FUSE PROTECTION OF DC SYSTEMS

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INTRODUCTION

Selecting a fuse that will provide the required protection for a direct current (DC) application is not as simple as it may sound. Alternating current (AC) circuits are more common than DC circuits; therefore, more is known about how electrical components, including overcurrent protective devices, operate on AC than is known about their operation on DC. The concept of DC is so simple that there is a tendency to assume that choosing overcurrent protection for DC applications is also simple. This is not the case.

To correctly select a fuse for a DC application, the DC capabilities of the fuse must be known as well as the critical circuit parameters and the overcurrent conditions under which the fuse is expected to operate. Most fuse data relates directly to AC applications not DC. Furthermore, DC circuit parameters vary widely from application to application and affect fuse performance significantly. Representing fuse performance for the large envelope of DC circuit parameters is not realistic. Some AC data can be correctly used for DC once there is a thorough understanding of what this data represents.

The intent of this paper is to give the reader a better understanding of DC capabilities of fuses and the critical DC circuit parameters that must be known to select appropriate fuses for DC applications. The tools presented may be directly applied to real life situations and include step by step examples.

DEFINITIONS AND RATINGS

There are terms associated with fuses to define before discussion of fuse application on DC circuits can be meaningful:

Fuse - An overcurrent protective device containing a calibrated current carrying member which melts and opens a circuit under specified overcurrent conditions.

Current Limiting Fuse - A fuse which will limit both the magnitude and duration of current flow under short circuit conditions.

Time Delay Fuse - A fuse which will carry a specified overcurrent for a minimum specified time with out opening.

Element (link) - the calibrated conductor in a fuse which melts when subjected to excessive current

Contacts - The external live parts of the fuse which provide continuity between the fuse and the balance of the circuit. Also referred to as ferrules, blades or terminals.

Ampere Rating - The continuous current carrying capacity of a fuse under defined test conditions.

Voltage Rating - Maximum voltage at which a fuse is designed to operate. Marked voltage ratings are assumed to be AC unless specifically labeled as DC. Note: For DC systems, the nominal voltage is usually given. The maximum system voltage must be known to properly select a fuse.

Interrupting Rating (IR.) - The maximum tested current a fuse can safely interrupt.

Minimum Interrupting Rating - The minimum current the fuse can safely interrupt.

Overcurrent - Any current in excess of rated conductor or component ampacity.

Overload - The operation of a system at a current level that will cause damage if allowed to persist.

Short Circuit - Excessive current flow caused by insulation breakdown or wiring error.

Fault current - Current flowing in a current path bypassing the connected load usually due to an accidental condition or component failure.

I^2t - A measure of the thermal energy associated with current flow. By definition $(I_{rms})^2$ X t, where t is the duration of current flow in seconds. Units are ampere squared seconds.

Clearing I^2t - the total I^2t passed by a fuse as the fuse clears a fault. The clearing I^2t is voltage dependent.

Melting I^2t - The minimum I^2t required to melt the fuse element.

Peak Let-Thru Current - The maximum instantaneous current passed by a current limiting fuse when clearing a fault current of specified magnitude.

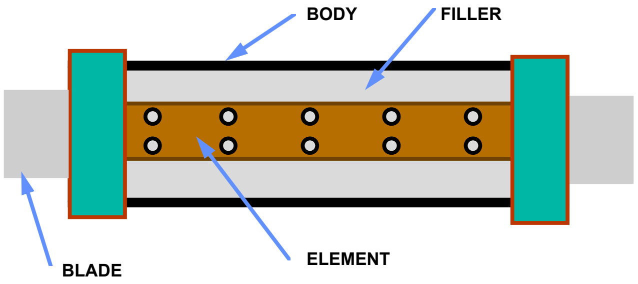
Coordination - The proper selection of series connected overcurrent protective devices which will isolate only that portion of an electrical system which has been overloaded or faulted.

Selectivity - Series connected fuses are said to be selective if the downstream fuse will clear all potential overcurrent conditions before the upstream fuse opens or is damaged.

The ratings shown on the fuse are AC ratings unless specifically marked as DC ratings. The DC capability of a fuse will be specified in the fuse manufacturers literature or can be obtained directly for the fuse manufacturer.

FUSE CONSTRUCTION AND OPERATION

A typical fuse consists of one or more elements enclosed by a fuse body and typically surrounded by an arc quenching medium such as silica sand commonly called filler. The elements are either welded or soldered to the fuse contacts. The diagram below depicts a typical fuse.



The fuse is a calibrated current carrying device designed to open under specific conditions. In the diagram above, note the reduced cross-section areas in the element, also called notches. Heat is generated by the element at a rate dependent upon the element resistance and load current. Effective heat transfer is provided by the filler which conducts the heat away from the element, through the fuse body and to the medium surrounding the fuse. The filler aids fuse performance by absorbing arc energy when the fuse clears an overload or short circuit.

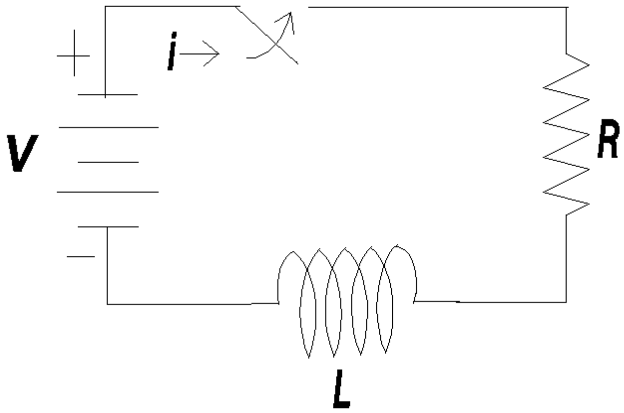
Under normal circuit operation, the fuse carries current. The element material, mass and notch configuration, along with the surrounding materials, all contribute to the fuse performance.

When a sustained overcurrent occurs, the element generates heat at a faster rate than the filler can conduct it away from the element. If the overcurrent persists, the element will reach its melting point at the notches and open. The larger the overcurrent, the faster the element melts: therefore, fuses have an inverse time current characteristic, which is desirable to protect conductors and electrical equipment.

DC STEADY STATE VERSUS DC TRANSIENT CONDITIONS

Whenever electricity is taught, steady state DC circuits are covered first because the concept is simple. In steady state DC systems, inductors become conductors with no resistance and capacitors become open circuits; therefore, the only circuit component that must be dealt with is resistance.

Unfortunately, when an overcurrent protective device is called upon to operate, the DC circuit is in a transient condition not steady state. Typically the only academic exposure given to DC transient conditions is when a switch is closed on a DC circuit having inductance and/or capacitance. A review of a simple circuit consisting of a voltage source, a resistor and an inductor will introduce us to some of the important DC transient concepts.



When the switch is closed on the above circuit, the instantaneous current, as a function of the short circuit current is given by:

Eq. 1 $I_{inst} = I_{sc}\,(1-e^{-n})$

where I_{inst} = Instantaneous current (amp)
I_{sc} = Short circuit current (amp)
n = number of time constants (tc)
tc = time constant = L/R (sec)

By definition, after one time constant the instantaneous current will have risen to 63 % of the maximum available current with rated voltage applied. In other words, the time constant gives us a measure of how much time it takes for the current to rise to maximum level.

As discussed earlier, fuses operate when the element melts; therefore, the heating effect of the current must be considered. The heating effect of current is given by the Root Mean Square (RMS) value of current. The mathematical definition of RMS current is given by:

Eq. 2 $I_{rms} = \left({}^{1}/_{T} \int_{0}^{T} i^{2}(t)\, dt \right)^{1/2}$

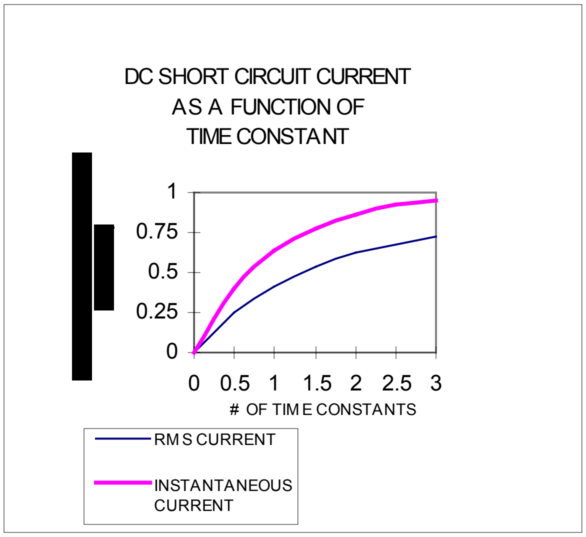
where:
T = time period over which we integrate
I_{rms} = RMS or heating effect of the current

By substituting I_{inst} of equation 1 as i(t) into equation 2 and letting T = the number of time constants, then integrating we get:

Eq. 3 $$I_{rms} = I_{sc} \left(1 + 2e^{-n}/n - e^{-2n}/2n - 1.5/n \right)^{1/2}$$

Equation 3 gives the heating effect of the current under transient conditions. Since the fuse is an RMS current sensing device, this is the current that causes fuse operation. Figure 1 below, illustrates the instantaneous and RMS current of a DC short-circuit in relation to the number of time constants. This chart will be used later to determine melting time current curves and the let thru characteristics of fuses when operating on DC circuits.

FIGURE 1



AC VERSUS DC OPERATION

It is true that some AC fuses are also suitable for DC circuit operation; however, testing is the only sure way to determine the DC voltage capability of a particular AC fuse. There is no “rule of thumb” that safely converts an AC voltage rating on a fuse to a DC voltage rating. To ensure a fuse will safely interrupt a DC circuit, the fuse must have been tested using circuit parameters representing the specific application. The key question is how much DC capability does an AC rated fuse have?

On a 60 Hertz, AC system, the current crosses zero 120 times per second. This natural zero crossing helps the fuse extinguish any residual arcing that occurs after the element melts. There is no natural zero crossing on DC circuits; therefore, the fuse must be capable of absorbing and extinguishing all of the energy in the DC arc.

The circuit time constant varies with circuit inductance and gives a measure of how fast the current can rise to a maximum and how fast the current can be forced back to zero. The time constant to be concerned with for DC applications is the inductive time constant, which is the inductance(Henries) divided by the resistance (ohms) or L/R in seconds. For a given short circuit, the longer the time constant, the longer it will take for the current to rise, the fuse element to melt and the more time to store energy in the circuit inductance; therefore, there will be more energy stored in the system. The fuse must be able to absorb the increased arc energy.

A comparison of how fast the current can rise to a maximum for AC and DC circuits will demonstrate the effect time constant has on DC applications. First, consider an AC short circuit. When a fault occurs on a 60 Hz., AC system, the current will reach its maximum value in 1/4 to 1/2 cycle or 4.17 to 8.33 mS, depending on the system power factor and where on the voltage wave the fault actually occurs. If the fault current is large enough so the fuse is operating in its current limiting range, the fuse will melt before the circuit reaches the maximum fault level. In other words, the fuse will melt in less than 1/4 to 1/2 cycle.

On a DC short circuit, the current will reach its maximum instantaneous value in approximately five time constants, shown in equation 1. A circuit with a 10 mS time constant, will reach its maximum instantaneous value in 50 mS, or 6 to 12 times longer than for the AC circuit. If the system has a circuit time constant of 100 mS, it will take 500 mS to reach the maximum instantaneous current, or 60 to 120 times longer than for the AC circuit. The RMS current is also affected by the time constant as shown in equation 3. Depending on the time constant and the level of fault current, the fuse may or may not melt before the circuit reaches its maximum instantaneous current. The longer it takes the fuse element to melt, the more time there is to store energy in the circuit inductance. The fuse must be capable of absorbing this increased energy during arcing.

There is a limit as to how much arc energy a fuse can absorb. The DC voltage rating of a fuse always has an associated time constant because both terms are needed to define how much arc energy the fuse can absorb. For fuses, the DC voltage rating is inversely proportional to the time constant. In other words, as the time constant of the circuit increases, the voltage capability of the fuse decreases.

DC FUSE STANDARDS

There are two agencies in the US that maintain fuse standards for DC applications, Underwriters Laboratories (UL) and Mine Safety and Health Administration (MSHA). Both agencies have standards containing DC test requirements that the fuse must pass before it is approved. The test requirements and applicable standards are shown in table 1 while table 2 gives the applicable time contants.

The most commonly used standard is UL 198L - DC Fuses for Industrial Use, which provides for DC rating of UL-class fuses used in industrial applications in accordance with the National Electrical Code (NEC). Fuses listed to UL 198L carry the UL label, the DC voltage rating and DC interrupting rating identified separately from the AC ratings by the designation “dc” following the rating. Note that the DC test parameters shown in Tables 1 and 2, define the fuse performance from overload to maximum interrupting rating.

MSHA was the first agency to establish test procedure and standards for rating DC fuses. MSHA requirements for DC-rated fuses are specified in the Code of Federal Regulations, Title 30, Part 28 and are administered by the US Department of Labor. Only time delay fuses can be tested and approved to the MSHA standard. These fuses are typically used in the mining industry where the MSHA label must be on the product to be acceptable for use. MSHA approved fuses bear the agency’s label and the appropriate DC voltage rating.

UL also has a Component Recognition program which allows them to track components that have no governing standard but are used in UL listed equipment. UL witnesses tests on such components to ensure that they operate properly for their intended purpose. Component Recognized fuses are special-purpose devices intended for use in a specific application.

Fuses that are Component Reconized for DC are only suitable for use in specific applications. The critical circuit parameters are maximum DC voltage, circuit time constant and the overcurrent conditions under which the fuse is required to operate. Once these critical parameters are determined they can be compared to the voltage, time constant and the minimum and maximum interrupting ratings of the fuse to ensure the fuse is capable of properly opening over the entire required current range.

TABLE 1
DC FUSE STANDARDS

O.L. Tests @ Rated Voltage	Applicable Standards	Fuses Tests Required On
200%	UL198L, MSHA, UL198M	ALL 200A and less
300%	MSHA, UL198M	above 200A
900%	MSHA, UL198M UL198L	ALL Ratings Time delay only

S. C. Tests @ Rated Voltage	Applicable Standards	Fuses Tests Required On
Max. DC IR	UL198L	ALL Ratings
Max Energy	UL198L	Fuses with IR>10KA
10kA	MSHA, UL198M	ALL Ratings
20kA	MSHA, UL198M	ALL Ratings

Note: All of the above tests are at Rated voltage and at a specified time constant.

TABLE 2
SPECIFIED TIME CONSTANTS FOR DC STANDARDS

Standard	DC Voltage	Time Constant (L/R)	TEST CURRENT
UL198L	60, 125, 160, 250,	.01 second	10kAor higher
	300, 400, 500, 600	$L/R = 1/2 (I)^{0.3}$	less than 10kA
MSHA & UL198M	300 or 600	16mS..............	10kAor higher
		8mS..............	1kA to 9.99kA
		6mS..............	100A to 999A
		2mS..............	Less than 100A

TYPICAL DC FUSE APPPLICATIONS

The four most common DC fuse applications illustrate the different circuit parameters.

General distribution applications, are typically found in industry. These systems are used for DC control and load circuits consisting mainly of coils, relays, and contactors. The intent of the fuse in this application is to protect bus duct and cables from short circuits. Other components on the system are generally self protected. Common voltages for general distribution circuits are 125 or 250 VDC with time constants of 10 ms or less. Fuses listed to UL 198L are usually employed in these applications. The maximum system voltage must be known for proper fuse selection, since the above are typically nominal voltages, not maximum.

Battery supplies and capacitors are usually part of a Uninterruptible Power Supply (UPS). UPS applications are common in hospitals, banks, airline, telecommunications or other organizations with critical computer loads that cannot be disrupted. Fuses in UPS systems are intended for short circuit protection. The UPS system itself is protected by semiconductor fuses while the UPS distribution system is safeguarded by UL class fuses. Overloads are controlled by the UPS system itself. UPS systems dc-link voltages can range from less than 120 VDC up to 650 VDC with circuit time constants usually less than 5 mS.

DC motor and DC drive applications are found at industrial sites such as steel mills, paper mills, rubber plants or locations that use extruders or adjustable-speed drive (variable speed machines). The voltage for these circuits range from 90 to 700 VDC with circuit time constants of 20 to 40 mS. Power semiconductor protection fuses that have been tested for DC applications with these time constants are typically used for DC motors and drives. These fuses are usually UL Component Recognized for DC as well as for AC applications.

Magnet and field supplies are highly inductive loads such as the field supply of a DC machine or the steel industry's overhead crane magnets. Typical voltages are 500 VDC or less, but the long circuit time constant of approximately 1000 mS is of major concern. It is significantly larger than those found in the other applications. The only way fuses can be safely used in these systems is if they are oversized so that they will never open under overload conditions. Under short circuit conditions fuses should operate only when the field is bypassed. If this is not done and the fuse is subjected to an overcurrent, the energy stored in the circuit inductance is greater than the fuse can absorb and the fuse will rupture (explode).

USING AC TIME CURRENT CURVES FOR DC APPLICATIONS

An average melting time current curve shows the time required for a fuse to melt under different RMS load currents. Under DC short circuit conditions, the effective RMS current is much different from the instantaneous current under DC short circuit conditions. The time current characteristic curve that will apply for a specific application depends on the specific time constant. Due to the number of different time constants that can exist, it is not practical for fuse manufacturers to draw DC time current curves. However, once the circuit time constant is known for a specific application, converting a time current curve to DC is not difficult. Once the RMS values of the current reaches steady state, the published time current curve can be used as given, The example will show that RMS steady state occurs at approximately 20 time constants.

Refer back to equation 3 which shows the relationship of the effective RMS current as a function of the available short circuit current and number of time constants. We will simplify this discussion as follows.

Eq. 4 $K = (1 + 2e^{-n}/n - e^{-2n}/2n - 1.5/n)^{1/2}$

Eq. 5 $I_{rms} = K I_{sc}$

Eq. 6 $I_{sc} = I_{rms} / K$

Table 3 shows values of "K" or RMS current from equation 4, as well as instantaneous current or I_{inst} from Equation 1 at various number of time constants.

TABLE 3
CURRENT AS A FUNCTION OF TIME CONSTANT DURING A DC SHORT CIRCUIT

# Of Time Constants (tc)	"K"	I_{inst}
0.5	.24134	.39347
1	.40999	.63212
1.5	.53001	.77687
2	.61705	.86466
2.5	.68141	.91792
3	.72992	.95021
5	.83827	.99326
7.5	.89451	.99945
10	.92196	.99995
15	.94868	1.0
20	.96177	1.0
25	.96954	1.0
30	.97468	1.0
50	.98489	1.0
100	.99247	1.0

Reviewing table 3 above it is apparent that steady state is approached in approximately 20 time constants for RMS current but only about 5 time constants for instantaneous currents.

FIGURE 2
AVEAGE MELTING TIME CURRENT CURVE 30A, 600VAC FUSE

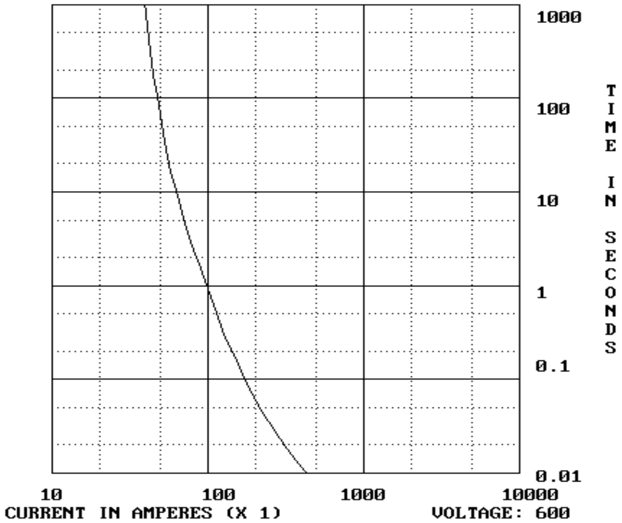


Figure 2 above is the average melting time current curve for a 30A, 600 VAC fuse that is also UL listed for 500 VDC to UL 198L standards. The time constant, "tc" of the DC circuit where the fuse is applied must be known before this curve can be converted for DC use. The procedure for converting a time current curve is presented as follows:

1. Choose a point on the fuse's time current curve and read the time "t" from the vertical axis and the current "Irms" from the horizontal axis.

2. Determine the number of time constants "n" at this point using equation 7 below.

Eq. 7 $n = t / tc$

3. Solve for "K" using equation 4 or table 3 above

4. Determine I_{sc} from equation 6. This is the value of DC short circuit current required to melt the fuse in "t" seconds.

5. Plot I_{sc} on the time current curve at time "t"

6. Select another point from the time current curve and repeat steps 1-5.

To illustrate this procedure, table 4 shows two DC conversion examples for the 30 A fuse whose time current curve is shown in figure 2. The examples are for circuit time constants of 2 mS and 10 mS.

TABLE 4
CONVERTING AC TIME CURRENT CURVE POINTS TO DC TIME CURRENT CURVE POINTS

Pt. from time current curve		tc = .002 second			tc = .01 second		
t (sec)	I_{rms} (A)	n	K	I_{sc} (A)	n	K	I_{sc} (A)
.01	**425**	5	.838	**507**	1	.41	**1037**
.015	**350**	7.5	.895	**391**	1.5	.53	**660**
.02	**310**	10	.922	**336**	2	.617	**502**
.03	**260**	15	.948	**274**	3	.73	**356**
.05	**215**	25	.970	**222**	5	.838	**256**
.1	**170**	50	.985	**173**	10	.922	**184**
.15	**155**	75	.99	**157**	15	.949	**163**
.2	**140**	100	.993	**141**	20	.962	**145**
.3	**128**	150	.995	**129**	30	.978	**131**
.5	**113**	250	.997	**113**	50	.985	**115**
1	**96**	500	.998	**96**	100	.992	**97**

It is apparent from table 4 above, that the AC time current curve and the DC time current curve mesh at approximately 20 time constants.

PEAK LET-THRU CURVES

Peak let-thru curves show the degree of current limitation a current limiting fuse has at different values of available AC fault current. As with the average melting time current curves, these only apply for AC applications. There is no way to convert a peak let-thru curve for a DC application. The procedure for determining peak let-thru currents for DC applications is beyond the scope of this paper. The fuse manufacturer should be contacted when this information is required.

SUMMARY

To safely apply fuses on DC applications, it is necessary to know the circuit parameters and have complete information on the DC capability of the fuse. It is hoped that this paper gives the reader a better understanding of the use of fuses on DC circuits. With a better understanding of the DC circuit parameters and the DC capabilities of fuses, selecting appropriate fuses for protection of DC systems can be done without difficulty.

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