Power Play

Considerations for Feeding Permanent Dimmer-per-Circuit Systems

by Steve Terry

It's unfortunate, but the sizing of feeders, transformers, and related switchgear for a permanent dimmer-per-circuit system is an area where confusion and misinformation are too often the norm. This confusion is so pervasive that in 1993 the *National Electrical Code* was modified to help clear up the mess. It's an interesting anecdote: In 1990 USITT proposed a change to NEC Article 520, Theaters and Similar Locations, to clarify the feeder requirements for permanent dimmer racks. NEC Code Panel 15 initially rejected the proposal, responding that the NEC was already quite clear on the subject, thank you very much. In response, USITT provided a copy of a Q & A column from a national electrical industry magazine, in which a reader had asked, "What size feeders should I use for a 96 x 2400 watt dimmer-per-circuit rack?" The response from the then Chief Electrical Inspector of the State of Washington *incorrectly* stated that the rack had to be fed at its full nameplate rating, or at least 640 amps three-phase. Upon reading this, NEC Code Panel 15 finally acknowledged that there was a problem. If a state chief inspector couldn't get it right, how was the poor local contractor or engineer going to specify the proper feeds? So, in the 1993 Code, Section 520.27 (C) was changed to read:

(b) Supply Capacity. For the purposes of determining supply capacity to switchboards, it shall be permissible to consider the maximum load that the switchboard is intended to control in a given installation, provided that:

(1) All feeders supplying the switchboard shall be protected by an overcurrent device with a rating not greater than the ampacity of the feeder.

(2) The opening of the overcurrent device shall not affect the proper operation of the egress or emergency lighting systems.

FPN: For computation of stage switchboard feeder loads, see Section 220.10

Section 220.10, referenced in the fine print note (FPN), speaks to the requirements for continuous and non-continuous loads and the application of any applicable demand factors. Since there are no published demand factors applicable to theatres, the bottom line is that a dimmer rack can be fed with enough power to control the inventory of fixtures (present and future) in a given facility. The one caveat is the requirement that if you are going use a derated feeder to feed a dimmer rack with less than its nameplate (full load) rating, then you must insure that the houselights and emergency lights are not affected if the main breaker trips. In practical terms this dictates a separate main breaker for emergency lighting and at least those houselight circuits that are used for egress lighting, if the system has a derated feed. Often, for convenience, the entire houselight system can be fed from a separate main. The result is that if you turn on too many stage lights and trip the main breaker, the audience will be able to sit in comfort reading their programs while you reset the breaker and relight the show!

How Much Power?

NEC Article 530 for Motion Picture and Television Studios provides a convenient demand table for establishing feeder sizes. This table is often misapplied to "theatres and similar locations" covered by Article 520. In fact there is no demand table applicable to article 520 venues, which means the end-user, theatre consultant, and electrical engineer must produce a load schedule. This document describes the loads connected to each dimmer for purposes of feeder size calculation. However, since there are usually many more dimmers in the system than will actually be used simultaneously in a single production, determining a plausible load schedule can be tricky.

For instance, if the theatre contains 288 dimmers of 2400-watt capacity (5,760 amps total capacity), but the owned fixture inventory is only 200 fixtures of 575 watts each (958 amps total load), that establishes a direction for derating. However, if the theatre will serve other clients who may bring in additional fixtures, or the primary user has a fixture inventory expansion plan in mind, those factors must be considered. For a convertible theatre space that can operate as both a proscenium and theatre-in-the-round, it is unlikely that the circuits on the upstage wall will be used when the entire production is downstage of the proscenium. This provides another source of derating data.

The trend towards more energy-efficient fixtures will have a big effect on power requirements. With the advent of new technologies, the typical 1000-watt fixture of 1993 has become a 575-watt fixture in 2002. The types of productions in a facility also have a major effect on the power situation. For example, a regional theatre that works with a fundamentally fixed inventory of fixtures is unlikely to need the same level of power overhead as a roadhouse that may host small plays, large touring musicals, and television awards shows.

As a general rule, the load schedule must include a load of some plausible size for *each and every circuit* in the system. Load schedules with no load on some circuits, or notes saying "future expansion" are not usually acceptable to electrical inspectors. Remember that the aim of the load schedule is to describe a system that has adequate capacity for future needs, not to prove how small a feeder can be used. In real life, the load schedule will rarely, if ever, match the loads in the hookup for a specific production. When the show is hung, some dimmers will end up with no load, while others will have higher loads than those entered in the load schedule. However, the sum of the loads entered on the schedule, across the entire system, should represent the power needs for a typical production, plus overhead for future expansion.

One final note on feeder sizing: It is not permissible to factor the dimming of loads into the derating equation. Thus, you cannot turn on 800 amps of connected load with a 400-amp feeder under the theory that "we'll never bring anything above 50%." This is absolutely *verboten*, since a dimmer at 50% does not draw half the current of the same dimmer at full; it is not a linear relationship between dimmer setting and RMS current. In addition, reduced levels create harmonics (see below), which play havoc with an undersized service. The load schedule must consider the *full* power of any loads that will be energized. However, it is permissible to apply a demand factor based on the assumption that some percentage of the fixture inventory will not be plugged in for a given production.

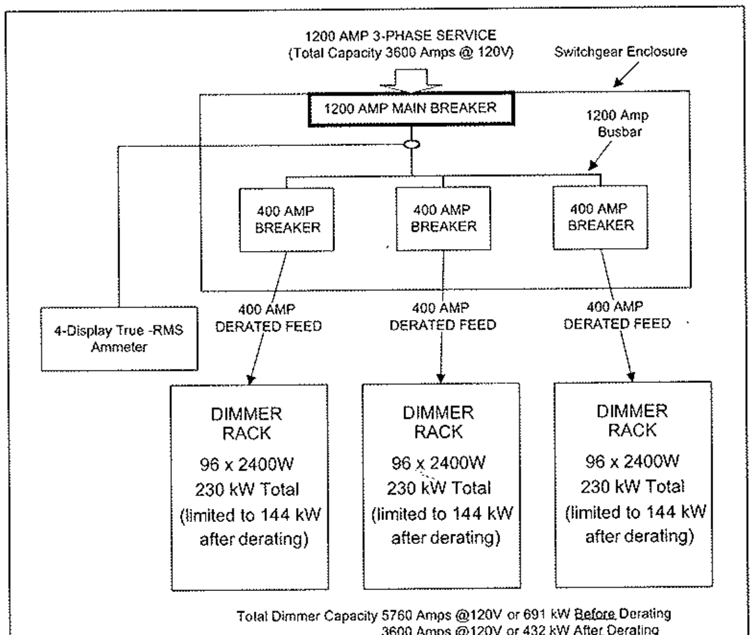
Feeder Derating with Style

Using the load schedule, when you finally determine the total amount of power to feed your system, the next question is *where* to derate? Let's say you have three racks with ninety-six 2,400-watt dimmers each. You decide that based on a reasonable load schedule for each dimmer rack, you want to feed the entire dimmer system with 1200 amps three-phase. Now you are faced with three choices:

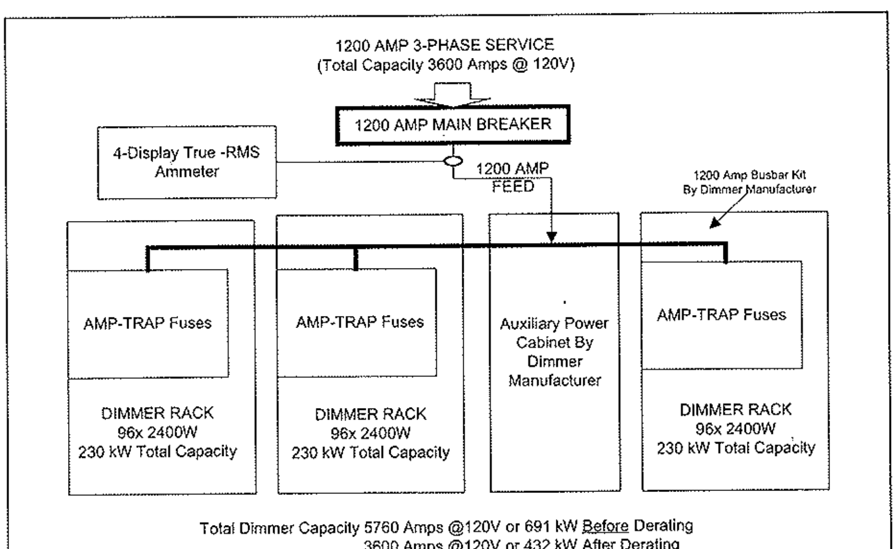
Scheme A. Install a 400 amp main breaker on each dimmer rack, with the three breakers fed from a 1200 amp main.

Your load schedule may indicate that 400 amps three-phase is an adequate size of feeder for each individual rack. However, this derating approach is the least desirable choice from a flexibility point of view. You determined that 1200 amps was the right amount of current for the system, but did you determine *where* that current would be needed? The load schedule was a reasonable determination of the total amount of power required, spread across all dimmers in the system. With a hardwired dimmer-per-circuit system, you could be in trouble if you have a requirement to put a heavy load on adjacent outlets that are in the same dimmer rack (an unusually big cyc lighting load, for instance). Since each group of 96 dimmers only has 400 amps available to it, you have limited the ability to "spot-load" the system to high capacity. Running cables from balcony rail dimmer outlets to feed cyc fixtures upstage is not a pretty solution to this problem! In addition, the 400 amp breaker feeding the rack does not allow 400 amps of continuous current, but only 320 amps (see circuit breaker discussion below). That's getting pretty thin for 96 2.4kW dimmers in most applications. Better to consider the other two alternatives below.

Scheme B. Bus all three racks together with a 1200 amp factory-provided busbar kit, and utilize the rack manufacturer's stock fuses on each rack to limit the fault current to the rack's rating and provide overcurrent protection. Feed the busbar with a 1200 amp main breaker.



Scheme A Provides individual rack feeder derating



Scheme B Bused racks with main breaker derating

This is a good solution for flexibility and economy. It allows the full 1200 amps to be deployed anywhere in the system up to the ratings of individual racks. Since individual racks may have busbar ratings less than 1200 amps, most manufacturers offer optional fuses as part of the dimmer bank assembly. These fuses come in two flavors: overcurrent protectors and fault current limiters, which are often described by the fuse manufacturer's trademark, "Amp-Trap." Some fuses combine both functions in one package. Since the entire rack/fuse/busbar assembly is listed as a unit, fuse type selection should be left to the dimmer manufacturer. And you don't need to worry about these fuses blowing; unless there is a catastrophic fault within the rack busing structure (you dropped a wrench onto the live busbar) the proper overcurrent coordination of the rack's branch circuit breakers will prevent the fuses from blowing under normal conditions. This solution is very economical to install since the electrical contractor's work and the amount of external switchgear is reduced because of the single feed and breaker. The one desirable feature that it lacks is the ability to shut down individual racks in case of a problem, or limit a fault to a single rack. When that single main breaker trips, the whole system is going dark.

Scheme C. Install an oversized 800 amp breaker to feed each rack, with all three breakers fed from a 1200 amp main breaker.

If your budget will tolerate it, this is the best solution. While your load schedule may have indicated that 400 amps per rack was adequate, you can use oversize breakers on each rack to allow the spot-loading capability of the bused arrangement above, while allowing shutdown of individual racks. This scheme has some cost premium because of the additional breakers, switchgear, feeder conductors, and installation labor.

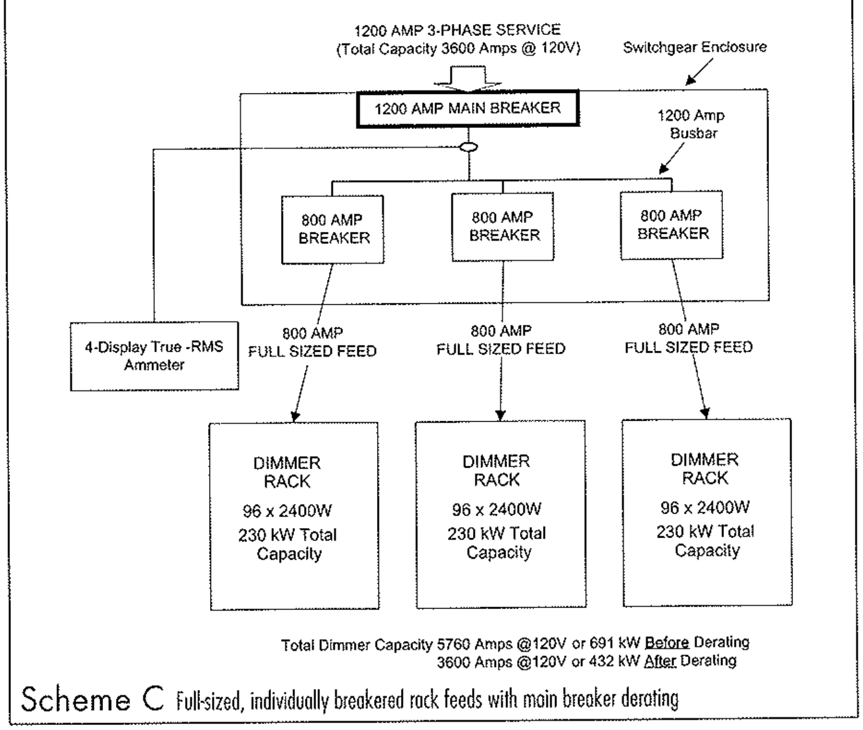
Solving for Harmonics

All modern SCR phase-control dimmer racks are non-linear loads. That is, they do not draw current in a sinusoidal waveform like a linear load such as a lamp. The waveform chopping of the dimmer creates a current waveform rich in triplen (third order) harmonics. These harmonics can overheat transformers, circuit breakers, and feeder conductors. The NEC mandates that the design of the power system takes into consideration the presence of harmonics caused by non-linear loads in Section 220.22 FPN No. 2. In general, the basic ways to cope with harmonics are:

A. Use a separate delta-wye transformer to feed the dimming system. Since triplen harmonics circulate in the delta primary of the transformer, they are stopped by the transformer and cannot propagate onto the rest of the building electrical system. This has the effect of helping the dimmer system comply with IEEE Standard 519 *Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems*. Many electrical engineers are applying the harmonic limits of this standard to dimming systems. The standard limits total harmonic distortion of the voltage waveform on the building electrical system to 5%.

B. Use oversize neutral conductors and busbars. Since triplen harmonic currents are of the zero-sequence variety, they sum rather than cancel in the neutral of a wye system. This can require oversize conductors to compensate for higher neutral currents. It is not uncommon to measure neutral currents in a dimming system that are 25% higher than phase currents.

C. Use 100% rated main breakers with electronic trip mechanisms. These breakers are less susceptible to false tripping caused by harmonic overheating of the thermal elements in a normal circuit breaker.



Scheme C Full-sized, individually breakered rack feeds with main breaker derating

Flying by Instruments

While the NEC does not require it, it is an excellent idea to install a three-phase, four-display true-RMS-responding ammeter on the feeders of any derated system. This meter should include a readout for the neutral as well as the three phases, since the neutral will generally operate at higher currents than the phases due to harmonics (see below). This type of meter is excellent insurance against surprise blackouts, especially when fixture inventories grow. You will need a separate four-display meter and set of current transformers for every main feed to the system.

Proper Transformer Selection

Standard transformers are listed for use with linear loads only. Therefore, the transformer feeding a phase control dimming system, which is a non-linear load, should have a K-rating. The K-rating means that the transformer is listed for non-linear loads, and is able to properly withstand heating caused by increased hysteresis losses, increased circulating current losses in the transformer primary, and increased eddy current losses caused by these loads. A common misconception about K-rated transformers is that they are just normal transformers re-labeled to the next smaller size, thus adding inherent derating to deal with the nonlinear load. This is simply not the case; K-rated transformers are built very differently than normal transformers. The core and windings have additional ventilation, there is more steel in the core and it has different saturation characteristics, and the primary has additional cross-section to deal with harmonic circulating currents. They may also have oversize neutral buses to deal with neutral overcurrents, and differently shaped conductors to combat eddy current losses. All these elements combine to allow the transformer to operate at or below rated temperature in the presence of harmonics. Transformers are available in different K-ratings depending on the amount of harmonics for which they are designed.

It has been argued by some that typical dimming systems do not really require K-rated transformers, since they generate the maximum amount of harmonics only when consuming less than full power due to reduced dimmer settings. This might be true when the dimmer system is only a small part of the load on a transformer. For example, if the dimming system uses only 150 kVA from a 1500 kVA transformer feeding everything else in the facility, the harmonic component of the dimming system is not likely to have an adverse effect on the transformer. But when a dedicated transformer is installed on a dimmer system in order to stop the propagation of harmonics or provide boosted line voltage to compensate for dimmer losses, it is likely that a much smaller transformer could be used on the same 150 kVA dimming system. In such cases, field experience has proven that a K-rated transformer is desirable, both to comply with the UL listing of the transformer, and extend its service life through lower temperature operation. In addition, dimmer systems always generate some harmonics even at dimmer settings of full, since there is always a certain amount of zero-crossing dead time in the dimmer output waveform and thus it is never a pure sine wave.

For a typical SCR phase-control dimming system, field experience in a number of installations has shown that a K-13 rating is an appropriate choice. This is not based on calculation of the dimmer system's precise harmonic content, since that is almost impossible to characterize because it is different for every possible permutation of dimmer settings and loads. Many engineers have trouble with this empirical method of K-rating, since a lot of familiar harmonic generating equipment such as variable frequency motor drives *can* be precisely characterized. However, field experience has validated this selection method.

Other transformer characteristics such as impedance, shielding, temperature rise, copper versus aluminum windings, and noise rating must also be taken into consideration. Finally, it is important to plan for the fact that K-rated transformers are typically 15% to 25% larger and heavier than a normal transformer of the same power rating.

Conductor Sizing

Feeder conductor sizing should be done using NEC Table 310.16. It's important to note that NEC Section 520.27 (B) requires that the neutral feeding SCR phase control dimmer racks be considered a current-carrying conductor. This is because of harmonics, since the neutral is not simply carrying the imbalance current of the three phases as it would in a linear load situation. The net effect is to cause derating of conductor ampacity to 80% of the values in Table 310.16 when there are four wires (three phases plus neutral) in a conduit. This reduces the overall heating of the four-wire system. Note that this derating will not be required if the feeder conductors are installed in a raceway (not a conduit) with not more than 30 total conductors, and where the cross-sectional area of the conductors does not exceed 20% of the cross section of the raceway (NEC Section 376.22). Even with the derating above, it may also be desirable to further increase the neutral size above the phase conductor size. The NEC does not specifically require this increase in size, but it creates a nice low impedance neutral to deal with overcurrents caused by harmonics. This minimizes dimmer interaction and flicker, two common symptoms of undersized neutrals.

For example, a ninety-six channel, 2,400-watt-dimmer rack fed at full capacity (640 amps three phase), would require two copper 90-degree C 500 kcmil conductors in parallel (ampacity 430 amps each x 0.8 = 344 amps each x 2 = 688 amps) for each phase and neutral. In selecting a wire temperature rating, it is important to make sure that the dimmer rack installation instructions don't conflict with your choice. For instance, in some dimmer racks, the installation instructions require the use of 90-degree C wire but at the 75-degree C ampacities listed in NEC Table 310-16 to compensate for the higher temperatures in the rack. Also, most circuit breakers are listed for use with 75-degree C wire, so breaker specifications must be factored into wire selection.

Circuit Breaker Selection

Standard molded-case circuit breakers are generally listed for operation at 80% of their rating. On a derated dimmer bank feeder this becomes an especially important consideration. When using a standard circuit breaker, the continuous available current is 80% of the breaker rating, not 100%. This might be overly limiting on a derated breaker (like the 400-amp breaker feeding a single rack in derating Scheme A above, which only yields 320 amps continuous). A good solution is to use an electronic-trip circuit breaker that is listed for operation at 100% of its rating. This would be a good choice for the main breaker on the entire system, but not such a good choice for individual breakers feeding each rack in the system, because 100% electronic-trip breakers are more expensive than standard units. This is yet another argument against installing multiple derated breakers as in derating Scheme A above. Using one 100% electronic breaker as the single point of derating is a preferable solution.

It's worth noting here that the *branch circuit breakers* in most listed entertainment dimmer racks are fully magnetic, and thus suitable for 100% loading. In the case of a typical entertainment dimmer, the rack is likely to have been tested by UL for 100% load, 100% duty cycle, so 2,400 watts on a 2,400-watt dimmer is fine. However, not all dimmers have this rating (most architectural dimmers are typically rated for only 80% continuous load), so it's worth looking at the dimmer specifications.

Is the load on a theatrical dimming system really continuous? That's a hard call, since the line of demarcation between a continuous and non-continuous load is three hours of operation. While that duty cycle may not occur in a normal theatrical production, it is certainly achievable during a rehearsal. Using a 100% main breaker removes worries about non-continuous loads that suddenly become continuous.

Another important breaker characteristic is the interrupting rating (expressed in kAIC or kilo-amps of interrupting capacity), or the ability to clear a short circuit or fault current. However, discussion of fault current coordination is outside the scope of this article, and is best left to the project electrical engineer.

Evaluating Existing Installations

Many of the issues raised in this article have come to light over the past twenty years, as the behavior of nonlinear loads such as phase control dimmer racks has become better understood. Most existing installations are probably code-complaint with the version of the NEC in effect at the time of installation, and are probably working well. However, a periodic electrical survey of existing installations is always a good idea. Such a survey might include power quality monitoring, infrared scans of switchgear, and monitoring of feeder currents (all three phases and neutral) during operation. Some of the questions to ask are:

- Has the fixture inventory grown significantly since the system installation? Is there still enough power?
- Are there power quality problems caused by the dimming system that are affecting other systems in the theatre? Crashing computers? Noisy sound system?
- Are circuit breakers operating at elevated temperatures? How about neutral conductors and busbars? An infrared scan of the switchgear is cheap insurance.
- Has the facility experienced main breaker tripping on the dimmer system due to overloads or continuous loads?

Answers to all these questions will provide direction as to whether the power distribution feeding the dimming system is due for an upgrade.

Engineering for Success

In conclusion, this article has discussed areas of electrical design that are often left to the project electrical engineer. An engineer who deals primarily with commercial or industrial power systems will often welcome guidance from the theatre consultant, systems integrator, or even the end user in helping to find his or her way through unfamiliar territory. However, it's important to remember that the engineer is the final authority on the design of the system, because his license is on the line when the system is reviewed by inspecting authorities. This type of electrical design is not a do-it-yourself project, and the project electrical engineer is the key participant in insuring the safety and usability of the system.

Author's Note: *Power Play was originally published in Lighting Dimensions magazine in 1997. In the ensuing five years, dozens of electrical engineers, contractors, and systems integrators have asked me for reprints. In the May 2002 ESTA Technical Standards Committee meeting, someone asked a series of great questions that might have been answered by Power Play. That seemed like a good trigger for updating and reprinting the article in Protocol. For this article (reprinted with permission from Lighting Dimensions, www.lightingdimensions.com), I have updated the National Electrical Code section references to those of the 2002 Code, so historical references to changes made in the past may not match the section numbers of earlier Codes.*

Steve Terry is the Vice President of Professional Services at ETC, where he leads the Projects, Technical Services, and Customer Services groups. Formerly, he was with PRG and prior to that, Production Arts. He is the co-chair of the ESTA Technical Standards Committee as well as the co-chair of the Control Protocols Working Group. He chaired the USITT committee that wrote the internationally accepted DMX512 standard. He is a USITT Vice-Commissioner for Engineering, and the alternate USITT representative on National Electrical Code Panel 15.