Understanding the Charger's Contribution to a DC Arc Flash

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Introduction

In a typical DC system with batteries and chargers, a short circuit event will consist of some contribution from both the battery and the charger power sources. Generally, the battery contributes significantly more short circuit current than the charger, and therefore more incident energy into an arc flash. Many engineers seek to include the charger's contribution into the short circuit calculations as well. This paper attempts to give some insight towards understanding the charger's short circuit current. For the sake of clarity, this paper will not examine battery short circuits. The prime factors that influence a charger's short circuit current are the charger's topology, Over Current Protective Device (OCPD), control system dynamics, and the location of the short relative to the charger's output terminals.

Chargers are available on the market in a variety of different topologies. For simplicity, charger topologies will be grouped into four categories; SCR, Ferro, Mag-Amp, and Switch-mode. Among the various manufacturers of chargers, there are certain degrees of design freedom towards attaining a successful product. In other words, different manufacturers of the same topology could have different design approaches to a viable and successful product, which cause the two designs to react differently to a short circuit event. Not all SCR chargers perform the same, not all Ferro's perform the same.

Acceptable Outcomes of a Charger Short Circuit Test

Strictly speaking to a charger's short-circuit performance, there are generally two acceptable scenarios:

1. Activating the OCPD
2. The charger quickly going into electronic current limit; (AKA: Constant Current or CC)

One equipment safety standard that most utility type battery chargers design, test, and list to is [1] UL-1012. As part of the test procedure performed by an NRTL to list to UL-1012, the charger will have to go through a short circuit test. Briefly speaking, a passing short circuit test result would be:

- (Scenario #1) Activation of the DC output OCPD, which needs to be repeated within a short time frame to ensure that the test result is repeatable.
- (Scenario #2) If the OCPD does not activate, and the charger goes into current limit, it is still possible to pass, but you have to wait up to 10 additional hours for the equipment to establish a new thermal equilibrium, and all temperatures must still be acceptable.

For the sake of this paper, only scenarios #1 and #2 will be deemed acceptable outcomes.

Short Circuit Measurement Apparatus

Being able to observe the capacitor discharge and the chargers subsequent short-circuit current in detail requires a fast sampling system such as a digital storage oscilloscope. Some tests were carried out at 2.5M (2.5x10^{6}) Samples per second, or once every 400nSec (400x10^{-9}). The tests at 1.25G Samples (1.25x10^{9}) per sec were found to be gross overkill, and we quickly settled on 1 to 2.5M Samples per second. Equally important, typical hall-effect clamp-on DC sensing probes do not have adequate bandwidth to capture capacitor current. The equipment employed here used high quality low inductance shunt bars with a custom shielded BNC cable connecting to the scope. To minimize the possibility of errant signal reflections, the shunt's Kelvin terminals were source terminated with a 50Ω resistor, the BNC cable itself was 50Ω, and the scope's input was set to 50Ω. To keep the small shunt signal free of interference, the BNC cable was shielded up to the last centimeter before connecting to the shunt. In some of the charger DC short circuit tests, the short was implemented with a 450amp 3-pole AC/DC rated contactor where all 3-poles were connected in parallel. Later, the contactor was replaced by a manually operated 500amp 3-pole molded case circuit breaker because it was found that not all 3 poles of the contactor were closing simultaneously as observable on an oscilloscope. All 3-poles of the molded case circuit breaker were more consistently operating at the same time. The short circuit apparatus used in most test instances, measured about 2mΩ. In most tests, the total round trip wire length between the charger's terminals and the short was kept to 4-feet or less to minimize inductance. The large 300Amp 130V charger required a 6-foot round trip wire length. Where reasonable, multiple conductors were connected in parallel to further reduce the test system's inductance.

The chargers were operating with approximately 10% resistive load at the moment the short circuit was applied to mimic pseudo realistic operating conditions, albeit without a battery connected. My goal was to understand how chargers perform in short circuit, not to test batteries.

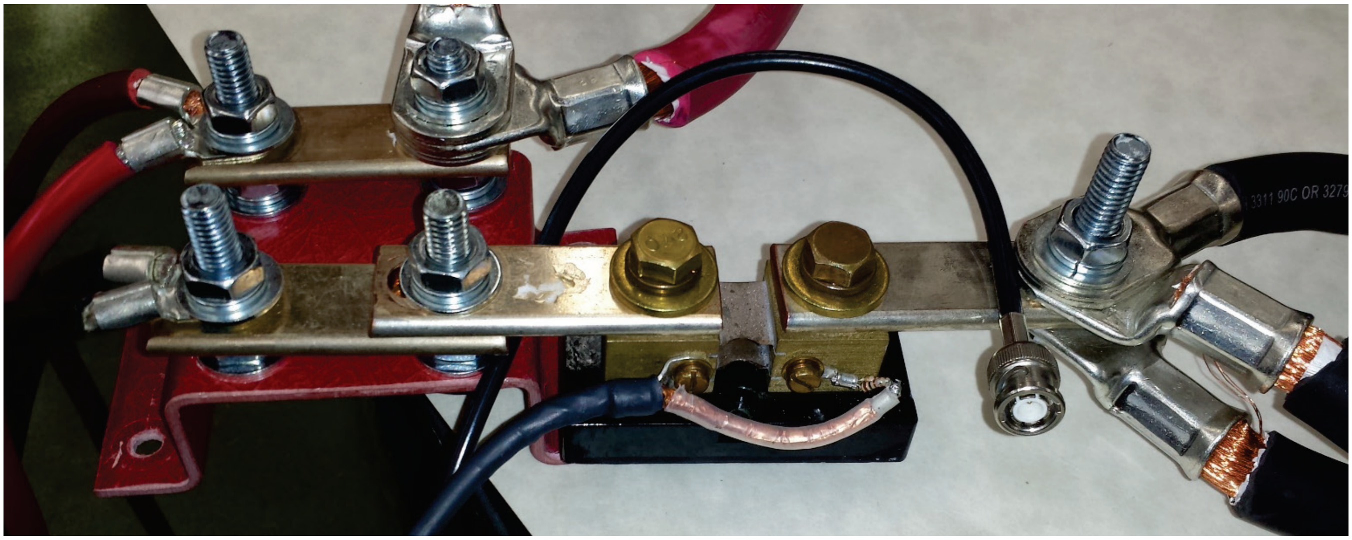


Figure 1. Short circuit test shunt bar with shielded and source terminated BNC cable on the Kelvin terminals

Empirical Short Circuit Testing by Topology

The SCR charger seems rather straightforward to evaluate. An SCR charger utilizes a simple linear power transformer (PT) that has its own impedance. Generally for efficiency, this is a low impedance PT, allowing a large amount of short-circuit current. For an SCR charger, the impedance of the PT for a given model is fixed, and the SCR phase delay is what controls the normal DC power. Among SCR chargers tested, some were "Filtered" and others had a "Battery Eliminator" filter as detailed in [2] NEMA PE 5. In our single phase SCR line, the "Filtered" charger consists of a single stage LC filter, and our Battery Eliminator consists of a 2-stage cascaded LC filter. The filter design mildly impacts the short circuit dynamic performance, but is generally ignored in worst case short circuit calculations. All SCR chargers in this test used the same control board. The single phase chargers were all powered from the same low impedance 240Vac line. All SCR chargers in this test utilized a DC output OCPD with a thermal/magnetic trip unit. The magnetic trip in these breakers are inherently 10x the overload current rating.

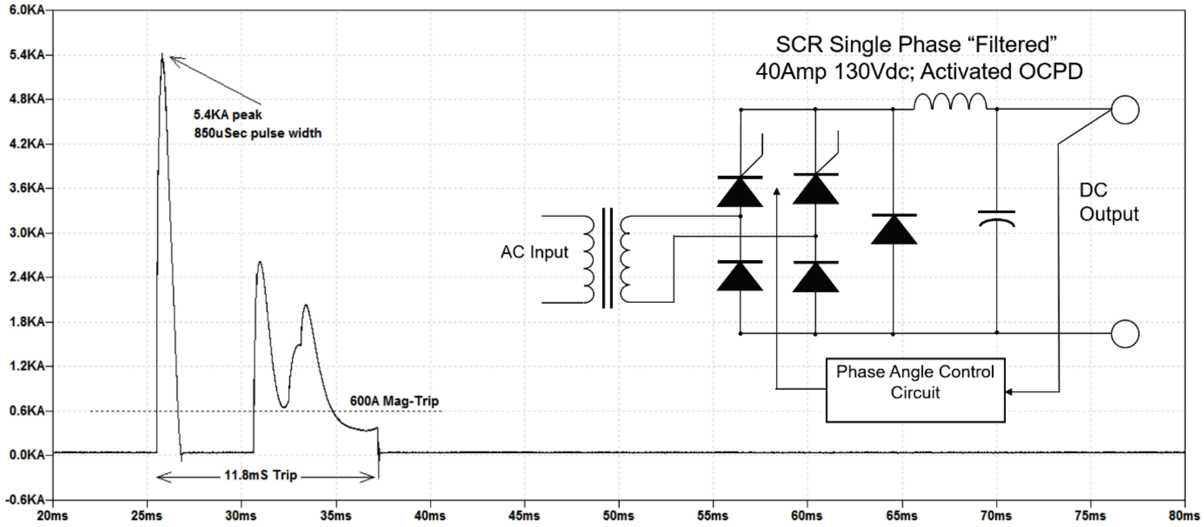


Figure 2. Single Phase Filtered SCR 40Amp 130V; Activated OCPD in 11.8mS

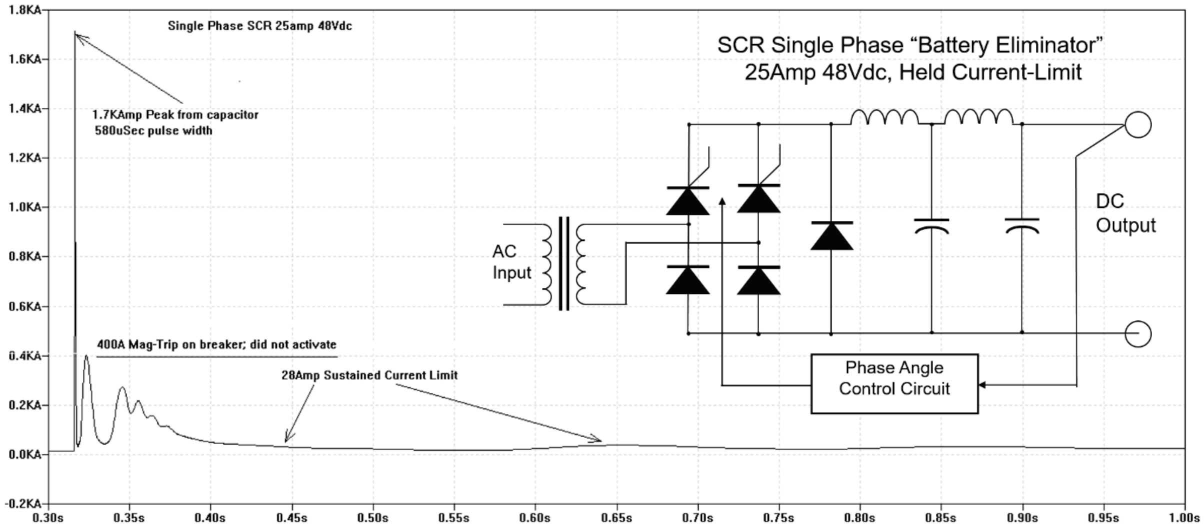


Figure 3. Single Phase Battery Eliminator 25Amp 48V; Held current limit @ 27.5Adc

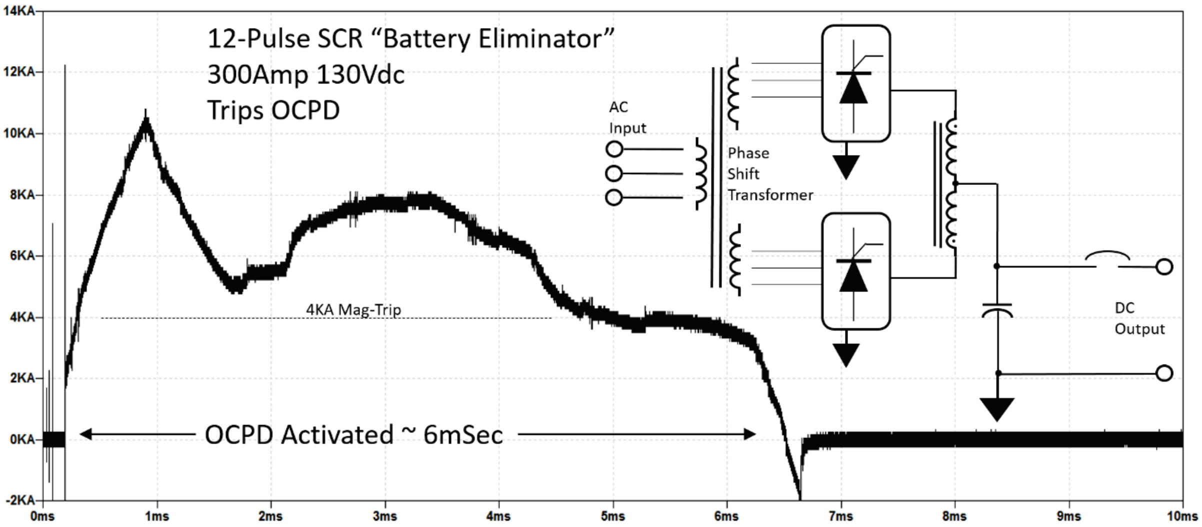


Figure 4. 12-Pulse SCR Battery Eliminator 300Amp 130V, Activates OCPD in ~ 6mSec

Mag-Amp chargers utilize a saturable reactor wired in series with the primary of the power transformer (PT). By operational definition, a saturable reactor is a variable reactor, using the property of variable impedance to control the flow of power to the main transformer's primary. Mag-amps are extremely fault tolerant but don't have a fast load transient response. The control current for the saturable reactor's center coil is derived from the DC bus, and the greater the coil control current, the greater the charger's output. Mag-Amps have a fail-safe should the OCPD fail to activate in a short circuit. Should the charger's OCPD fail to activate in a DC short circuit, there wouldn't be any control current available to drive the center coil, and the primary of the PT will be sourced with the high impedance of an un-driven saturable reactor, naturally limiting the power. In some Mag-Amps, the output current in a short circuit folds-back to less than the normal current-limit set-point. The impedance of a Mag-Amp's transformer system including the saturable reactor is variable with the line and the load. Because the impedance is variable, the short circuit current is very difficult to reasonably estimate.

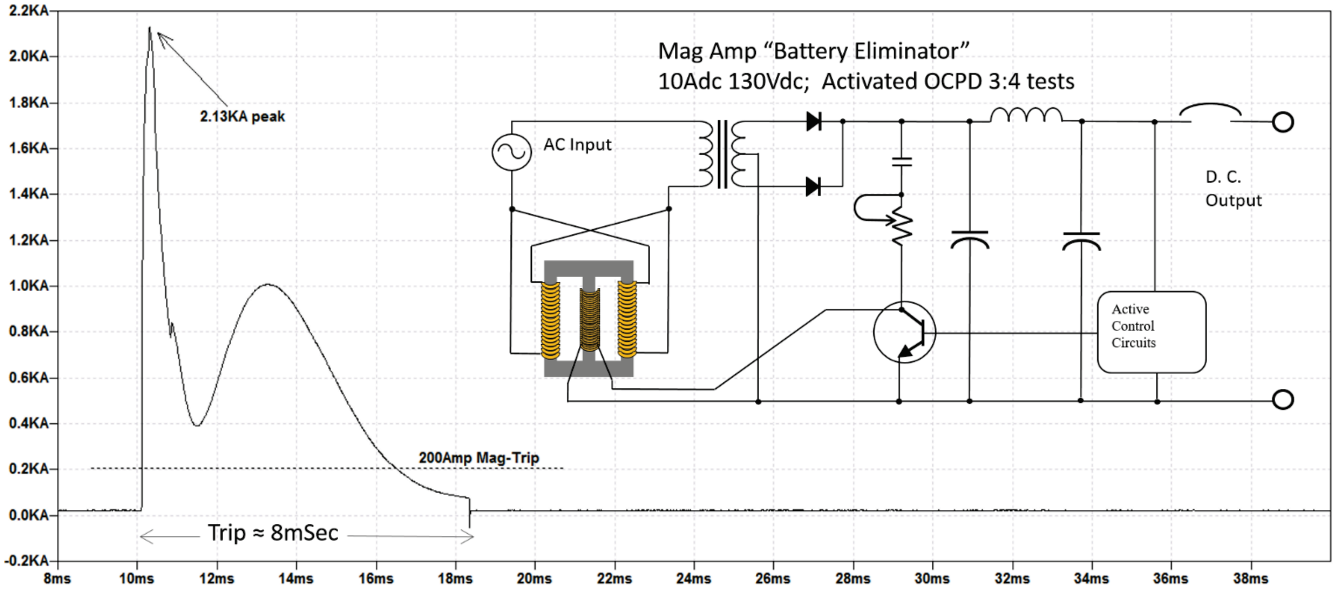


Figure 5. Single Phase Mag-Amp Battery Eliminator 10Amp 130Vdc Activated OCPD 3:4 Tests.

Controlled Ferro-resonant chargers, also known as a "Ferro" are unique. The Ferro regulates the normal DC output by energy transfer from a resonant tank circuit and modified flux linkage within the PT to the output circuit. The primary of the Ferro PT operates linearly, but the secondary flux is typically operated in saturation facilitated by magnetic shunts separating primary and secondary fields. Generally, the impedance of the Ferro circuit is variable in order to regulate the normal DC output. Some dynamic current may be sourced by the resonant tank circuit into the load. Because the impedance is variable, the short circuit current potential of the PT is very difficult to reasonably estimate.

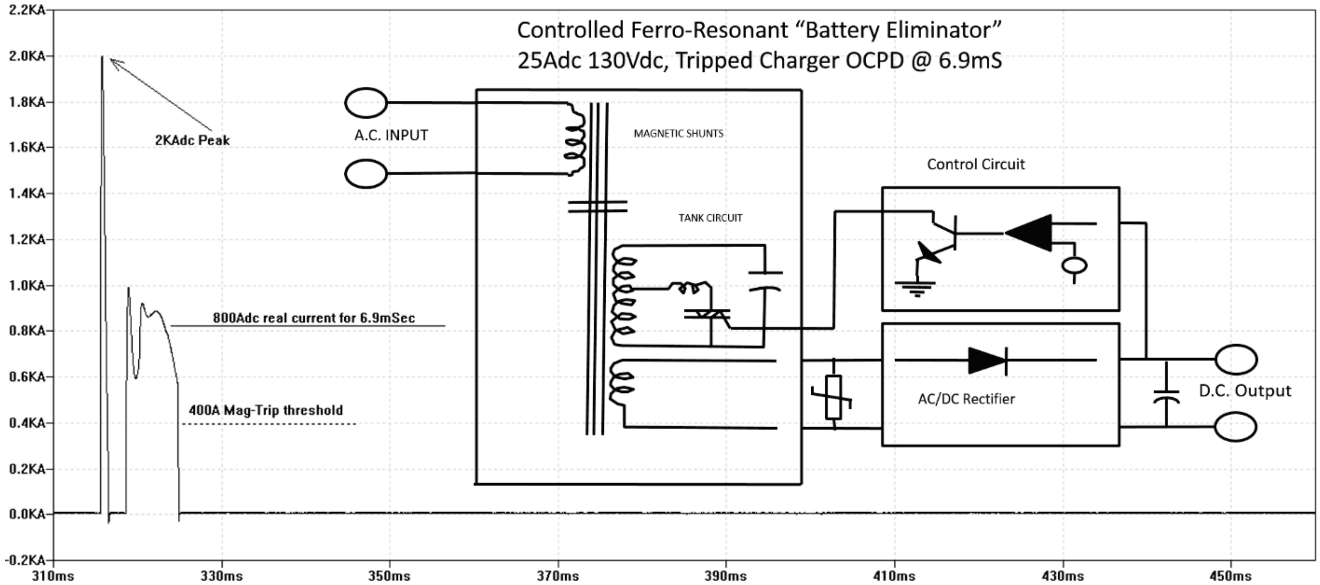


Figure 6. Single Phase Ferro 25Adc 130V, Activated OCPD @ 6.9mS

Switch-mode high frequency chargers actually branch into more topologies than we can practically cover. Generally, the switch-mode charger is implemented in two major internal stages, each with its own control loop. The first stage is normally a boost type Power Factor Corrector (PFC) to maximize available power from the line, and to control lower frequency harmonics. The PFC will normally regulate to a voltage slightly above the peak of the line voltage, often 390Vdc for a 240Vac input. The second stage will take the high output voltage from the PFC, switch at high frequency, stepping it down through an isolating transformer to the output rectifier with a small filter capacitor. The output stage will often have a fast load transient response. Generally, the boost PFC and the output stage from various manufacturers operate at frequencies ranging from 50KHz to 500KHz. Often the control loops employed on these topologies will utilize current mode control having cycle-by-cycle (at high frequency) current limiting. Due to cycle-by-cycle current limiting, and multiple cascaded power stages, estimating the short circuit current of a switch-mode charger by transformer impedance is not practical. Switch-mode short circuit test results may vary in-between manufacturers. When current mode control is implemented, there could easily be 200,000 times per second to catch the short circuit and limit the observed fault current.

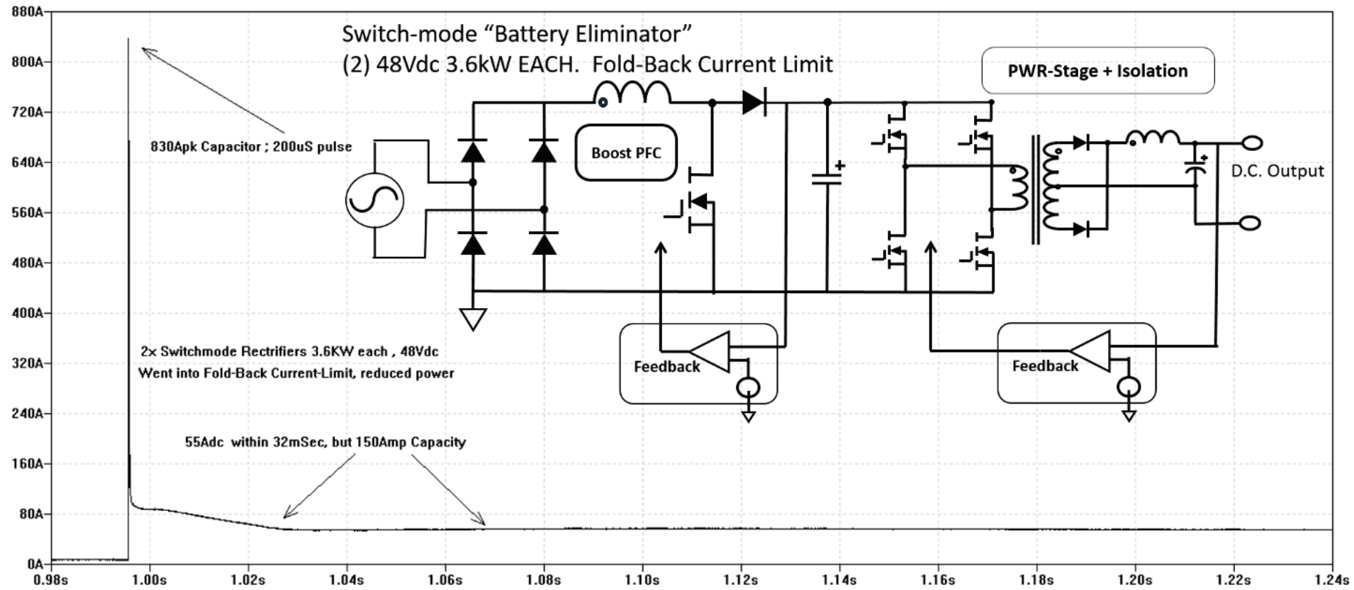


Figure 7. Switch-Mode Battery Eliminator 48Vdc 3.6KW each, 2-parallel; Fold-back current-limit reducing short-circuit power

When any one of these four charger topologies are subjected to a short circuit, there is a race against time for one of two things to happen; activate the charger's OCPD, or the control will put the charger into current limit. Which is faster, the current-limit, or the OCPD? A basic thermal overload circuit breaker will not interrupt a short circuit as quickly as a dual element thermal/magnetic circuit breaker, but even the "instantaneous" magnetic circuit breakers are not so fast or consistent.

Charger Short-Circuit Tested:	Charger		Filter specification to NEMA PE5	Internal OCPD		Current Limit	Cap Joules	Cap Pk Current	Repeatable Short-CKT Test Result:
	Vdc	Adc		Thermal	Magnetic				
SCR 3-phase 12-Pulse	125	300	Battery Eliminator	400amp	4000amp	330Adc	2281.5	16KA	Trip OCPD
SCR single-phase	125	40	Filtered	60amp	600amp	44Adc	507.0	5.4KA	Trip OCPD
SCR single-phase	48	25	Battery Eliminator	40amp	400amp	27.5Adc	53.9	1.7KA	Current-Limit
Ferro single-phase	125	25	Battery Eliminator	40amp	400amp	27.5Adc	760.5	2KA	Trip OCPD
Mag-Amp Single Phase	125	10	Battery Eliminator	20amp	200amp	12Adc	278.9	2.13KA	3:4 times Trip OCPD
Switch-mode (2-parallel)	48	75x2	Battery Eliminator	100Amp Fuse		75Adc	2.9	400A	Current-Limit Fold-back

Table 1. Charger topology test result summary

Modeling the Charger's Short Circuit Current

In all four of the represented topologies, it is popular to use "filtered" or "battery eliminator filtered" chargers whose ripple performance is outlined in [2] NEMA PE 5. All these topologies will incorporate capacitors on the output circuit that can produce a substantial amount of current for a quick duration. As you can see, even small chargers have capacitors capable of producing a few kilo-amps of peak current. The pulse current duration is short lived because there are only so many Joules stored in a capacitor. As noted in [3] IEEE 946 and duplicated in our own testing, the high peak current delivered from a filter capacitor is frequently too quick to activate the magnetic trip element of most circuit breakers. Occasionally, we have enough Joules stored in the capacitor to invoke activation of the OCPD. The actual peak current from a capacitor is practically limited by the wiring impedance between the capacitor itself to the short circuit to much less than the theoretical peak output current. The "ΔT" portion of the equation is generally in the µSec range for succinct wiring, but can extend into mSec for some ratios of L/R. The total amount of energy the capacitor will put into a short in Joules is exponentially related to the DC bus voltage.

$$I_{Cap} = C\left(\frac{\Delta V}{\Delta T}\right) \qquad Joule_{Cap} = \frac{1}{2}(CV^2)$$

Nominal system voltage	Joules Stored in 30,000µF
12Vdc	2.16
24Vdc	8.64
48Vdc	34.56
125Vdc	234.375
250Vdc	937.5

Table 2. Shows Joule storage increases for system voltage

Modeling the basic rectifier transformer requires insight into the design. After the initial wave front of the capacitor, the "real" current is sourced by the rectifier transformer through the rectifying circuit. The transformer impedance will be used to estimate a "worst case" DC Bolted short circuit current without counting the electronic current limit, or OCPD operation.

The DC short-circuit current of the charger with defective current limit and defective OCPD *would be* significantly higher than the charger's normal operation. The typical transformer used for galvanic isolation and voltage transformation within a charger provides some inherent current limiting. Generally, an SCR charger will use a low impedance transformer for efficiency. Ferro and Mag-Amp inherently have more impedance in the total circuit and generally limit short circuit current a bit more. The DC inductor part of the filter circuit is generally not modeled when the current limit and the OCPD has failed to operate because the current would be high enough to saturate the core, dropping the reactive impedance to the wire resistance. Of all the approaches I have reviewed to model the DC short circuit current of a rectified transformer, I gravitate to the one outlined by [4] Johannes Schaeffer circa 1965 in "Rectifier Circuits: Theory and Design". Essentially, the DC filter is ignored, and the short circuit path is treated as a true 0Ω "Bolted short" across the rectifier diodes. Since in a full bridge, the rectifier diodes normally allow the secondary current to flow in both directions, the transformer impedance is common to both current directions and the prospective DC short circuit. When the DC is shorted, the current is limited by the transformer impedance perceived at the secondary. From the winding voltage, and the impedance, you can estimate a worst case bolted short circuit current that is very conservative. For brevity, we are going to skip over the transient current and get right to the maximum worst case current. Real life DC fault currents would be less than this calculated worst case DC bolted short circuit current due to:

A. Wiring impedance between the fault and the transformer, including wiring within the charger's enclosure.

B. Some residual impedance of a DC filter inductor.

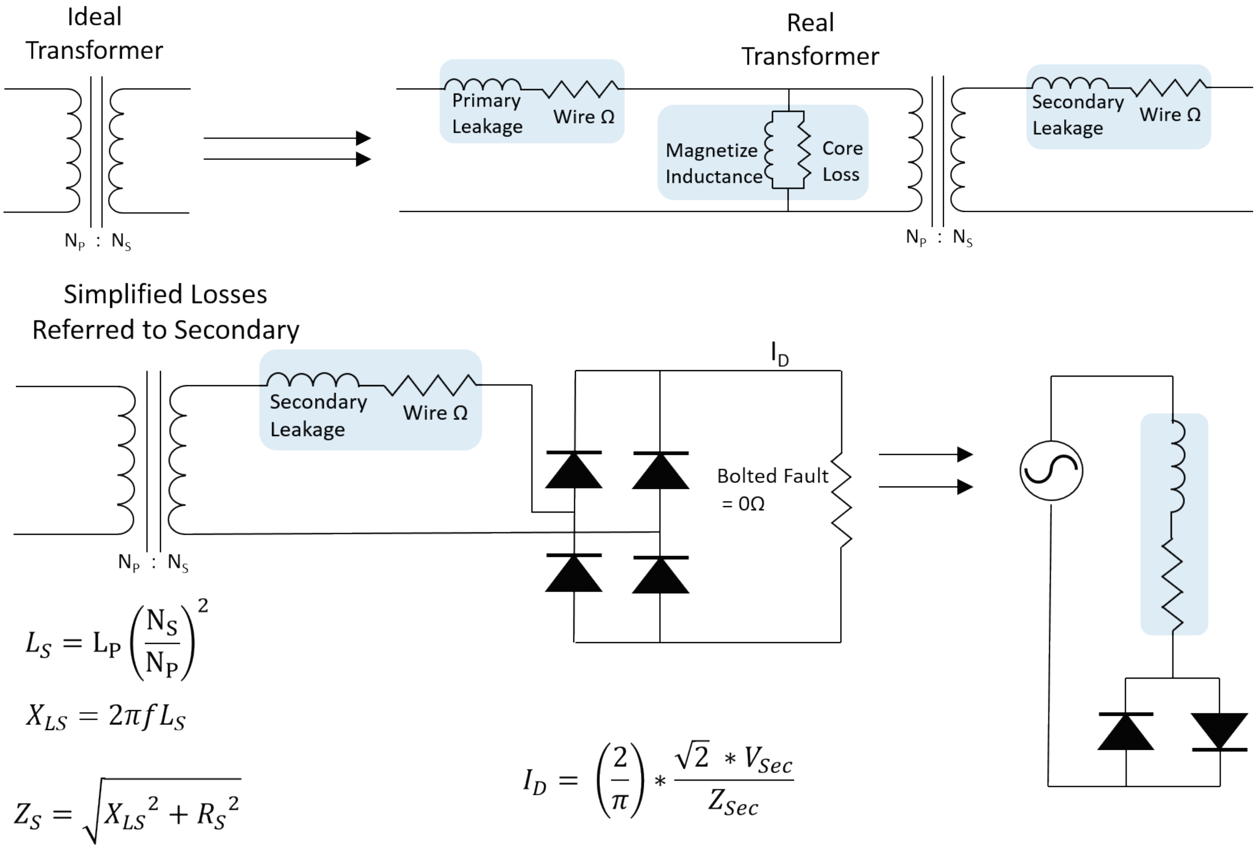
C. Preceding impedance of the source feeding the primary of the charger's transformer

D. Phase-delay in an SCR charger, quiescent operating mode of the Mag-Amp and Ferro

E. Fast operation of the control loop putting the charger into current-limit

F. Activation of the DC output OCPD

G. Activation of the AC input OCPD



$$L_S = \mathrm{L_P}\left(\frac{\mathrm{N_S}}{\mathrm{N_P}}\right)^2$$

$$X_{LS} = 2\pi f L_S$$

$$Z_S = \sqrt{{X_{LS}}^2 + {R_S}^2}$$

$$I_D = \left(\frac{2}{\pi}\right) * \frac{\sqrt{2} * V_{Sec}}{Z_{Sec}}$$

Figure 8. Method to estimate transformer impedance for worst case DC short circuit current

At this point in the design stage, one could look up the time/current curve for the charger's OCPD and make a rough guess as to whether the device will activate or not. The determination of OCPD activation or not should be further refined by transient analysis neglected here to incorporate the "build-up" time of the fault current when more circuit inductances are considered.

The single phase SCR charger rated 130Vdc @ 40Adc had a calculated DC short circuit current of 2.4KA, but in practice with a quiescent SCR phase delay, and all the other non-incorporated inductances, the measured short circuit was closer to 1.2KA. As indicated above, the DC OCPD did activate. The reason the OCPD activated as opposed to current limit, was that in this instance, the OCPD was faster than the control loop correction. By tweaking the closed loop control coefficients in this charger, we were able to tune the control to beat the OCPD, and it now can operate in current limit upon a sudden short circuit. Same charger, same circuit board, simply tweaking a parameter changed the short circuit behavior of the charger.

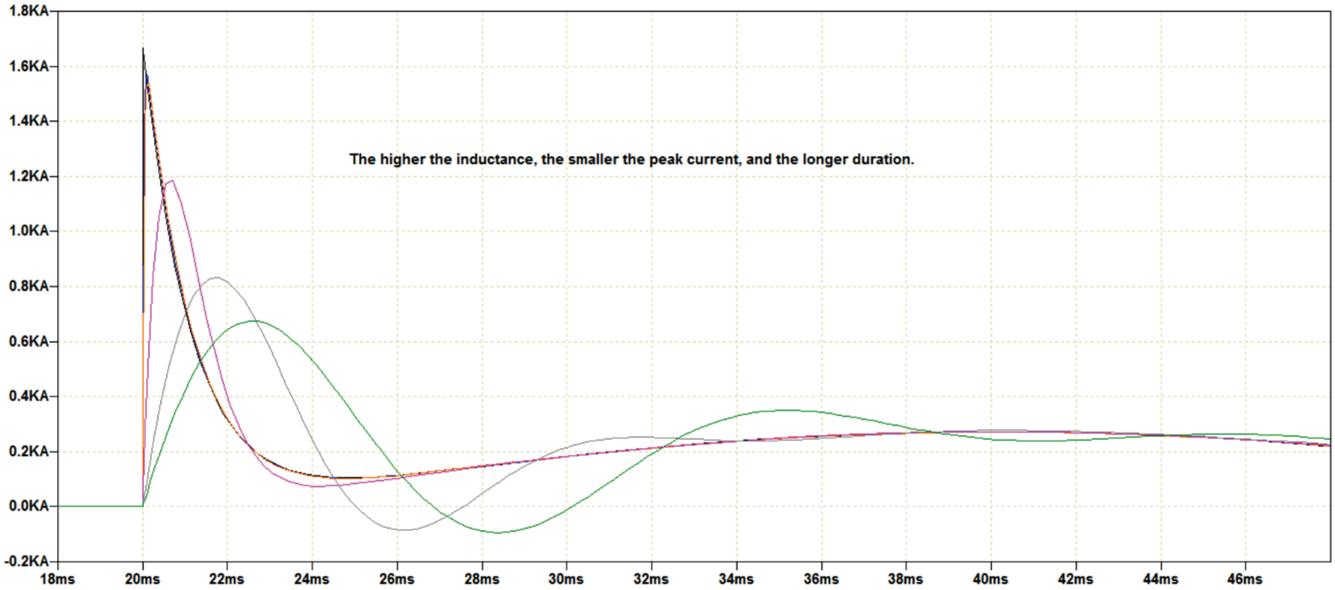


Figure 8. Plot of a fault current with different wire lengths. The greater the inductance, the lower the peak current, and the greater time integral.

Estimating the Charger's Arc Flash Incident Energy

A battery charger is a bit different in terms of incident energy calculations than a battery, transformer, or generator. Historically analyzed sources such as batteries, transformers, and generators are low impedance voltage sources, capable of very large short circuit currents. Engineers have more practice evaluating these traditional sources for arc flash incident energy. They can and often should be equipped with an OCPD electrically close to the source to help protect the distribution wiring from short circuit faults, and lower the arc flash incident energy

A typical battery charger for stationary applications is a current limited constant potential design. Under normal conditions, the charger supports the constant loads of the DC system with the battery at full charge. The float voltage is chosen to counteract the self-discharge of the battery, keeping it at full charge. Clearly the charger regulates voltage as it is held constant between no load and full rated load. In fact, gain in the feedback loop of a charger greatly reduces the constant voltage output impedance. However, when the battery has been discharged well below the float voltage of the charger such as in an extended power outage, the battery voltage will more or less be dictated by the state of charge. When the battery is at a low charge level, the charger will operate in current limit, which is a constant current source. A current source is very high impedance. Chargers are unique from batteries and transformers, in that a charger intentionally operates as either a constant voltage source or as a constant current source based on the demands of the DC system. The control modes of CC or CV can be implemented in hardware or in software.

As indicated in the short circuit test results above, some chargers will activate the OCPD, while others will continue operating in current limit. Rather than guessing which short circuit scenario is represented by your charger, or slugging through calculating a unique topology, I would suggest to consult the charger manufacturer to obtain the short circuit performance data.

Arc flash calculations should be calculated in the worst case scenario.

- A voltage source (low impedance) can be modeled by the Thevenin Equivalent Circuit where "looking-in" from the output terminals yields an ideal voltage source in series with the internal resistance.
- A current source (high impedance) can be modeled by the Norton Equivalent Circuit, where "looking-in" from the output terminals yields an ideal current source in parallel with the internal resistance.

For any given voltage source or current source, the maximum power delivered to the load occurs when the load impedance observed by the terminals is equal to the source impedance. The wire resistance to the fault and the arcing resistance are effectively in series as observed by the terminals of the voltage or current source. Since we are after the worst case scenario, arc flash should be calculated at an operating point which delivers maximum power into the fault. This approach simplifies the analysis.

For either Voltage Source or Current Source, maximum power is
delivered to the load when the load = the source impedance.
The Load = Wire + Arc impedance

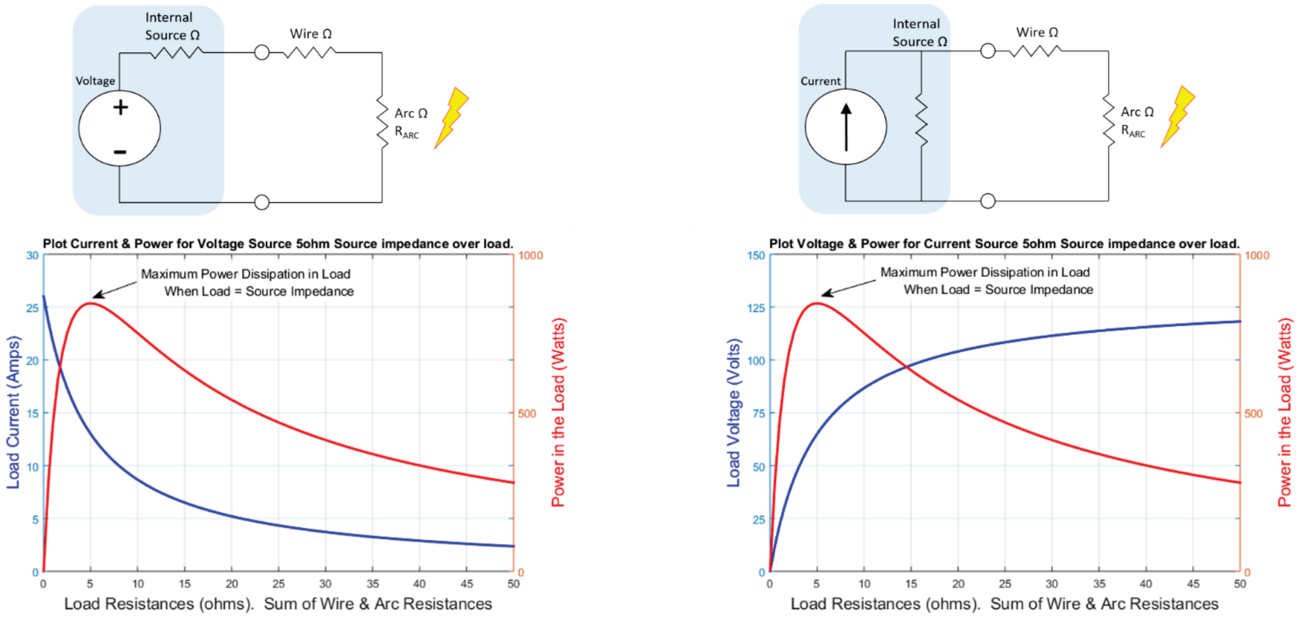


Figure 10. Maximum Power Operating Point for voltage source or a current source.

For the sake of this paper, I only want to solve for the worst case arc flash incident energy. Energy in calories is directly related to Joules and Watts. By only evaluating arc flash incident energy at the maximum power point of the given source, all permutations or possible wire length and or arc flash gap distance and associated convergence can be eliminated. Arc Flash calculations used herein referenced [5], [6], and [7].

Description	Variable Name and/or formula	SCR-40A-130V	Original Calc SCR-25A-48V
Charger Current Limit Ampacity	A_{CL}	44	27.5
Nominal DC system voltage = Vdc	V_{SYS}	130	54
Current Source Impedace	$Norton_{ResCC} = \frac{V_{SYS}}{A_{CL}}$	2.9545	1.9636
Breaker Therm/Magnetic trip	Fuse	60/600	40/400
Fuse time from Current/Time charts against I_{DSC}. If unknown, use 2-seconds	T_{ARC}	0.012	2
Typical working distance 18-inches	Working_Inch	18	18
Working Distance in CM	$D = Working_{Inch} * 2.54$	45.72	45.72
Bolted DC Short Circuit Current	$I_{DSC} = \left(\frac{2}{\pi}\right) * \frac{\sqrt{2} * V_{Sec}}{Z_{Sec}}$	2,436.90	3,627.00
Calculates Thevenin Resistance of source	$R_{SYS} = \frac{V_{SYS}}{I_{DSC}}$	0.053	0.015
Maximum Power Theorum current from Volt Source	$I_{ARC} = \frac{V_{SYS}}{2 * R_{SYS}}$	1,218.45	1,813.50
Maximum Power Theorum	$P_{MAX} = \frac{\left(\frac{V_{SYS}}{2}^{2}\right)}{R_{SYS}}$	79,199.25	48,964.46
Total arc energy in Joules	$E_{MaxJ} = P_{MAX} * T_{ARC}$	950.39	97,928.91
Total arc energy in Calories	$E_{MAXcal} = E_{MaxJ} * 2.3885$	227.00	23,390.32
Resultant Incident Energy in calories/cm^2	$IE_{MaxCal} = \frac{(0.01 * V_{Sys} * I_{ARC} * T_{ARC})}{D^2}$	0.009	0.937

Table 3. Arc Flash Calculations for 2 charger sizes

The 40Amp 130Vdc charger with a fast acting 12mSec OCPD resulted in a very small arc flash incident energy of 0.009 calories/CM^2. When the charger activates the OCPD, the calculations seem strait forward and simple enough. How did the smaller SCR charger 25Amp 48Vdc end up with more than 100x the Incident Energy of the larger 40Amp 130Vdc charger?

1. The smaller charger did not trip the OCPD, it operates in current limit 27.5Adc; Scenario #2.
2. The Incident energy calculation and preceding calculations assume the fault current is 3,627Amps, and not the 27.5Amps of current limit.
3. The transformer in the 25A-48V charger actually had a lower impedance percentage; albeit a lower power rating.
4. When the OCPD does not operate, the term T_{ARC} needs to extend to a whole 2-seconds.
5. We need to modify the calculation method to accommodate a charger operating in as a high impedance current source, the current limit mode.

Description	Original Calc SCR-25A-48V	Revised Calculation for Scenario#2 charger short circuit = Current limit	Revised Calc SCR-25-48V
Charger Current Limit Ampacity	27.5	A_{CL}	27.5
Nominal DC system voltage = Vdc	54	V_{SYS}	54
Current Source Impedace	1.9636	$Norton_{ResCC} = \frac{V_{SYS}}{A_{CL}}$	1.9636
Breaker Therm/Magnetic trip	40/400	Fuse	40/400
Fuse time from Current/Time charts against I_{DSC}. If unknown, use 2-seconds	2	T_{ARC}	2
Typical working distance 18-inches	18	Working_Inch	18
Working Distance in CM	45.72	$D = Working_{Inch} * 2.54$	45.72
Bolted DC Short Circuit Current	3,627.00	When Bolted DC current is the current limit, use the current limit	27.50
Calculates Thevenin Resistance of source	0.015	$Norton_{ResCC} = \frac{V_{SYS}}{A_{CL}}$	1.964
Maximum Power Theorum current from Volt Source	1,813.50	$V_{Arc} = I_{DSC} * \frac{R_{SYS}}{2}$	27.00
Maximum Power Theorum	48,964.46	$P_{MAX} = \frac{\left(\frac{{V_{SYS}}^{2}}{2}\right)}{R_{SYS}}$	371.25
Total arc energy in Joules	97,928.91	$E_{MaxJ} = P_{MAX} * T_{ARC}$	742.50
Total arc energy in Calories	23,390.32	$E_{MAXcal} = E_{MaxJ} * 2.3885$	177.35
Resultant Incident Energy in calories/cm^2	0.937	$IE_{MaxCal} = \frac{(0.005*({A_{CL}}^{2}*R_{SYS})*T_{Arc})}{D^2}$	0.007

Table 4. Arc flash calculation compares Original vs. Revised calculation for a charger that current limits upon short circuit.

The final result of 0.007cal/cm^2 is more realistic for the 25Amp 48V charger operating in current limit, as opposed to 0.937cal/cm^2 using half the transformer's theoretical bolted short circuit current.

Closing

The charger's short circuit performance clearly has a lot of variables.

- The timing of control circuits vs. OCPD largely dictates if the charger's OCPD will activate, or if the charger goes into current limit when subjected to a short circuit for low impedance transformer designs.
- The transformer impedance method doesn't work well in Ferro and Mag-Amp designs, and the switch-mode is quite complicated to evaluate.
- In short, some chargers will enter current limit, and others will trip the charger's OCPD.
- Tripping the OCPD is the safest method in an arc flash because it removes the charger as a contributing source of incident energy, but the ability to activate the OCPD can be hindered by large wire inductance between the short and the power source.
- Arc flash calculations need to be adjusted for a charger operating as a high impedance current source, AKA; current limit.
- Consult the charger manufacturer for specific test results on short circuit performance.

- No industry standards exist today which mandate that the charger should activate the OCPD as opposed to operating in current limit.
- Practical wiring inductance will limit fault current and may prevent the OCPD from operating as expected.

Glossary

Bolted Short Circuit A short circuit created with both nearly zero resistance, and nearly zero inductance for a near zero impedance. A bolted short circuit is considered to have such low impedance that the apparatus to create the short circuit can totally be ignored in calculations.

Calorie Unit of energy, generally in terms of energy and time. 1 Calorie/Second = 4.1868 watts.

ESR Equivalent Series Resistance. This is the internal resistance of a capacitor between the ideal electrostatic elements, and the accessible connection terminals of the capacitor.

Joule Unit of instantaneous energy. 1 Joule = 1V*1A. 1 Joule sustained for 1 second = 1 watt.

NRTL Nationally Recognized Testing Lab. An NRTL is a United States Occupational Safety and Health Administration (OSHA) designation given to testing facilities that provide product safety testing and certification services to manufacturers. An NRTL may be an independent lab, or could be UL themselves that perform required product safety testing to a particular standard such as UL-1012.

OCPD Over Current Protective Device. An OCPD is generally a molded case circuit breaker or a fuse. For convenience to the end user, it is popular to use a molded case circuit breaker in the design of stationary utility type battery charger.

UL Underwriters Laboratory. UL is an NRTL that creates, maintains, tests, and enforces equipment safety standards.

Watt Unit of work in terms of energy and time. 1 watt = 1 Joule sustained for 1 second.
1 watt = 0.23885 Calories. 1 watt = 1000 Joules*0.001 Seconds.

References

[1] UL 1012 Standard for Power Units Other Than Class 2

[2] NEMA PE 5 (2003) National Electrical Manufacturers Association Standard for Utility Type Battery Chargers.

[3] *Recommended Practice for the Design of DC Auxiliary Power Systems* IEEE 946-2004

[4] "Rectifier Circuits: Theory and Design", Shaffer Published 1965 John Wiley and Sons, Inc.

[5] Daniel R. Doan. "Arc Flash Calculations for Exposures to DC Systems" IEEE *Transactions on Industry Applications.* VOL 46 No.6, Nov. /Dec. 2010.

[6] NFPA 70E 2015: Standard For Electrical Safety in the Workplace

[7] A. Gattozzi, J.D. Herbst, A. Kwasinski, R. Hebner, et al. "A DC Arc Model for Series Faults in Low Voltage Microgrids" *IEEE Transactions on Start Grid*, Dec. 2012