Setting Standards for Excellence

Engineering Series Ratings: Is It Practical?

By the
National Electrical Manufacturers Association

The 2005 National Electrical Code (NEC) introduces a change regarding series ratings for circuit breakers that deserves careful review before applying an engineered series rating. The additional paragraph 240.86 (A) reads:

> (A) Selected under Engineering Supervision in Existing Installations.
> The series rated combination devices shall be selected by a licensed professional engineer engaged primarily in the design or maintenance of electrical installations. The selection shall be documented and stamped by the professional engineer. This documentation shall be available to those authorized to design, install, inspect, maintain and operate the system. This series combination rating, including identification of the upstream device, shall be field marked on the end use equipment.

Notice that this new paragraph deals exclusively with existing installations and provides for a licensed professional engineer to determine the series rating in these installations. Any series rating applied in a new installation or where the equipment is replaced in an existing installation would need to comply with paragraph (B), which requires the application of tested combinations. Several issues need to be understood related to the new paragraph (A):

- Why is this provision just for existing installations?
- Is an added series rating a solution for the situation for which this is intended?
- What information does a licensed professional engineer need and what information does he/she have that will permit him/her to determine an effective series rating?

Existing Installations

The substantiation for permitting engineered series ratings only on existing installations is to address conditions where available fault current has been increased after installation due to an upgrade in the electrical distribution system. With the modification, the existing equipment and overcurrent protective devices are underrated for the higher fault current. Under the NEC revision, an overcurrent protective device (OCPD) having an interrupting rating at least as high as the increased fault current can be added to protect the installed system, if a licensed professional engineer determines that a series rating exists using this device and the installed OCPDs.

Utilities and other service operators occasionally revise their systems to provide for increased energy demand, for power quality and other reasons. When these system changes result in a higher available fault current that exceeds the rating of installed equipment, a serious hazard exists to the facility and to those working with or near the under-rated electrical equipment. Options for correcting this situation include replacing the equipment with properly rated equipment, replacing OCPDs with higher-rated OCPDs, or applying higher impedance transformers or reactors and similar equipment modifications to reduce the available fault current. Some of these options can be complex and costly, so it is reasonable that a simple and low cost solution would be desired. However, even with simple improvements the true cost could be high if the improvements do not provide the expected protection and give a false sense of security.

Attempted Corrections with Series Ratings

This definition of a series rating appeared in a 1994 article by the National Electrical Manufacturers Association (NEMA):

> Series rating: A short-circuit interrupting rating assigned to a combination of two or more overcurrent protective devices which are connected in series and in which the rating of the downstream device(s) in the combination is less than the series rating. [1]

From the definition, we see that the series rating will be higher than the rating of the downstream circuit breaker(s). By locating the higher-rated circuit breaker or fuse electrically ahead or upstream of the lower rated circuit breaker, the higher-rated device will protect itself and the lower rated downstream circuit breaker, if the series is properly selected. So, in the case of installed equipment that becomes under-rated, adding a fully rated fuse or circuit breaker electrically ahead of it might be considered as a method of protecting it. The challenge is how to select the OCPD to be added to be sure that it will provide the required protection. Let's look at two methods – the Selection of Certified Rating Method and the Analytical Method – as possible ways to select this device.

Selection of Certified Rating Method

Let's examine the simple 3-tier system of Figure 1, typical of a number of commercial installations. Then, consider adding series devices as in Figure 2.

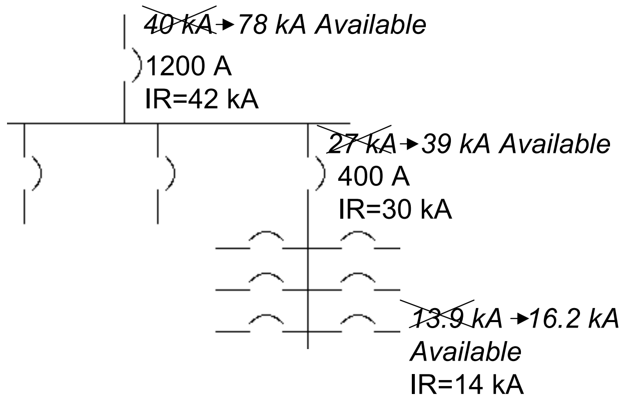

Figure 1
Typical installation with increased available fault current

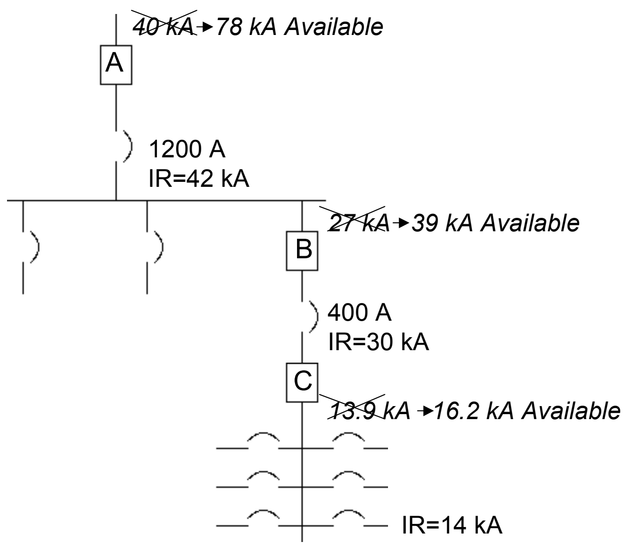

Figure 2
System of Figure 1 with added series protective devices

Suppose we added a rated OCPD at location A (device A), on the supply side of the main. We would have to determine that the added device A will protect both the 1200 A main circuit breaker and equipment in which it is installed. This step, if successful, would be an improvement in protecting the main and equipment, but it does not necessarily help us in protecting the feeders or the downstream system protected by the feeders.

The first step is to determine whether a tested series rating already exists between device A and the installed 1200 A main circuit breaker. If the rating is marked on the equipment, we know that by installing device A, the 1200 A main circuit breaker and the equipment in which it is installed would be protected. If a component recognized series rating is found to exist, but it does not appear on the equipment label, we know only that the overcurrent protective devices will perform acceptably together under special test conditions, but we do not know whether they will perform acceptably in the end use equipment, such as the switchgear or switchboard. The integrity of the enclosure, busing, and insulators in the end use equipment must be considered as is required for application of tested series ratings.

Analytical Method

If a tested series rating is not available, we might attempt an analytical method. From an analytical viewpoint the performance of two OCPDs together for a series rating should be considered acceptable if all of the following four criteria are met by the upstream OCPD:

(1) It reduces the let-through current to a value below the interrupting rating of the downstream circuit breaker.
(2) It clears the circuit at a time before the contacts of the downstream circuit breaker begin to open.
(3) Items (1) and (2) are true for all current levels from the rating of the downstream circuit breaker through the series rating of the combination (not just at the maximum current level of the system).
(4) It has an interrupting rating at or above the engineered series rating.

The question an engineer will have to answer is how to know whether the first three criteria are met.

While these criteria identify the ability of the upstream OCPD to protect the downstream circuit breaker, they do not determine whether they will perform acceptably in the end use equipment, such as the switchgear or switchboard. One way of predicting whether the equipment is also protected is to estimate the let through current and duration under which the equipment would have been tested. If these values are lower with the added device in the circuit, the equipment is most likely protected. But how would an engineer determine the conditions under which the equipment would have been tested?

Downstream Circuit Breakers

The analysis above relates to protecting the main circuit breaker and its end use equipment by adding another device at location A. It has not addressed protection of the equipment on the load side of the main including the feeders and branches. Looking at Figure 2 again, we see that available fault current has increased for both the feeder and branch locations and exceeds the interrupting ratings of circuit breakers in these positions. A fault on the load terminals of the 400 A feeder will be seen by the feeder, the main, and the added device A. The four criteria listed above for this situation must once again be considered, but here there are two sets of contacts that may open and add dynamic impedance. In this case, if the contacts of either the feeder, or the main open before device A clears, the protection is unknown. By taking energy, the load-side device causes the supply-side device to open later than it would by itself, or perhaps to not open at all.

Protection of branch circuit breakers adds yet another set of contacts to consider. The likelihood that a device with a continuous current rating of the main would be adequate for protecting the branch circuit breakers becomes even lower.

In order to protect feeder and branch circuit breakers in the system, it may be necessary to add OCPD devices at locations B and C in Figure 2 to provide sufficient protection for the system including all disconnects. These added devices would need to be fully rated for the fault current available at their specific location in the system.

Tested Series Ratings

It is important to understand that prior to this addition in the 2005 NEC, 240.86 permitted only those series ratings that were marked on the end use equipment. In other words, the series rating was evaluated by the certifying organization prior to the original installation of the equipment. The means of certifying these ratings for molded-case circuit breakers (MCCBs) was by several rigorous series of tests detailed in UL 489, *Standard for Molded-Case Circuit Breakers, Molded Case Switches and Circuit Breaker Enclosures*, and UL 67, *Standard for Panelboards*. Under this certification process, the performance requirement and application of series ratings is clear.

Are Analytical Methods Effective?

If the four criteria in the method above are rigorously met and the end use equipment can be found to be satisfactory, the analysis should be effective. However, meeting the criteria with real equipment and devices may not be practical. Obtaining information related to the first three criteria may be difficult since it is not published and will be unique to the conditions present.

One analytical method used in the past for estimating some series ratings was the Up-Over-Down method for protection of some equipment by current limiting fuses. However, as related to series ratings, it was found that if the downstream circuit breaker contacts were to open before the upstream fuse clears, the protection is unknown. The reason protection cannot be predicted in this way is that the two devices are sharing the energy of interruption. Contact separation is the beginning of circuit interruption by the downstream circuit breaker. Remember this breaker is not rated for the circuit with the increased fault current that it is attempting to clear. This action by the circuit breaker introduces a dynamic impedance in the circuit and takes some of the energy of interruption from the upstream device, which slows clearing by the upstream device. The result is that the downstream circuit breaker often attempts to interrupt more energy than it is designed to take and it is therefore not protected. Publications in references 2, 3, and 4 describe this interaction.

The primary difficulty in meeting the analysis criteria is the fact that circuit breaker contacts open very rapidly, especially when the fault current is higher than the rating of the circuit breaker. Some typical contact separation times for MCCBs from series tests are listed in Table 1. Even current-limiting circuit breakers and fuses do not generally operate rapidly enough to clear before circuit breaker contacts start separating. In such cases, the only way to determine whether a series rating is satisfactory is by test.

TABLE 1
Typical Contact Separation Times for Circuit Breakers in Series Rating Short Circuit Tests

Circuit			Branch Circuit Breaker	
Volts	Current, kA	Phase	Rating, Amperes	Contact Separation time, ms
240	100	3	30	0.3
240	100	3	100	0.3
240	150	3	150	0.8
120/240	22	1	100	1.6
480	65	3	60	0.7
480	35	3	250	1.6
240	100	3	250	1.1
480	100	3	800	2.0
480	100	3	1000	2.1
480	100	3	2000	1.9

All of the circuit breakers represented in Table 1 are of designs from the 1980s or before. Even the fastest current-limiting circuit breakers or fuses do not clear faster than these contact separation times. Further, for intermediate short circuit current levels, current-limiting OCPDs operate slower than they do at these very high short circuit levels. In general, MCCB contacts will always start separating before any OCPD of the same rating in the circuit is able to clear the circuit. IT IS NOT PRACTICAL TO DETERMINE SERIES RATINGS BY ANALYTICAL METHODS FOR MCCBS.

For decades, circuit breaker design engineers have attempted to determine an analytical method that will avoid the enormous amount of testing associated with developing and maintaining series ratings by test. Even sophisticated numerical analysis has not been successful to date.

Low-Voltage Power Circuit Breakers

Series ratings are not generally applied to the large, low-voltage power circuit breakers (LVPCBs). Fused circuit breakers have been developed to allow very high interrupting ratings with the limiter fuse protecting the circuit breaker above its normal interrupting rating. Since LVPCBs generally operate more slowly than MCCBs, it would seem more practical to engineer a series rating for LVPCBs than for MCCBs. The same four-point analysis mentioned above would apply for LVPCBs as well as for MCCBs.

An engineer attempting to analytically determine such a series rating should be aware that some fused LVPCBs have additional contacts and heavier operating springs than the standard circuit breaker to allow them to withstand the higher current they will see when subjected to a short circuit above their rating. These design differences also address higher temperatures they experience when operated together with a fuse. For these reasons, ANSI/IEEE C37.13 paragraph 10.8 recommends against the application of cascade ratings, another name for series ratings. Rather than adding a device in the circuit, it may be more practical to replace the under-rated circuit breaker with one of the proper rating.

Degrees of Protection

Attempting to engineer a series rating may not be as practical as the exercise would seem at first glance. As circuit breaker engineers have found while developing series ratings by test, there are many factors influencing the degree of protection offered by one OCPD for a lower rated circuit breaker in the same circuit. No method other than testing has proven successful.

However, the new 240.86(A) was added to the NEC in an attempt to provide some genuine help for installations that are operating today with available fault current well above the rating of the installed equipment. It seems to make sense that adding a fully rated device in the circuit ahead of the installed equipment would at least add a degree of protection that is not available without more extensive and costly improvements to the system. For someone working in under-rated equipment, it is more assuring to know that a properly rated OCPD is someplace in the system rather than depending on protection by utility transformer protection, which is usually not designed to protect the low-voltage equipment. Members of NEC Code-Making Panel 10 in their deliberations considered this new paragraph to add a "degree of protection."

In testing for series ratings, non-conforming results include: damaged internal parts of the downstream circuit breaker that would not allow it to be turned on again, bursting of the circuit breaker's molded case, or arcing from the circuit breaker to the end use equipment enclosure. A long list of criteria exists with which the series devices must comply. Those who write the standards consider each criterion essential to the safe application of the rating. If the same criteria are not expected for application with existing installations, it is reasonable to question whether the provisions of 240.86(A) are truly series ratings. If a degree of protection is acceptable, as compared to demonstrated compliance with all requirements, provision for special protective measures for existing installations in which the fault current has increased should be clarified and should not be considered a series rating.

Summary

The rationale for adding 240.86(A) to the 2005 NEC is to address a real problem facing a number of installations, however the solution in the revised wording may not be a valid solution. The ideal solution is to have equipment installed that has ratings suitable for the application and that is the intent of the revised wording. Circuit breaker manufacturers, based on many years of experience of designing and testing circuit breakers, understand that a series rating can only be determined by test. An analytical approach for engineering series ratings is enumerated above that would be effective if devices satisfy the specified criteria. However, because of interaction between the devices involved, engineering a series rating without testing is not practical where MCCBs are involved and product standards recommend against the application of series ratings using low-voltage power circuit breakers.

[1] National Electrical Manufacturers Association, “Series Ratings,” *IAEI NEWS*, Richardson, TX, March/April 1994, pp. 23-25.
[2] Bernie DiMarco and Steven Hansen, “Interplay of Energies in Circuit Breaker and Fuse Combinations,” *IEEE Transactions on Industry Applications*, May/June 1993, pp.557-561.
[3] C. W. Kimblin and Y. K. Chien, “Integrated Series Ratings of Protective Devices,” *IEEE Conference Record of 1995 Annual Pulp and Paper Industry Technical Conference*, pp.183-189.
[4] G. D. Gregory and W. Stoppelmoor, “Test for Series Connected Circuit Breakers,” *IEEE Transactions on Industry Applications*, May/June 2003, pp. 605-611.

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APPENDIX A

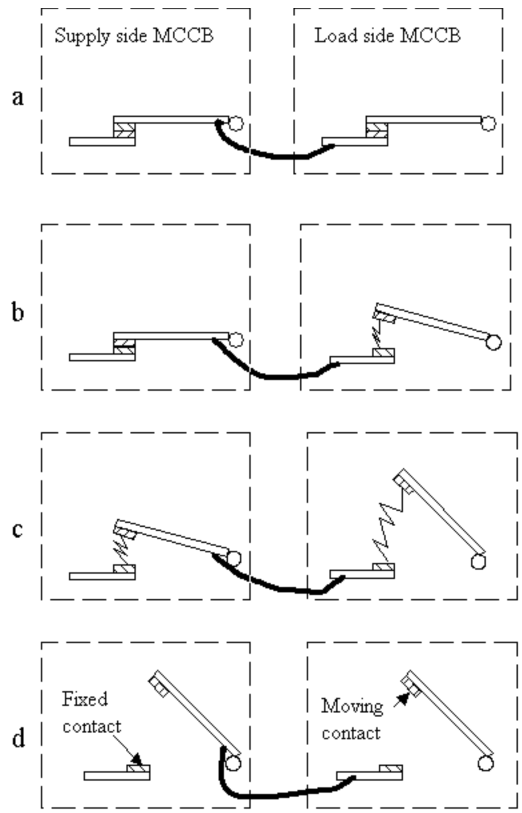

Figure A
Sequence of contact openings

DYNAMIC BEHAVIOR

Overcurrent protective devices (OCPDs) exhibit electrically dynamic behavior as they operate automatically to open a circuit. They are dynamic in that they open automatically when they detect an overcurrent condition. As related to series ratings, the dynamic behavior is the continuous changing of impedance during the opening operation as they clear the circuit. At the point of initiation of a short-circuit condition in a circuit protected by the device, it is fully closed and appears as a conductor to the circuit. Its impedance is near zero. As a circuit breaker senses the short circuit and begins to open the circuit, an arc will form between the fixed and moving contacts. If the device is a fuse, the arc is between segments of the fuse links. The device clears by extinguishing the arc, at which point the impedance of the device is infinitely large.

Let's look at how these changing circuit conditions impact overcurrent protective devices connected in series. For this purpose it will be helpful to think about the sequence of conditions that occur during the interruption, which is outlined in Figure A.

Condition (a), short-circuit initiation: As the short-circuit starts, the contacts of both devices are closed. Both the supply-side and load-side devices act as conductors in the circuit carrying the short circuit. The sensing elements (not shown in the diagram) are beginning to detect an overcurrent condition.

Condition (b), first contact separation: The load-side device begins to open first. It is first because it has a lower continuous current rating and will detect an overcurrent at a lower value than the supply-side device. Also, it will have smaller mechanical parts with lower mass, lower inertia than those of the supply-side device and they will begin moving first under influence of the same circuit forces. When the supply-side device is a fuse, it has a thermal mass or inertia that will cause it to remain closed as the load-side circuit breaker contacts separate.

By opening first, this load-side circuit breaker is attempting to interrupt the circuit alone, without the help of the supply-side device. That is, the smaller device takes all of the energy of interruption during this period. It also has developed an internal impedance that begins to limit short-circuit current. As a result of this dynamic impedance, the supply-side device does not see the same short circuit it would if it alone were attempting to clear the circuit. By taking energy, the load-side device causes the supply-side device to open later than it would by itself, or perhaps to not open at all.

If both devices have the same continuous current rating, there will be a race for first to begin opening. In this case, when the supply side device begins to open first, Condition (b) is bypassed and the load-side circuit breaker will not have to attempt to clear the short circuit alone. However, it will see the entire short circuit current and will share interruption energy as in Condition (C).

Condition (c), second contact separation: For series protection, eventually the supply-side device opens to share the energy of interruption. The degree of protection will depend on the dynamic coordination of the devices. If the supply-side device is a current-limiting device in its current-limiting mode, it will develop interruption voltage (impedance) rapidly and take most of the final stages of interruption. If the supply-side device is not current limiting or is a current-limiting device operating below its threshold of current limitation, it may develop voltage slowly and leave much of the final interruption to the load-side device.

Condition (d), clearing: In the Figure A diagram, both devices are fully open. We anticipate that the load-side circuit breaker will be open. It is not essential that the supply-side device be open at the end of the interruption, but to provide series protection, it will most often be open.

There are many variables involved in determining the degree of sharing of energy of interruption. We can identify mass of parts, spring forces, latch loads, thermal inertia (mass) and similar physical variables involved with either the upstream or downstream device. There are also electrical variables such as power factor, electrical angle of fault initiation, and system configuration that will impact the degree of sharing. The problem of determining performance of two OCPDs under these conditions is not elementary and has not been solved for ready application.