

Power quality in the age of LEDs: Part 3

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Final Draft

In this next part of this series, we will examine how the 2017 National Electrical Code (NEC) addresses the heat generated by harmonic currents and why it may, according to NEC 310.15 require the de-rating of stage distribution cable and conductors. But getting a handle on exactly how much a conductor should be de-rated is like trying to get hold of the proverbial greased pig, that's because there is no specific regulation in the code book that pertains to the harmonic currents drawn on phase conductors by LED power supplies. The code addresses the issue in so far as it does at all, as part of the larger issue of permissible ampacities and operating temperatures of current carrying conductors in NEC 310.15.

Table 400.5(B) Ampacity of Cable Types SC, SCE, SCT, PPE, G, G-GC, and W.
[Based on Ambient Temperature of 30°C (86°F). See Table 400.4.]

Size (AWG or kcmil)	Temperature Rating of Cable								
	60°C (140°F)			75°C (167°F)			90°C (194°F)		
	D ¹	E ²	F ³	D ¹	E ²	F ³	D ¹	E ²	F ³
12	—	31	26	—	37	31	—	42	35
10	—	44	37	—	52	43	—	59	49
8	60	55	48	70	65	57	80	74	65
6	80	72	63	95	88	77	105	99	87
4	105	96	84	125	115	101	140	130	114
3	120	113	99	145	135	118	165	152	133
2	140	128	112	170	152	133	190	174	152
1	165	150	131	195	178	156	220	202	177
1/0	195	173	151	230	207	181	260	234	205
2/0	225	199	174	265	238	208	300	271	237
3/0	260	230	201	310	275	241	350	313	274
4/0	300	265	232	360	317	277	405	361	316
250	340	296	259	405	354	310	455	402	352
300	375	330	289	445	395	346	505	449	393
350	420	363	318	505	435	381	570	495	433
400	455	392	343	545	469	410	615	535	468
500	515	448	392	620	537	470	700	613	536
600	575	—	—	690	—	—	780	—	—
700	630	—	—	755	—	—	855	—	—
750	655	—	—	785	—	—	885	—	—
800	680	—	—	815	—	—	920	—	—
900	730	—	—	870	—	—	985	—	—
1000	780	—	—	935	—	—	1055	—	—

¹The ampacities under subheading D shall be permitted for single-conductor Types SC, SCE, SCT, PPE, and W cable only where the individual conductors are not installed in raceways and are not in physical contact with each other except in lengths not to exceed 600 mm (24 in.) where passing through the wall of an enclosure.

²The ampacities under subheading E apply to two-conductor cables and other multiconductor cables connected to utilization equipment so that only two conductors are current-carrying.

³The ampacities under subheading F apply to three-conductor cables and other multiconductor cables connected to utilization equipment so that only three conductors are current-carrying.

Figure 1: NEC-Table-400.5(B). Note the ampacities under subheading D shall be permitted for single-conductor type cable only where the individual conductors are not installed in raceways and are not in physical contact.

When we compare the ampacity of conductors in free air (Figure 1 - NEC Table 400.5 (B)) with that enclosed in conduit (Figure 2 - NEC 310.15(B)16), we immediately see that the same size conductor is de-rated significantly when enclosed. For instance 4/0 cable has an ampacity of 405A in free air, but only 260A when enclosed in conduit with two additional current-carrying conductors. The different insulation of portable cable and of conductors used in conduit can't account for their different ratings since they are all 90°C conductors. Their rating is purely a result of the difference in the temperature rise of copper inside conduit as opposed to its rise in free air. When enclosed in conduit the additional heat generated by adjacent current carrying conductors and the effect they have on heat dissipation warrants the lower ampacities in table NEC 310.15(B)16). While the de-rating is significant, it is important to note that it is based upon the heat generated by current at the fundamental frequency (60Hz) only. The exponential increase in heat generated by current at higher frequencies, as noted in part 2 of this series, is not taken into account in this table even though recent research has shown that it can increase the I^2R losses by over 100%. Let's look at Table 310.15 (B)(16) in more detail.

In NEC 310.15, the code dictates that no conductor running through a raceway or conduit shall be used in such a manner that the operating temperature exceeds the temperature rating of the conductor. These designations are given in Table 310.15(B)(16) for three classes of cable insulation; 60, 75, and 90 degrees Celsius. For example, 4/0 cable is rated to carry no more than 260A at an operating temperature of 90°C (194°F.)

Size AWG or kcmil	Temperature Rating of Conductor (See Table 310.13.)						Size AWG or kcmil
	60°C (140°F)	75°C (167°F)	90°C (194°F)	60°C (140°F)	75°C (167°F)	90°C (194°F)	
	Types TW, UF	Types RHW, THHW, THW, THWN, XHHW, USE, ZW	Types TBS, SA, SIS, FEP, FEPB, MI, RHH, RHW-2, THHN, THHW, THW-2, THWN-2, USE-2, XHH, XHHW, XHHW-2, ZW-2	Types TW, UF	Types RHW, THHW, THW, THWN, XHHW, USE	Types TBS, SA, SIS, THHN, THHW, THW-2, THWN-2, RHH, RHW-2, USE-2, XHH, XHHW, XHHW-2, ZW-2	
COPPER			ALUMINUM OR COPPER-CLAD ALUMINUM				
18	—	—	14	—	—	—	—
16	—	—	18	—	—	—	—
14*	20	20	25	—	—	—	—
12*	25	25	30	20	20	25	12*
10*	30	35	40	25	30	35	10*
8	40	50	55	30	40	45	8
6	55	65	75	40	50	60	6
4	70	85	95	55	65	75	4
3	85	100	110	65	75	85	3
2	95	115	130	75	90	100	2
1	110	130	150	85	100	115	1
1/0	125	150	170	100	120	135	1/0
2/0	145	175	195	115	135	150	2/0
3/0	165	200	225	130	155	175	3/0
4/0	195	230	260	150	180	205	4/0
250	215	255	290	170	205	230	250
300	240	285	320	190	230	255	300
350	260	310	350	210	250	280	350
400	280	335	380	225	270	305	400
500	320	380	430	260	310	350	500
600	355	420	475	285	340	385	600
700	385	460	520	310	375	420	700
750	400	475	535	320	385	435	750
800	410	490	555	330	395	450	800
900	435	520	585	355	425	480	900
1000	455	545	615	375	445	500	1000
1250	495	590	665	405	485	545	1250
1500	520	625	705	435	520	585	1500
1750	545	650	735	455	545	615	1750
2000	560	665	750	470	560	630	2000

Figure 2: NEC Table 310.15(B)(16)

There are several premises on which this table is based that should be noted. First, NEC Table 310.15(B)(16) uses a baseline ambient temperature of 86°F. When the temperature is something other than 86°F, code requires the adjustment of the allowable or maximum current a conductor can safely carry. be adjusted. The ambient temperature correction factors are given in a second Table 310.15(B)(2) (Figure 3.)

CORRECTION FACTORS							
Ambient Temp. (°C)	For ambient temperatures other than 30°C (86°F), multiply the allowable ampacities shown above by the appropriate factor shown below.						Ambient Temp. (°F)
21–25	1.08	1.05	1.04	1.08	1.05	1.04	70–77
26–30	1.00	1.00	1.00	1.00	1.00	1.00	78–86
31–35	0.91	0.94	0.96	0.91	0.94	0.96	87–95
36–40	0.82	0.88	0.91	0.82	0.88	0.91	96–104

Figure 3: NEC Table 310.15(B)(2)

It is also worth noting that this table is based on a maximum of three current carrying conductors installed in a raceway or conduit. In a 3-phase wye-connected system, the ampacities given are only true if the load is sinusoidal and no current returns on the neutral (i.e. when the three phase legs are balanced.) If the neutral is carrying no current, then it emits no heat. Even when the phases

are unbalanced, and the neutral returns the difference between the phase legs, the current on the neutral will not generate much heat because I^2R losses at the fundamental frequency (60Hz) are low. But, as we saw in part 2 of this series, that is not the case when powering large quantities of non-linear LED fixtures. The pulsed current they draw is rich in harmonics that generate a lot of heat by increased skin and proximity effects. Not only do the phase conductors generate more heat, but the neutral becomes a super heater. The greater heat in the neutral is generated not only by the greater resistance of too much current (1.7X) running through the same copper, but also by the greater resistance caused by the harmonic portion of the current running only on the outer skin of the copper. The combined effect makes the neutral a major contributor to ambient temperature rise inside conduit.

For this reason Article 310.15(B)(5)(c) adds “*On a 4-wire, 3-phase wye circuit where the major portion of the load consists of nonlinear loads, harmonic currents are present in the neutral conductor; the neutral conductor shall therefore be considered a current-carrying conductor.*” The adjustment factor for more than three current carrying conductors in a conduit is given in NEC Table 310.15(B)(3)(a) (Figure 4.)

Table 310.15(B)(3)(a) Adjustment Factors for More Than Three Current-Carrying Conductors in a Raceway or Cable

Number of Conductors ¹	Percent of Values in Table 310.15(B)(16) through Table 310.15(B)(19) as Adjusted for Ambient Temperature if Necessary
4-6	80
7-9	70
10-20	50
21-30	45
31-40	40
41 and above	35

Number of conductors is the total number of conductors in the raceway or cable, including spare conductors. The count shall be adjusted in accordance with 310.15(B)(5) and (6), and shall not include conductors that are connected to electrical components but that cannot be simultaneously energized.

Figure 4: NEC Table 310.15(B)(3)(a)



Figure 5: Left: 8'x20' Quasar Science soft box. Middle: 8'x12' Quasar Science soft box. . Right: 8'x6' Quasar Science soft boxes.

Let's now apply the prescriptions of NEC 310.15 to the stage production we have used as an example in parts one and two of this series. As you may recall, the house set was lit by large soft boxes made up of 8' Quasar Science Q100 LED tubes zip-tied onto Speedrail frames (see Figure 5). There were a total of five 8' x 6' boxes, two 8' x 20' boxes, as well as an 8' x 12' box for a total of 250 8' Quasar Science Q100 LED tubes.



Figure 6: PQM readings of the Quasar Science LED tubes. Note: disproportionate amount of 3rd order harmonics (3rd, 9th, etc.) in the FFT on the right)

As we saw by their power quality meter (PQM) readings in Part 1 (Figure 6), the current drawn by 8' Quasar Science LED tubes is very distorted. With a power factor (PF) of .51, each 8' Quasar Science LED tube has an apparent power of 140VA for its 70W output. While it draws RMS current of 1.12A, the crest factor of its distorted current waveform is about 3.3 and its peak current is 3.7A. The current they draw is harmonically rich with a total harmonic distortion (THD) of 68.1% and large 3rd, 5th, 7th, and 9th components.

In part two of this series we examined the affect the distorted current drawn by such a large number of 8' Quasar Science LED tubes had on the power quality of the stage. According to the FFTs of the distorted current drawn on each phase leg and on the neutral, there was considerable harmonic content. For example, the high leg (shown in Figure 7) carried 300A of current, 63.8A of which was 3rd harmonic and 16.8A of which was 5th harmonic, with a total harmonic distortion of 22%.



Figure 7: The FFT of the high phase leg shows that it carried 300A of current, 63.8A of which was 3rd harmonic and 16.8A of which was 5th harmonic.

With such harmonic distortion, one would expect the increase in skin and proximity effect would substantially increase the resistive value of the stage distribution conductors resulting in a substantial increase in the amount of heat generated and trapped in the conduit that carries the conductors from the main switchboard in the electrical room to the company switch on the stage floor. (Thus far we have focused only on stage feeder cable, but the same is true of the multiple conductors bundled in the Socapex cable used to power clusters of Quasar tubes.)



Figure 8: Of the 105A returning on the neutral 99.3A consists of 3rd harmonic current.

When we apply the prescriptions of NEC 310.15 to de-rate the current carrying capacity of the stage conductors we find its like trying to grab hold of a greased pig. The resources provided by the NEC (the allowable ampacity tables of Article 310.15, the ampacity tables of Informative Annex B, and the ambient temperature correction factors in 310.15(B)(2)) provide little practical guidance for a set

electrician to de-rate cable based on its operating temperature because a stage electrician has no means of measuring that temperature.

The NEC summarizes the principal determinants of operating temperature in an Informational Note. Let's look at which apply here. They are as follows:

- “(1) Ambient temperature — ambient temperature may vary along the conductor length as well as from time to time (an example often cited in NFPA training materials is that of feeder run through an attic crawl space where seasonal temperatures can reach 125⁰F.)*
- (2) Heat generated internally in the conductor as the result of load current flow, including fundamental and harmonic currents.*
- (3) The rate at which generated heat dissipates into the ambient medium. Thermal insulation that covers or surrounds conductors affects the rate of heat dissipation.*
- (4) Adjacent load-carrying conductors — adjacent conductors have the dual effect of raising the ambient temperature and impeding heat dissipation.”*

Given that only 20% or less of the energy supplied to an incandescent lamp generates light in the visible spectrum, and the remaining 80% generates heat, the three 24k Fresnels hanging just below the perms generated a lot of heat. Since heat rises, the ambient temperature in the catwalks reached temperatures of 95⁰F-105⁰F.



Figure 9: Stage high box in the perms

For convenience powering chain motors and lighting loads, this stage has a company switch high in the catwalks (Figure 9). According to NEC Table 310.15(B)(2) conductors supplying the high box would have to be de-rated to 91% of the allowable ampacity given in NEC Table 310.15(B)(16). The 4/O copper rated to carry 260A at 86⁰F is now rated to carry 236A at 100⁰F. Since the ambient temperature outside the conduit reached over 100⁰F, one can safely assume the temperature inside the conduit containing four conductors carrying heat generating harmonic currents was quite a bit higher. How high we have no way of accurately knowing.

As we saw in part 2 of this series, harmonic currents increase the operating temperature of cable in conduit in two ways: the phase conductors generate more heat as a result of increased resistance due to skin and the proximity effects (the second determinate of operating temperature listed above), and triplen harmonics stacking on the neutral make the neutral an additional heat emitting conductor (the fourth determinate of operating temperature listed above). NEC 310.15 provides a de-rating table that takes into account heat emitted by the neutral. Table 310.15(B)(3)(a) would require that we de-rate our 4/O copper by an additional 20%. The 4/O normally rated to carry 260A at 86⁰F is now rated to carry only 188A because a fourth heat emitting conductor enclosed in the conduit (the neutral) has the dual effect of raising the ambient temperature and impeding heat dissipation.

While NEC 310.15 provides a de-rating table that takes into account the heat generated by the 90A of 3rd harmonic current returning on the neutral, it provides no means of accounting for the additional heat generated by the 63.8A of 3rd harmonic and 16.8A of 5th harmonic current drawn on the phase conductors. As noted previously, the de-rating of conductor ampacity given in the Table 310.15(B)(16) takes into account only heat generated by the fundamental frequency of 60Hz - nowhere in NEC 310.15 is the increase due to I²R losses at higher frequencies taken into account even though the EU research cited in part 2 showed that the heat generated by the harmonic currents drawn by non-PFC LED power supplies can increase the I²R losses by over 100%.

EU countries, by comparison, are more attuned to the effects of harmonics than we are in the US because their grid is not protected by a front line of delta-wye connected transformers as are grids in North America. Without a transformer primary to trap them, third order harmonic distortion reaches all the way back to the utility generators in EU countries. For this reason, the International Electrotechnical Commission (IEC) has published a de-rating table that takes into account third harmonic currents. The table can be found in BS7671 Appendix 11. In addition, LED luminaires manufactured or sold in EU countries are subject to the prescriptive harmonic limits of EN standard 61000-3-2. For example the 55

Arri S60 Skypanels also lighting the set are power factor-corrected so that they draw a sinusoidal current free of harmonic distortion.

NEC 310.15 is, by comparison, of little help to the set electrician distributing power on a stage because it is simply not feasible for them to measure operating temperatures (the basis of de-rating in NEC310.15) within a conduit. From parts one and two of this series, we know that the harmonic currents measured on the phase and neutral conductors would cause a substantial increase in the operating temperature inside the conduit, but we have no practical means of measuring how much.

The consequences of failing to de-rate the ampacity of cable as required by NEC 310.15 range from the invisible deterioration of cable insulation over time, to the neutral catching fire. Why would the neutral catch fire? As demonstrated in part two of this series, the neutral conductor of a 3-phase wye distribution system can return up to 1.7x the current on the neutral as is present on the phase conductors. Since this elevated current consists primarily of triple-N (?) harmonic currents, the neutral conductor of a 3-phase wye system can become severely overheated when supplying large quantities of LED fixtures or any other load with low power factor. And, since the neutral conductor of a distribution system has no over-current protection as do the phase conductors, the severe overheating of the neutral by the triple-N (?) harmonics can overheat the cable to the point that the insulation catches fire.

Even if operating temperatures never reach the point of causing catastrophic failure, the heat generated by harmonic currents can still do damage to a distribution system. Recent research by the European Committee for Electrotechnical Standardization found that for every 14.4° F (8° C) increase above the maximum conductor operating temperature the life of cable will be halved (CENELEC Std. HD603 S1:1994/A2: 2003 E.) For this reason alone, it is important to de-rate stage conductors when supplying non-power factor corrected LED lights in large quantities.

Without a practical means of further de-rating phase conductors when they carry harmonic currents, what's a conscientious set electrician to do? They can look at how other industries deal with analogous situations. CBEMA (the Computer and Business Equipment Manufacturers Association) has developed a simple formula (see Figure 10) for de-rating service equipment that serves the non-linear switch mode power supplies powering the hundreds of desktop computers used in large offices. Using the peak current drawn by the (a non-linear) load (see Figure 11), the formula provides a de-rating factor for service equipment to protect it from the excessive heat generated by harmonic currents.

$$dF \text{ (De-rating Factor)} = (1.414 \times \text{RMS Current}) / (\text{PEAK Current})$$

Figure 10: The Computer and Business Equipment Manufacturers Association's (CBEMA) formula for de-rating distribution equipment when harmonic currents are present.

To come up with a de-rating factor for the 8' Quasar Science Q100 LED fixtures, all a set electrician needs to know is the peak value of the spiked current they draw – the source of the harmonic currents. Since many of today's multi-meters can provide both crest factor and True RMS current measurements, it is a simple calculation to determine the peak current: peak current = crest factor x RMS current. Let's go through the exercise of determining the CBEMA de-rating factor for a load consisting predominantly of Quasar Science LED tubes using the information we have already gathered from our sample production.

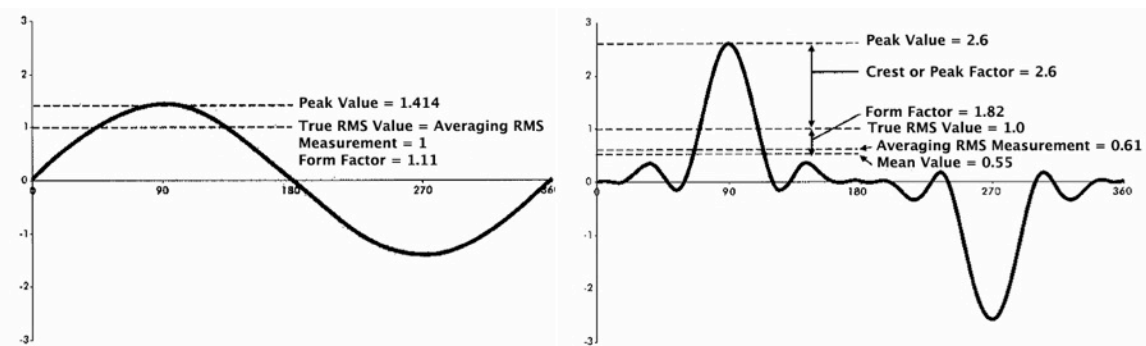


Figure 13: Values for a sinusoidal current (left.) Values for the distorted current waveform drawn by a non-linear power supply with a Crest Factor of 2.6 (right.)

According to our power quality meter reading, the 8' Quasar Science tubes draw an RMS current of 1.12A with a crest factor of 3.3. If we plug these numbers into the equation above, we see that CBEMA recommends that we de-rate our service equipment to 43% of its rated ampacity when supplying Quasar Science LED tubes ($dF = 1.414/3.3 = 0.43$), which roughly coincides with the results obtained in the EU study cited in part two of this series.

As you may recall, in *Calculation of harmonic losses and ampacity in low-voltage power cables when used for feeding large LED lighting loads (ADVANCED ELECTROMAGNETICS , VOL . 3, NO . 1, OCTOBER 2014)*, the authors came to the conclusion that conductors bundled in free air should be de-rated by at least 40 percent when supplying large quantities of LEDs. But, since in this case, the four heat-emitting conductors are enclosed in conduit, the current carrying capacity of the conductors must be de-rated an additional 20% according to NEC Table 310.15(B)(3)(a). The end result is that the current carrying capacity of conductors should be de-rated to 48% of their rated ampacity when powering large quantities of 8' Quasar Science LEDs. Which means that the 600 MCM copper cable supplying the 400A company switches of this stage should be de-rated from the 475A given in NEC Table 310.15(B)(16) to only 204A according to the CBEMA guidelines. In the next and final part of this series, we will explore the

use of Harmonic Mitigating Transformers (HMTs) to regain the distribution capacity lost to the heat generated by the harmonic currents drawn by non-linear power supplies.