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A High-Performance Distribution Substation Bus Topology

Ralph E. Fehr, III, P.E.
Senior Member IEEE
Adjunct Professor, University of South Florida
4202 E. Fowler Ave. – ENB 118
Tampa, Florida 33620 USA
r.fehr@ieee.org

Abstract

The ring bus configuration, a topology commonly used at transmission voltage levels, can provide significant enhancements in system reliability and improvements in operating procedures, while remaining an economical and cost-effective design. This paper analyzes the enhancements in reliability and improvements in operating procedures afforded by incorporating the ring bus topology at the transmission level, and then explores further enhancements in reliability and operation by implementing the ring bus configuration on the distribution system.

Key Words

Reliability, substation, topology, planning, FRIENDS

1. Introduction

The distribution substation provides the interface between the high-voltage utility transmission system and the medium-voltage distribution feeder system. It typically consists of at least one power transformer, high- and medium-voltage bus work, high- and medium-voltage protective devices (i.e. circuit breakers), and various auxiliary devices to support these major components. While many distribution substation topologies exist, the radial bus configuration, or a variant of it, is the standard topology for most distribution substations. Radial buses have an attractive characteristic: only one circuit breaker is required per branch terminated on the bus. Minimizing the number of circuit breakers keeps the construction cost of the substation minimal, as circuit breakers tend to be costly components.

Radial buses should not be implemented at transmission voltages, however, for numerous reasons that adversely impact system reliability. The most obvious system impact is caused by a bus fault. This scenario requires the tripping of every circuit breaker on the radial bus, which results in the de-energization of the entire bus. Similarly, the failure of a circuit breaker to trip during a line fault (breaker failure) also requires every breaker to trip, thus clearing the entire bus. And, of course, a transformer fault either trips the main breaker, if one is used, or all feeder breakers otherwise, thereby de-energizing the entire distribution bus.

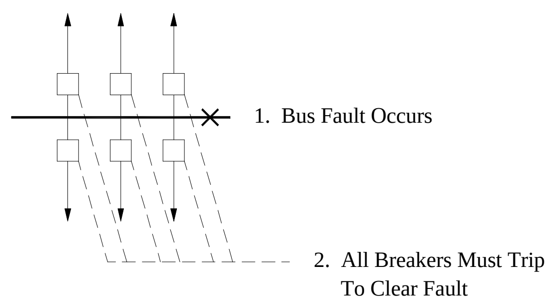

Fig. 1a – Bus Fault Clearing on a Radial Bus

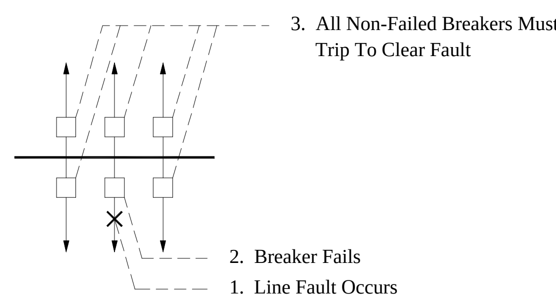

Fig. 1b – Line Fault Clearing with Breaker Failure on a Radial Bus

Clearing a transmission-voltage bus is unacceptable in virtually all cases because of the number of branches that are removed from the network in the process. Most transmission systems are designed for double-contingency operation, meaning that an n-bus system must perform within expectations (acceptable voltages and flows) with n–2 branches in service. Clearing an entire bus removes more than two branches from the network, thus necessitating more stringent (and less economical) planning criteria.

The need to plan for higher-order contingencies than n–2 can be mitigated by utilizing a substation bus topology that is more robust than the radial bus. Such a topology would not require more than one unfaulted branch to be removed from the network during bus fault or breaker failure conditions. Several topologies meet these requirements, but most require the use of more than one circuit breaker per branch, such as the breaker-and-a-half topology, which requires three circuit breakers for each pair of branches. The requirement for additional circuit breakers increases the cost of the substation substantially, so minimizing the number of circuit breakers required in a substation is a fundamental goal of the substation design engineer. One topology, however, meets the above requirements of not de-energizing more than one unfaulted branch under all realistic contingency scenarios while maintaining the economy of one circuit breaker per branch like the radial bus. This topology is the ring bus.

While the ring bus requires only one circuit breaker per branch, unlike the radial bus, it does not require bus differential protection. This benefit arises because faults on the bus structure of the ring bus are detected by the branch protection, since all parts of the ring bus itself lie within a branch protection zone. This is not the case with the radial bus, since the branch protection zones look from the bus-side bushings of the feeder circuit breakers down the feeder, not backward toward the bus.

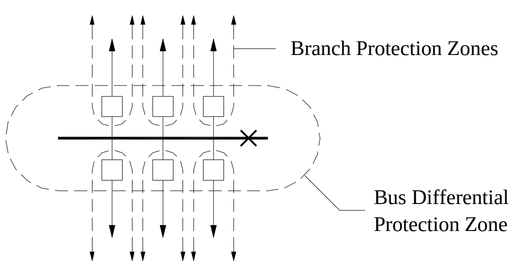

Fig. 2a – Detection of Bus Faults on a Radial Bus

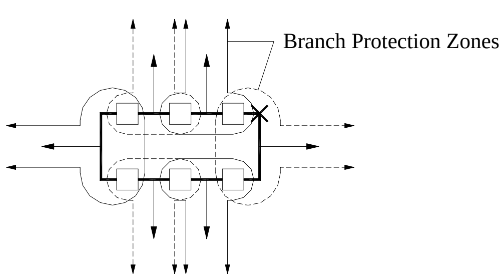

Fig. 2b – Detection of Bus Faults on a Ring Bus

Employing the ring bus topology at transmission voltages is commonly done for the aforementioned reasons. The ring bus topology, however, is seldom utilized at the distribution voltage level. This is ironic, because the primary reasons for using the ring bus configuration on the transmission system are to improve the reliability of the system. But most reliability issues on a power system originate at the distribution voltage level[1]. Knowing that, it follows that incorporating the ring bus topology on the distribution system could lead to significant enhancements in reliability while remaining an economical and cost-effective design. In fact, the ring bus topology shows promise to significantly improve the reliability and maintainability of the distribution system without significantly increasing the cost. In applications where service interruptions are of concern, the ring bus is an especially attractive distribution substation topology.

2. Reliability Benefits

The same general reliability benefits realized by implementing the ring bus configuration at transmission voltages are also gained when utilizing the topology at the distribution level. Neither a bus fault nor a failed circuit breaker clears the entire bus as with a radial design.

Another major improvement in system reliability is gained by applying the ring bus at distribution voltages. Most reliability issues originate on the distribution system. There are several reasons for this, including the failure rates of distribution-class equipment compared to those of transmission-class equipment, substantially lower BIL ratings for distribution components, and circuit exposure (many more circuit-miles of distribution compared to transmission, thereby increasing the probability of a distribution outage). But perhaps the largest influence to reliability is the fact that the distribution system is radial whereas the transmission system is not. The networked nature of the transmission system boosts the reliability of that part of the system tremendously. While the distribution system remains mostly radial, use of the ring bus topology in the distribution substation moves the network-radial interface one step lower. In a ring bus distribution environment, only the feeders themselves are radial; the distribution substations are not.

Consider a four-feeder distribution substation serving a 50 MVA load. Assuming uniform circuit loading, each feeder serves $50 \div 4 = 12.5$ MVA of load. If the substation is configured as a radial bus, a bus fault, failure of a feeder breaker, or transformer failure clears the bus, thereby de-energizing the entire 50 MVA of load.

When the substation is configured in a ring bus topology, no single event can clear the entire bus. A bus fault would cause either two or three circuit breakers to trip, depending on the exact location of the fault. If only two breakers trip, one branch connected to the ring bus would be de-energized. If that branch is a feeder, the load lost is 12.5 MVA. Tripping three breakers would de-energize two adjacent branches on the ring bus. If both branches were feeders, the load lost would total 25 MVA. Even this worst-case scenario keeps 50% of the substation load energized. This improvement in availability is especially significant where either momentary or sustained interruptions are of concern. And by carefully selecting where on the ring bus various circuits are terminated, even more significant improvements in reliability can be realized. For example, a feeder and the backup feeder for that feeder should not be terminated in adjacent ring bus positions, so that a single contingency cannot de-energize both.

One of the branches lost when a pair (or three) circuit breakers trip could be a transformer that supplies the ring bus. If that transformer is the only source to the ring bus, all loads supplied by the substation would be de-energized, but that contingency can be easily remedied.

A second source, which is treated simply another branch, can be added to the distribution ring bus for increased reliability. With a second transformer, the loss of one transformer does not de-energize the bus. By carefully designing the ring bus, breaker failure would never de-energize both sources (the two transformers should not be terminated in adjacent ring bus positions).

Use of more than one transformer in a substation is common with the radial bus topology. Typically, each transformer supplies one radial bus, and the buses are connected together with normally-open tie breaker. When a transformer becomes disconnected from the distribution bus, some means of source transfer must be executed. This is usually a break-before-make, or dead transfer. Such a transfer results in a brief interruption of service to all feeders on the bus normally served by the failed transformer. Although the transfer is fairly quick (a matter of seconds) and is automatically implemented, it can be quite objectionable when high power quality expectations exist.

Unlike with the radial bus, a second source supplying a ring bus does not require a tie breaker or other additional components – just one more circuit breaker position in the ring bus. Both transformers would be operated in parallel, eliminating the need for a source transfer scheme as well as the accompanying momentary interruption. The parallel transformer operation also increases fault current on the distribution system. While higher fault current may require higher equipment interrupting ratings, it also improves system performance during the starting of large motors. This benefit can be substantial, especially when voltage dip issues are of concern.

When furnished with a second source, especially a source supplied from a transmission line other than the one supplying the first source, a highly reliable distribution bus results. Since the two transformers could be paralleled across the transmission system, care must be exercised to assure the transformer loadings will be comparable and no excessive flows exist through one transformer, a portion of the ring bus, and back to the transmission system through the second transformer. The through-flow scenario would be more likely during outages on the transmission system. Load flow analysis can predict potential operating problems, and those problems can be resolved by judiciously specifying the impedances and de-energized tap settings of the transformers.

The availability of a doubly fed bus is substantially higher than that of a bus with a single source. Interruption of service to the entire substation becomes a very unlikely scenario. Ring buses with two or more sources can be thought of as "power rings."

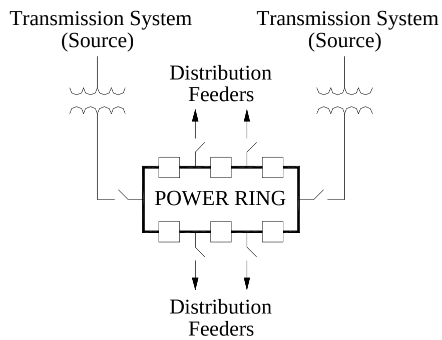

Fig. 3 – Power Ring

A power ring provides a reliability level comparable to that of a transmission-voltage substation. Loss of the entire bus is a very remote scenario. Outage restoration with a power ring topology is facilitated by the operations benefits described in the next section. The dual combination of higher availability and faster restoration in the event of a service interruption makes the power ring topology very attractive in applications where high reliability is paramount.

3. Maintenance and Operations Benefits

Another benefit realized by applying the ring bus configuration to the distribution system is a simplified switching process to allow circuit breaker maintenance. To allow a radial bus feeder breaker to be removed from service for maintenance, all of the load served by that feeder must be transferred to another source. Even during light load periods, transferring the entire feeder load to another source may result in a lengthy and complicated switching procedure. As the load level increases, it may become impossible to serve the feeder's entire load from other sources without violating operating criteria such as voltage limits and equipment loading levels. If a circuit breaker is used to connect the source to the bus, maintenance of this source circuit breaker is even more difficult, as the entire load of the bus must be supplied from other sources. These difficulties impose major constraints on system maintenance. At best, the constraints mean that circuit breaker maintenance can only be done at certain times, possibly at a higher-than-necessary cost due to complicated and time-consuming load switching. At worst, maintenance of critical circuit breakers, devices that could require a significant maintenance program because of their complicated mechanical nature, may be neglected. Compromising the integrity of circuit breakers will adversely impact both the system reliability and the operating budget.

The ring bus topology allows any circuit breaker, even a source breaker, to be removed from service at any time, simply by tripping it and opening its disconnect switches. This is because each branch is served by not one but two circuit breakers under normal conditions. Only one breaker is necessary to keep a branch in service, so the other can be maintained without load switching. After removal of a circuit breaker from service, the ring topology is lost until the circuit breaker is returned to service. But even in this non-optimal configuration, the reliability offered by the temporary bus configuration is no worse than that provided by the radial bus in its normal configuration. Not only does the elimination of load switching reduce the time and cost to switch the circuit breaker out of service for maintenance, but it also reduces the probability of switching errors, which could lead to customer outages, equipment damage, or personnel injury. When devices other than circuit breakers must be maintained, line disconnect switches allow the ring topology to be restored after a branch is removed from service.

4. Conclusions and Future Work

While the radial bus configuration has become a de facto standard topology for distribution substation designs, substantial improvements in reliability and operating versatility can be realized by employing a ring bus design in the distribution substation. The same arguments for reliability improvement apply to implementing the ring bus on the distribution system as apply to implementation on the transmission system, where the ring bus is widely utilized to improve reliability. Since most reliability issues originate at the distribution level, it logically follows that reliability improvements on the distribution system will be significant in improving overall system reliability. The construction cost of a ring bus design is close to that of a radial bus, but the benefits afforded by the ring bus make it as attractive a topology at the distribution voltage level as on the transmission system. Maintenance and operating flexibilities are inherent to the ring bus topology. These benefits are perhaps more valuable at the distribution level than at the transmission level, due to the relative complexity of switching distribution loads compared to that of transmission lines, and to the far greater number of distribution substations and circuits that exist compared to the number of transmission-level facilities. And incorporation of a second source to form a "power ring" increases the reliability of the distribution substation to rival that of a transmission-voltage facility.

Future work in this area involves incorporation of the power ring topology into the framework of FRIENDS (Flexible, Reliable and Intelligent Electrical eNergy Delivery Systems)[2] to provide improvements in the reliability of the power source while maintaining a cost-effective infrastructure. Substation design methods to further economize construction cost without sacrificing reliability, maintainability, or operating flexibility will also be investigated.

5. References

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