in EVs, demanding battery management systems (BMS) which are also appropriate.

The first battery technology option is still the most widely used lead-acid battery. For simplicity, we concentrated on just one type and product, but with the needed comparable mass of battery cells. In order to reduce future maintenance needs, this is a valveregulated lead-acid (VRLA) absorbent glass mat (AGM) battery and a widely available 13.2 V and 65 Ah product. The theoretical minimum needed in terms of mass of battery cells is m = 84 t, when directly shorted with a 45C discharge rate on all 3990 batteries.

The alternative to lead-acid is Li-Ion technology. The use of electric specifications for a larger one-cell (3.6 V) polymer lithium battery with a 65 Ah capacity, as used in some European EVs, reduces the net mass of the batteries in the whole system to m = 15.7 t. As previously, this is now, with 16263 batteries, directly shorted above manufacturer's specifications with a 40C discharge rate.

The disadvantages of Li-Ion over VRLA batteries include their higher price and more complicated BMS. On the other hand, with Li-Ion batteries we can expect a longer life cycle and a lower monthly discharge.

C. Capacitor add-ons

Adding a capacitor add-on with a sufficient capacitance after the three-phase rectifier and before the DC load could drastically lower the time constant in the desired direction, with an outcome similar to a transformer-rectifier system with a parallel synchronized low voltage surge generator. The setup, when properly adjusted, works well at voltage and current calibration measurements and therefore also at the melting period of the fuse link. Unfortunately, after arcing begins, the testing circuit falls into oscillations.

D. Capacitor banks

Most basic surge generator designs are able to source high currents with the desired rise times but are inappropriate after reaching their peak value. Long duration impulse current generators, such as those used in line discharge tests, mainly consist of a bank of series inductance and parallel capacitance. Their output waveform is, in comparison with basic surge generators, more rectangular in shape. The duration of the pulse time depends on the number of stages used, as well as inductance and capacitance per stage. For example, the n = 10 stages from the capacitor bank shown in Fig. 2 are able to generate a t_{90} = 9 ms-long pulse with a I^2t = 90 MA^{2}s Joule integral. Each stage contains a C_C = 50000 μF capacitance with a weight of m_{C1} = 500 kg. Given that we expect that the fuse link total clearing time for a positive test will be shorter, such a setup has no impact on the test during the pulse of the generator. However, the long duration impulse current generator alone fails to supply a compulsory recovery voltage for possible re-arcing events in a 1-minute period.

E. Capacitor bank add-ons

Finally, we can combine a capacitor bank, instead of a capacitor add-on, with a three-phase rectifier in a parallel setup. Fig. 2 represents a simplified schematic of the whole laboratory setup.

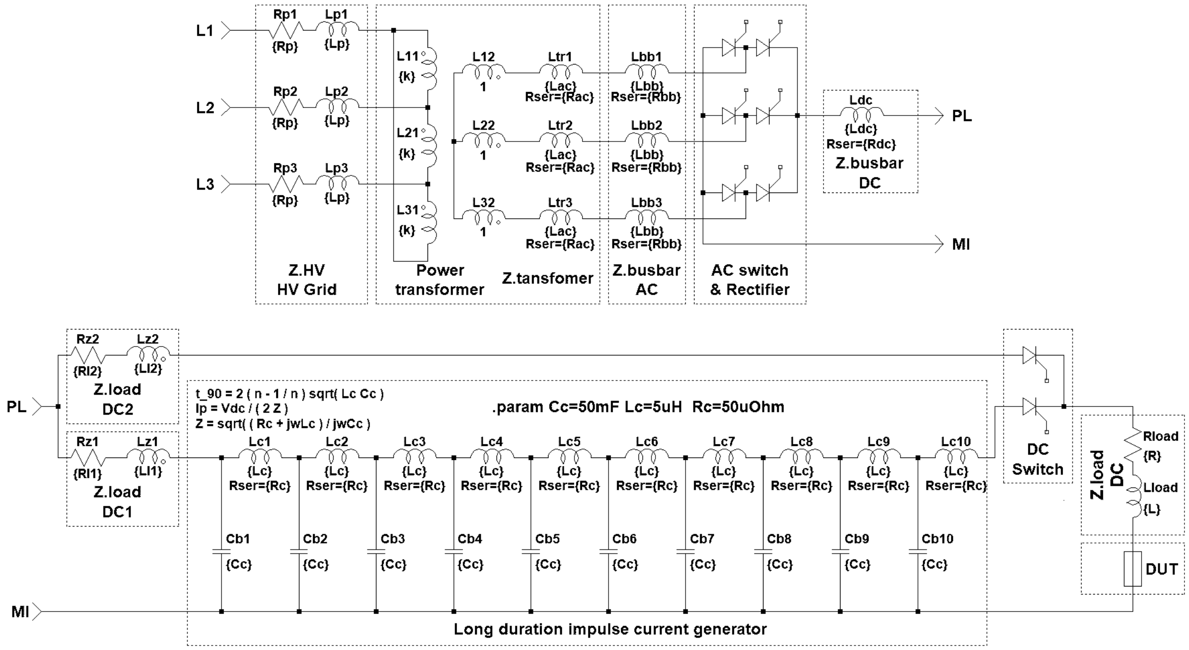

Figure 2. Capacitor bank add-on laboratory setup for testing interrupt rating of fuse links

The upper part of the schematic is a common transformer-rectifier setup with all simplified influences: HV grid, transformer, and AC and DC busbars. The DC1 load is the supply path for the capacitor bank of the impulse generator and also prevents system oscillations. The second supply path, through the DC2 load, bypasses the capacitor add-on and enables a correct recovery voltage, although with a lower prospective current of 7.8 kA in this example. If the current at this time becomes greater than the customer's defined upper limit, the test must be considered a fuse link failure. Our laboratory experience shows that re-arcing, even at relatively small current levels, leads equally to unavoidable fuse link failure.

In Fig. 3, traces *a* and *b* represent currents in a current calibration test with this capacitor bank add-on setup and a purely theoretical DC voltage source, coil, and resistor reference design respectively. Both traces are accordingly up to 9 ms. Also, when adding a 500 A fuse link model, the design demonstrates similar outcomes in traces *c* and *d*.

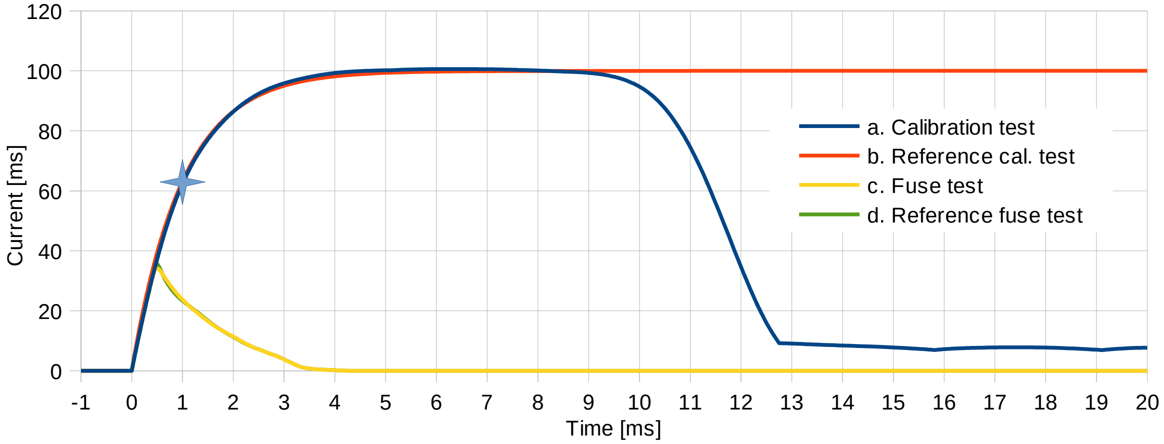

Figure 3. Calibration and fuse link current traces with a capacitor bank add-on setup

IV. CONCLUSION

All possible laboratory setups for DC fuse links for battery applications testing have their strengths and weaknesses. The high-power transformer and rectifier setup (III.A) is generally usable across a variety of other tests, including AC tests, but requires the exchanging of all main parts. Battery system setups (III.B) are the most equivalent source. The demand for a high cell density, BMS, and a single reliable DC switch constitutes a rather unique challenge. The consistently problematic direct joining of capacitors and coils in the capacitor add-on setup (III.C) works well only in a circuit which is exactly tuned and becomes impossible to manage in different real-world environments. A long duration impulse current generator, from the capacitor bank setup (III.D), works surprisingly well, but only until the end of the pulse, as voltage sags appear over a longer duration. The final setup to be investigated (the capacitor bank add-on setup III.E) corrects the recovery voltage and appears, of all the setups with capacitors, to be the most promising – especially in light of the likely additionally demand for a further lowering of the time constant in the future.

Offering shorter time constants for breaking capacity testing of DC fuse links in laboratories will be difficult, but is within reach. As there is no solution in terms of simple equipment reconstruction, the only solution is building new equipment, The uncertainty around whether the desired time constants will stay at the same boundaries as at the present deepens the danger in terms of investment in this area.

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