Background:

As a follow-up to Mike Holt's article on conductor sizing and overcurrent protection, this article will address an additional criteria for conductor sizing that is often overlooked, short-circuit protection of conductors.

Short-circuit protection of conductors depends upon the available fault current and the type and speed of the overcurrent protection device. If one looks at the fine print note in Section 240-1, it alludes to the fact that other requirements are present for conductor protection as well and reads:

> "FPN: Overcurrent Protection for conductors and equipment is provided to open the circuit if the current reaches a value that will cause an excessive or dangerous temperature in conductors or conductor insulation. See also Section 110-9 for requirements for interrupting rating and Section 110-10 for requirements for protection against fault currents."

Section 110-9 addresses the interrupting rating of the overcurrent device required based upon short-circuit current. Section 110-10 addresses the overcurrent protective device, component short-circuit current ratings and protection of the circuit components by the overcurrrent protective device to prevent "excessive damage". This is especially important because it is not just protection against overloads, it is also protection from short-circuits.

Introduction:

Now the question remains, how can we verify protection of conductors from "extensive damage" against short-circuits? The answer depends upon the interpretation of "extensive damage". Information on conductor short-circuit current is available based upon the amount of damage the user allows. One level of protection is based upon the insulation of the conductor. Formulas and charts from the IEC and the Insulated Cable Engineers Association (ICEA) are available to illustrate this level of protection. The charts determine how much time and current is required to raise the temperature of the conductor from the operating temperature to a temperature where slight damage to thermoplastic insulation occurs. For conductors with 75 deg. C thermoplastic insulation, the damaging temperature is typically 150 deg. C. Another level of protection is based on the Soares "validity" rating. The validity rating corresponds to the amount of current required to cause the copper to become loose under a lug after the conductor has had a chance to cool back down. This validity rating is based upon raising the copper temperature from 75 deg. C to 250 deg. C, which is the annealing temperature of copper. In addition, a third level of protection promoted by Onderdonk allows the calculation of the current necessary to cause the conductor to melt (75 deg. C to 1,083 deg. C).

Table 1 illustrates the conductor rating for 5 seconds as well as the maximum I^2t (ampere^2 seconds) rating based upon conductor size and the conductor damage level (ICEA, Soares or Onderdonk).

However, depending upon the damage level selected, the overcurrent protective device selected and the resulting opening time, the amount of current the conductor can handle will need to be adjusted. If we select the ICEA insulation damage level as the desired protection level for conductors, we can establish more usable information with respect to the clearing time of the overcurrent protective device. Since some devices such as airframe/power circuit breakers exist which can have short-time delays up to 30 cycles, we must analyze the opening time up to this level. Table 2 shows the amount of current the conductor can handle based upon different clearing times (up to 30 cycles) with respect to the ICEA insulation damage level.

Table 1: Comparison of Conductor Current Ratings (Based on RMS Amperes)

Cond Size	Cond Area Circ. Mils	5 Second Rating (Amps)			I^2t Rating (Amperes Squared Seconds)		
		ICEA Insulation 150 Deg. C	Soares Annealing 250 Deg. C	Onderdonk Melting 1083 Deg. C	ICEA Insulation 150 Deg. C	Soares Annealing 250 Deg. C	Onderdonk Melting 1083 Deg. C
14	4110	97.31	139.84	251.35	47346	97774	315881
12	6530	154.61	222.18	399.34	119517	246812	797382
10	10380	245.76	353.17	634.79	301994	623640	2014813
8	16510	390.90	561.74	1009.68	764007	1577732	5097229
6	26240	621.27	892.79	1604.72	1929882	3985352	12875605
4	41740	988.25	1420.16	2552.63	4883238	10084258	32579535
3	52620	1245.85	1790.34	3218.00	7760768	16026576	51777572
2	66360	1571.17	2257.83	4058.27	12342860	25488942	82347942
1	83690	1981.48	2847.46	5118.10	19631350	40540229	130974616
1/0	105600	2500.23	3592.93	6458.01	31255818	64545637	208529659
2/0	133100	3151.33	4528.59	8139.79	49654561	102540438	331280679
3/0	167800	3972.91	5709.22	10261.88	78919977	162975743	526530956
4/0	211600	5009.94	7199.46	12940.49	125497294	259161440	837281168
250	250000	5919.11	8505.98	15288.86	175179408	361758775	1168745667
300	300000	7102.93	10207.18	18346.63	252258347	520932636	1682993761
350	350000	8286.76	11908.38	21404.40	343351639	709047199	2290741508
400	400000	9470.58	13609.57	24462.17	448459284	926102464	2991988908
500	500000	11838.22	17011.97	30577.71	700717631	1447035100	4674982669

Table 2: Maximum Short-Circuit Current Rating In Amperes (Per ICEA Insulation Damage)

Cond Size	Cond Area Circ. Mils	Maximum Short-Circuit Current Rating In RMS Amperes								
		1/2* Cycles 0.0083 Seconds	1 Cycle 0.0167 Seconds	2 Cycle 0.0333 Seconds	3 Cycle 0.0500 Seconds	6 Cycle 0.1 Seconds	12 Cycle 0.2 Seconds	18 Cycle 0.3 Seconds	24 Cycle 0.4 Seconds	30 Cycle 0.5 Seconds
14	4110	2384	1685	1192	973	688	487	397	344	308
12	6530	3787	2678	1894	1546	1093	773	631	547	489
10	10380	6020	4257	3010	2458	1738	1229	1003	869	777
8	16510	9575	6771	4788	3909	2764	1954	1596	1382	1236
6	26240	15218	10761	7609	6213	4393	3106	2536	2197	1965
4	41740	24207	17117	12104	9883	6988	4941	4035	3494	3125
3	52620	30517	21579	15259	12459	8810	6229	5086	4405	3940
2	66360	38486	27213	19243	15712	11110	7856	6414	5555	4968
1	83690	48536	34320	24268	19815	14011	9907	8089	7006	6266
1/0	105600	61243	43305	30621	25002	17679	12501	10207	8840	7906
2/0	133100	77192	54583	38596	31513	22283	15757	12865	11142	9965
3/0	167800	97316	68813	48658	39729	28093	19865	16219	14046	12563
4/0	211600	122718	86775	61359	50099	35426	25050	20453	17713	15843
250	250000	144988	102522	72494	59191	41854	29596	24165	20927	18718
300	300000	173986	123026	86993	71029	50225	35515	28998	25113	22461
350	350000	202983	143531	101492	82868	58596	41434	33831	29298	26205
400	400000	231981	164035	115990	94706	66967	47353	38663	33484	29949
500	500000	289976	205044	144988	118382	83709	59191	48329	41854	37436

*** When comparing these values for 1/2 cycle with the available RMS symmetrical fault current, multiply the available RMS symmetrical by 1.3 to account for asymmetry during the first half cycle.**

The next step to analyzing protection of conductors against short circuits depends upon the overcurrent device selected and available fault current. The overcurrent protective device can either be a current limiting fuse or circuit breaker (current liming or non-current limiting).

Current Limiting Devices:

A device, which opens in one-half cycle or less, may or may not be classified as "current-limiting". The device can be labeled current limiting only if it meets the requirements of UL/CSA (489/22.2 No. 5 for molded case circuit breakers or UL/CSA 248 for fuses).

The requirement for molded case circuit breakers is that the device must limit the asymmetrical fault current to a value below the equivalent symmetrical fault current. If the circuit breaker is not current-limiting, but clears within approximately one-half cycle, the available symmetrical fault current must be multiplied by a factor of 1.3 to account for asymmetry. Even if the molded case circuit breaker is current-limiting, the degree of current limitation is typically less than a rejection type fusible device.

The requirements for current-limiting fuses are based on the fuse type (Class) and upon the maximum I^2t let-through as shown in Table 3. If the device meets the performance criteria, it meets the standard for that class of fuse and can be listed/certified per UL/CSA.

The values shown in the table to the right can be used to compare the maximum I^2t let-through for the fuse to the I^2t rating of the conductor. As long as the I^2t let-through of the fuse is less than the I^2t rating of the conductor, the conductor is protected under short-circuit conditions.

Table 3:

Max Let-Through (Ampere^2 Seconds) per UL 248 - Table A

Fuse Class	I^2t Max Let-through Value		
	50 kA	100 kA	200 kA
Class J			
30	7,000	7,000	7,000
60	30,000	30,000	30,000
100	60,000	80,000	80,000
200	200,000	300,000	300,000
400	1,000,000	1,100,100	1,100,100
600	2,500,000	2,500,000	2,500,000
Class RK1			
30	10,000	10,000	11,000
60	40,000	40,000	50,000
100	100,000	100,000	100,000
200	400,000	400,000	400,000
400	1,200,000	1,200,000	1,600,000
600	3,000,000	3,000,000	4,000,000
Class RK5			
30	50,000	50,000	50,000
60	200,000	200,000	200,000
100	500,000	500,000	500,000
200	1,600,000	1,600,000	2,000,000
400	5,200,000	5,000,000	6,000,000
600	10,000,000	10,000,000	12,000,000
Class T			
30 300V	3,500	3,500	3,500
600V	7,000	7,000	7,000
60 300V	15,000	15,000	15,000
600V	30,000	30,000	30,000
100 300V	40,000	40,000	40,000
600V	60,000	80,000	80,000
200 300V	150,000	150,000	150,000
600V	200,000	300,000	300,000
400 300V	550,000	550,000	550,000
600V	1,000,000	1,100,000	1,100,000
600 300V	1,000,000	1,000,000	1,000,000
600V	2,500,000	2,500,000	2,500,000

An example examining both the phase and grounding conductor is given on the following page.

Short-Circuit Protection of Wire and Cable:

Fusible Systems

The circuit shown originates at a distribution panel where 40,000 amperes RMS symmetrical are available. The # 10 THW copper conductor is protected by a Bussmann LOW-PEAK® fuse sized per NEC 240-3 (30A maximum for # 10 conductor).

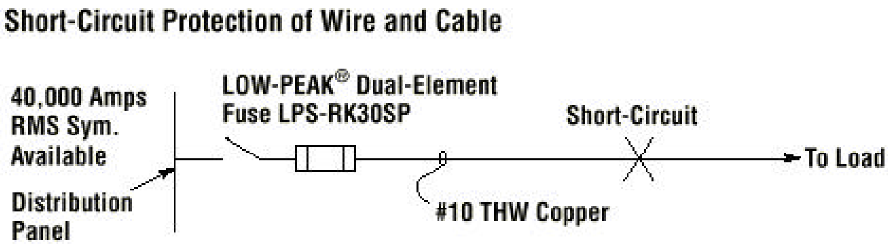

Table 1, shows the I^2t withstand rating of # 10 THW copper to be 301,994 000 ampere^2 seconds per the ICEA Insulation damage level. Since the Bussmann LOW-PEAK® is a Class RK1 current limiting fuse, the maximum I^2t let-through per UL/CSA 248 can be found per the table on the previous page. The maximum I^2t let-through for a Class RK1 fuse at a fault not greater than 50,000A is 10,000 ampere^2 seconds. Since the I^2t let-through of the fuse, 10,000, is considerably less than the I^2t withstand of the # 10 conductor, 301,994, the conductor is protected against short-circuits. In addition, since the minimum grounding conductor per NEC 250-122 is also # 10, the grounding conductor is protected as well.

Table 4, on the next page, compares the maximum I^2t let-through for the fuse with the withstand of the conductor. If the I^2t withstand of the conductor is greater than the I^2t let-through of the fuse; the conductor will be protected. The table shows the minimum size conductor able to be protected under short-circuit conditions by the fusible device.

Circuit Breaker Systems

In the previous example a 30A, Class RK1 fuse was protecting a # 10 conductor. If the 30A fusible device were replaced with a 30A, molded case circuit breaker with a clearing of 1/2 cycle would the # 10 conductor be protected?

Since the I^2t let-through of the circuit breaker is not known, Tables 2 must be used. If the 30A circuit breaker is current limiting, at a 40,000A fault, with a clearing time of 1/2 cycle, per UL 489, the let-through current could be as high as 40,000A RMS and still be marked current limiting. If the device was not current limiting, the let-through current could be as high as 40,000 X 1.3, or 52,000A. The maximum short-circuit current rating of # 10 conductor is 6,020A for 1/2 cycle (per ICEA). Since the let-through current of either the current limiting or non-current limiting circuit breaker could be much greater than the short-circuit current rating of the conductor, protection can not be assured for either the phase or equipment grounding conductor.

Table 5, on the next page, can be utilized to analyze conductor protection by current-limiting and non-current limiting circuit breakers. Note in the tables, the size of the conductor has increased due to the limited degree of current-limitation or the increased opening time of the device (compared to a fusible system). When using molded case circuit breakers, insulated case circuit breakers or low voltage power circuit breakers, conductors must be carefully analyzed for protection. This is especially true for equipment grounding conductors since the NEC allows for reduced sizing of the equipment grounding conductor despite the fact that available ground fault currents can be equal to or perhaps greater than the available three phase short-circuit currents.

Table 4:

Conductor Short-Circuit Protection (ICEA Values) Minimum Conductor Size, Based on UL 248				Conductor Short-Circuit Protection (ICEA Values) Minimum Conductor Size, Based on UL 248			
Fuse Class	Short-Circuit Current (RMS Amperes)			Fuse Class	Short-Circuit Current (RMS Amperes)		
	50 kA	100 kA	200 kA		50 kA	100 kA	200 kA
Class RK1				Class J			
30	14	14	14	30	14	14	14
60	14	12	12	60	14	14	14
100	12	12	12	100	14	14	14
200	8	8	8	200	12	10	10
400	6	6	6	400	8	8	8
600	4	4	4	600	6	6	6
Class RK5				Class T			
30	12	12	12	30 300V	14	14	14
60	10	10	10	600V	14	14	14
100	8	8	8	60 300V	14	14	14
200	6	6	4	600V	14	14	14
400	3	3	3	100 300V	14	14	14
600	2	2	2	600V	14	14	14
				200 300V	12	12	12
				600V	12	10	10
				400 300V	10	10	10
				600V	8	8	8
				600 300V	8	8	8
				600V	6	6	6

Table 5:

Circuit Breaker's (Clearing or STD***) Setting	Short-circuit Current (RMS Amperes)				
	10 kA	25 kA	50 kA	100 kA	200 kA
1/2 cycle C.L.*	#6	#3	1/0	4/0	350
1/2 cycle N.C.L.**	#6	#2	2/0	250	500
1 Cycle	#6	#2	2/0	250	500
3 Cycle	#3	1/0	4/0	500	900
6 Cycle	#2	3/0	300	600	-
12 Cycle	1/0	4/0	500	900	-
18 Cycle	1/0	300	600	-	-
24 Cycle	2/0	300	600	-	-
30 Cycle	3/0	350	700	-	-

*** C.L. = Current Limiting Circuit Breaker. Values are based upon UL 489/CSA 22.2 No. 5 requirements to limit short-circuit currents to the symmetrical values.**
**** N.C.L. = Non-Current Limiting Circuit Breaker**
***** STD = Short Time Delay**