



# Understanding hidden electrical diversity in entertainment lighting systems

BY STEVE TERRY

ELECTRICAL DIVERSITY is one of the least understood areas in entertainment lighting systems, but it has profound implications in how these systems are designed and used. “Electrical diversity” describes the concept that not all lighting circuits are fully loaded, and they are probably not all energized simultaneously. Application of electrical diversity allows system designers and users to take advantage of these facts when deciding on the code-mandated size and number of conductors to use to distribute power in a system, and indeed how much total power is needed to feed to that system. To understand how electrical diversity works, let’s take a typical medium-sized theatre (call it the “Rialto”) as an example.

applied by the system designer and then hidden from the end-user: the wiring of the system, both in conduit and in permanently installed flexible cords and cables.

In the Rialto, some branch circuits are wired in conduit all the way from the dimmer rack to the outlet, while circuits on the flying pipes are serviced by a combination of wire in conduit and flexible multi-conductor cable between the connector strip on each pipe and junction boxes on the grid. It is these flexible cables that allow the electric pipes to fly freely to any height below the grid. The electric pipes in the Rialto are 50’ long and each has 32 – 20A circuits on 18” centers. The connector strip on each pipe is a

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The Rialto has 384 dimmers of 2400 watt, 20 amp capacity feeding 384 20-amp circuits throughout the theatre. The four-rack dimmer bank is fed by a 1200 A three-phase feed bused across all the dimmer racks, making the total 120-volt power available to the system 3600 amps. This is our first example of diversity, since the nameplate rating of the dimmer system is 7,680 amps at 120 volts. We can therefore say that the system *feeder* assumes about 47% diversity, calculated by dividing 3,600 by 7,680. This is well understood, since the size of the feed and the nameplate rating are readily visible. Presumably, this 47% diversity on the feeder was determined by a typical schedule of loads to be used in the facility, plus some margin for expansion.

However, there is another area where electrical diversity is often

UL-listed device, and has a rating label that states “32 – 20A , 120V circuits.” The gridiron junction box feeding the multi-conductor drop cables to the connector strip is also UL-Listed, and also has a rating that states “32 – 20A , 120V circuits.”

Ask any experienced production electrician how many loads of what size he or she can plug into that connector strip, and the answer will invariably be, “Why, 32 twenty amp loads, of course. I’ve got a 20 amp dimmer feeding each circuit, the connector strip and the gridiron junction box are fully rated, and I have 3600 amps of power feeding the dimmer system. In fact, the light plot for my next production calls for 32 - 2000 watt fixtures on the first electric, so I’ll have an extra 400 watts per circuit.”

In fact, that answer is very likely wrong, because the electrician has just bumped into “hidden diversity.” To understand the correct answer to the loading question, we must go back and examine decisions made by the system designer in selecting the permanently installed flexible drop cables between the gridiron junction box and the connector strip in question. Upon examination, we find that the connector strip is fed by two cables, each of which is Type SO, 12 AWG conductor size, 36 conductors, with a temperature rating of 90°C. Each cable feeds 16 circuits using 32 current-carrying conductors and four grounding conductors.

Now, let’s compare this setup with the standard method of determining ampacity of flexible cords and cables in Article 400 of the *National Electrical Code (NEC)*. Table 400.5(A) gives the ampacity for various types of flexible cable with three current-carrying conductors, and Table 400.5 provides the ampacity adjustment factor for more than three current carrying conductors.

| Number of Conductors | Percent of Value in Tables<br>400.5(A) and 400.5(B) |
|----------------------|---|
| 4 – 6                | 80  |
| 7 – 9                | 70  |
| 10 – 20              | 50  |
| 21 – 30              | 45  |
| 31 – 40              | 40  |
| 41 and above         | 35  |

**Table 400.5 Adjustment Factors for More Than Three Current-Carrying Conductors in a Flexible Cord or Cable**

If we plug in our 12 AWG cables with 32 current-carrying conductors, we find an ampacity adjustment of 40% of the values in Table 400.5(A). Type SO 12 AWG has an ampacity of 20 amps in Table 400.5(A). When we multiply 20 amps by 40%, we come up with an ampacity of only 8 amps per circuit ( $20 \times 0.4 = 8$ ). If we use this calculation, these circuits must have an overcurrent protective device of not more than 8 amps each!

This can’t be right, because the circuits at the Rialto are protected by 20 amp circuit breakers on the dimmers feeding them. What’s going on here? When the system designer was picking the cable sizes to feed the connector strips, it was quickly determined that to get a full 20 amps to all 32 circuits would require either a large number of cables with fewer conductors per cable, or very large conductors in each cable, due to the ampacity adjustment factors of Table 400.5. The designer likely said “Wait a minute, this is a theatre! They don’t turn on all the circuits at once, and they don’t load them all to 100%. They have *diversity*.”

Seeking relief from the Draconian adjustment factors of Table 400.5, the designer fled to *NEC* Article 520, which governs the special occupancies *Theaters, Audience Areas of Motion Picture and*

*Television Studios, Performance Areas, and Similar Locations*. Article 520 modifies the general requirements of the *NEC* in chapters 1 through 4, including Table 400.5, to allow for special conditions found in these occupancies.

## Introducing NEC Table 520.44

| Size<br>(AWG) | Temperature Rating of<br>Cords and Cables |                 | Maximum<br>Rating of<br>Overcurrent<br>Device |
|---------------|---|-----------------|---|
|               | 75°C<br>(167°F)                           | 90°C<br>(194°F) |   |
| 14            | 24  | 28              | 15  |
| 12            | 32  | 35              | 20  |
| 10            | 41  | 47              | 25  |
| 8             | 57  | 65              | 35  |
| 6             | 77  | 87              | 45  |
| 4             | 101                                       | 114             | 60  |
| 2             | 133                                       | 152             | 80  |

**Table 520.44 Ampacity of Listed Extra-Hard-Usage Cords and Cables with Temperature Ratings of 75°C (167°F) and 90°C (194°F)\* [Based on Ambient Temperature of 30°C (86°F).**

\* Ampacity shown is the ampacity for multiconductor cords and cables where only three copper conductors are current-carrying as described in 400.5. If the number of current-carrying conductors in a cord or cable exceeds three and *the load diversity factor is a minimum of 50 percent*, the ampacity of each conductor shall be reduced as shown in the following table:

| Number of Conductors | Percent of Ampacity |
|----------------------|---------------------|
| 4–6                  | 80                  |
| 7–24                 | 70                  |
| 25–42                | 60                  |
| 43 and above         | 50                  |

**Note:** *Ultimate insulation temperature. In no case shall conductors be associated together in such a way with respect to the kind of circuit, the wiring method used, or the number of conductors such that the temperature limit of the conductors is exceeded.*

*A neutral conductor that carries only the unbalanced current from other conductors of the same circuit need not be considered as a current-carrying conductor.*

*In a 3-wire circuit consisting of two phase conductors and the neutral conductor of a 4-wire, 3-phase, wye-connected system, the neutral conductor carries approximately the same current as the line-to-neutral currents of the other conductors and shall be considered to be a current-carrying conductor.*

*On a 4-wire, 3-phase, wye circuit where the major portion of the*

*load consists of nonlinear loads such as electric-discharge lighting, electronic computer/data processing, or similar equipment, there are harmonic currents present in the neutral conductor, and the neutral conductor shall be considered to be a current-carrying conductor.*

There are some notable features in this table:

- Where Table 400.5(A) only provides ampacities for Type SO cable with a 60° C temperature rating, table 520.44 covers cables of 75° and 90° C. This produces higher ampacities for a given wire gauge than those of Table 400.5(A). For instance, a 90° C, 12 AWG cable with three current-carrying conductors has an ampacity of 35 A, compared to 20 A for Table 400.5(A). Note that the table does not actually allow one to draw 35 A through a 12AWG cable, because the right-hand column limits the overcurrent protective device on the circuit to 20 A. Therefore, the higher ampacity of 90° C cable merely provides a higher starting point for ampacity adjustment when faced with high conductor counts in the cable.
- Table 520.44 provides a less stringent ampacity adjustment table for more than three current carrying conductors in the cable. Note that for our 32 current-carrying conductors in the Rialto, this table allows an adjustment factor of 60%, rather than the 40% of Table 400.5.

- **As a tradeoff for the less stringent adjustment factor, Table 520.44 demands a minimum of 50% diversity on the circuits in the cable. This requirement is buried in the asterisked note to the table. It is this requirement that produces the hidden diversity on our Rialto circuits.**

- Our Rialto cables of 32 current carrying conductors in a 90° C cable have an ampacity of 21 amps per circuit, which is above the 20 A overcurrent protective device of our dimmers—a proper design choice.

Once we determined that the system designer used Table 520.44 to select the drop cables to our Rialto connector strips, we also realize Table 520.44 provides the correct answer to the question we posed to our production electrician: “How many loads of what size can we plug into that 32-circuit connector strip?” We are constrained by 50% diversity on these 32 circuits. This means we can load each circuit to 100% of its rating, but only turn on 50% of the circuits simultaneously. Or, we can load all circuits to 10 A each, and turn them all on at once. Or, we can fully load some circuits, and connect no load to others. Or, we can use some combination of these three conditions, just as long as we insure that the total energized load across the 32 circuits does not exceed 320 A, split evenly between the two drop cables. Note that using dimmed power

levels as a method of creating 50% diversity won't work. This is because there is a non-linear relationship between dimmer settings and power output.

## Why are the ampacities of Table 400.5 and Table 520.44 so different?

The portable cords and cables of Article 400 assume a temperature rating of only 60°C, with resulting lower ampacities. However, 90°C cables are now common, so why does Article 400 ignore them? The answer lies in the expected use of these cords and cables. Article 400 assumes that one or both ends of a portable cable will be *terminated in a connector* and those connectors are likely to have a terminal rating of only 60°C. Therefore, it doesn't matter what the temperature rating of the cable is, it must be used at the ampacity matching the temperature rating of the lowest rated device. In this case that's the 60°C connector.

On the other hand, Table 520.44, in addition to its 50% diversity requirement, assumes that the cable will be terminated at each end in a *terminal block* that is rated at 90°C or higher. That is the reason that Table 520.44 specifically addresses 75°C and 90°C portable cords.

## The UL Listing approach and why cable diversity is hidden

If we examine the manuals on our Rialto system, the labels on the equipment, and even the system electrical drawings, we are not likely to find that 50% diversity requirement for our 32-circuit connector strip. How could such an important NEC-mandated requirement be so well hidden from end users of the system, especially since it is likely present in the majority of installed entertainment lighting systems? The reasons are subtle.

Connector strips and gridiron junction boxes are rarely UL-listed *as a unit* with the flexible cable that connects them. That cable is typically selected, provided, and terminated by the installer, or by a supplier other than the connector strip manufacturer. The cable may appear on system drawings as "By Others." The UL rating of the two devices does not necessarily *assume or require* a flexible cable between the two devices that has an ampacity adjustment factor applied, along with required diversity. In our Rialto example, one might choose to use 32 cables with two current-carrying-conductors each that were not bundled together. While such an approach is impractical, it's an example of an allowable approach that would have no ampacity adjustment or diversity requirement. A generic connector strip listing anticipates such an approach.

UL actually has a requirement in the UL 1573 standard for marking connector strips where diversity *is* required by the cable

feeding the connector strip, and that cable is included in the listing of the connector strip:

*59.4 When an ampacity reduction factor associated with note (a) in Table 18.3 is applied to the flexible cord or cable used to supply a borderlight, connector strip, or drop box, the unit shall be marked where visible during use with the word **WARNING** and the following or equivalent wording: **Risk of Fire.** \_\_\_\_\_ must be operated with a load diversity factor of 50 percent minimum. The blank is to be filled in with the term "borderlight," "connector strip," or "drop box," as applicable.*

Table 18.3 turns out to be a duplication of the ampacity adjustment factors in NEC 520.44, and the ampacity Table 18.1 it references also turns out to match the ampacities of 520.44.

**... every currently-installed wiring device fed by a drop cable sized to NEC 520.44 is subject to the 50% diversity requirement ...**

## The labeling conundrum

Have you ever seen one of those labels in a theatrical lighting system? Think hard—you'd probably remember the "Risk of Fire" part. Try as I may, I can't recall ever seeing such a label in the field. However, there is a new class of device emerging where you are likely to see such a label: the self-contained, packaged hoist which includes the lifting machinery, connector strip, and drop cable that are UL-listed as a unit. The appearance of this type of label might be a source of discussion or consternation among specifiers and users who believe that the 50% diversity is a new reduction in the rating of this type of power distribution. In fact, *every* currently-installed wiring device fed by a drop cable sized to NEC 520.44 is subject to the 50% diversity requirement—even if it is well-hidden—and we've been living with that for many years without notable failures.

## Why haven't there been more problems?

If we accept that most circuits in the field fed by flexible drop cables have a hidden 50% diversity requirement, and that few users know about this requirement and how to manage it, the next logical question is, "Why haven't there been more failures of drop

cables due to overloading?” The answer probably lies somewhere in these points:

- The historical per-circuit connected load on entertainment lighting systems is far lower than one would imagine. This has been driven primarily by the appearance of high-efficiency 575 W tungsten-halogen lamps. A survey of 119,862 connected loads in dimmer-per-circuit systems conducted by ETC (see [http://www.etcconnect.com/img/whitepapers/survey\\_article.pdf](http://www.etcconnect.com/img/whitepapers/survey_article.pdf)) returned these results for 120 V markets:
  - 91% of all surveyed dimmers are 2.4 kW capacity
  - 17% of all surveyed dimmers have no load
  - 60% of all surveyed dimmers are loaded to 1150 W or less
  - Only 23% of all surveyed dimmers are loaded to 1150 W or more (Such light loading of dimmer systems implies a historical built-in diversity of even less than 50%.)
  - Entertainment lighting systems have inherently low duty cycles—they are off most of the time. Even if spot overloading of flexible cords has been occurring, this low duty cycle has kept cable failure rates low.
  - Even as on-all-the-time arc-source fixtures on non-dimmed circuits have increased in popularity, common practice is to limit the number of fixtures to one per circuit, continuing the light loading approach.

## Conclusion

Most, if not all permanently installed entertainment lighting system wiring devices fed by flexible cables are subject to a 50% diversity requirement set by NEC Table 520.44. Specifiers and users need to be aware of this requirement as it applies to their specific installation, and manage loads accordingly. Managing loads will become

especially important in the future as lighting fixtures move from tungsten loads to alternate sources. While these sources are likely to be more efficient and lower power than tungsten, they are also likely to have switch-mode power supplies that are on all the time, as opposed to the low duty cycle of tungsten sources. In addition, these power supplies often create harmonics (another source of overcurrent) when they are operating at full load, while phase-control dimmers used with tungsten loads only generate harmonics when consuming less than full power.

As new products appear that are UL-listed as complete units including wiring devices and flexible cable, they will likely have warning labels mandating 50% diversity. Specifiers and users should be aware that these labels will simply be documenting a condition that has been a hidden de facto standard for many years. ■

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## What happens if diversity is ignored?

As an experiment for this article, we asked the question: "What happens if we purposely ignore diversity required by the NEC and fully load a multiconductor cable?" We set up a 12/26 Type SO 90°C multiconductor cable with 24 current-carrying conductors in 12 circuits, in a vertical drop configuration. Each of the 12 circuits was loaded to 20 amps, just one amp below the 21 amp limit set by Table 520.44 for 24 current-carrying conductors. The ambient temperature was normalized to 40° C (104° F), a temperature likely to be found in the fly loft of a theatre above hot lights. For the purposes of this experiment, additional NEC-mandated ampacity adjustment factors for ambient temperatures over 30° C (86° F) from table 310.16 were ignored. In this case, the higher ambient temperature would have reduced the ampacity of our cable from 21 amps to 19.11 amps.

The results were as follows:

| Celsius Time | Thermo | C1   | C2   | C3   | C4   |
|--------------|--------|------|------|------|------|
| 7:45 a.m.    |        | 46.9 | 48.8 | 53.7 | 52.0 |
| 8:00 a.m.    |        | 56.8 | 61.4 | 67.0 | 66.6 |
| 8:15 a.m.    |        | 67.7 | 72.5 | 79.0 | 79.7 |
| 8:45 a.m.    |        | 75.6 | 82.4 | 90.0 | 91.7 |
| 9:00 a.m.    |        | 78.1 | 85.3 | 92.8 | 94.6 |
| 9:15 a.m.    |        | 78.6 | 86.7 | 94.3 | 96.3 |
| 9:30 a.m.    |        | 78.5 | 87.4 | 95.0 | 97.1 |
| 9:45 a.m.    |        | 78.8 | 87.4 | 95.1 | 97.2 |
| 10:00 a.m.   |        | 79.1 | 87.5 | 95.3 | 97.2 |

### Thermocouple locations:

- C1 Outside of outer jacket
- C2 Inside of outer jacket
- C3 Inside outer ring of conductors
- C4 Inside inner ring of conductors

You can see that the test violated the requirements of Table 520.44, specifically: *"Ultimate insulation temperature. In no case shall conductors be associated together in such a way with respect to the kind of circuit, the wiring method used, or the number of*

*conductors such that the temperature limit of the conductors is exceeded."*

Any temperature over 90° C in the test (indicated in red) violated the ultimate insulation temperature of our test cable.

In addition to a clear code violation, such overtemperature conditions create the risk of fire and severely shortened cable life.

Finally, the jacket temperature in our test reached 79.1° C, or 174° F, which represents a substantial touch hazard.