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Flexible Busbar Solution for High Current Density Applications

Whitepaper

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Abstract— As power demand usage at datacenters and other facilities like nuclear power plants, battery energy storage systems, telecommunications and industrial facilities increases exponentially, the use of cables both in the primary and secondary medium voltage and low voltage has become difficult to design and implement.

These power distribution systems at facilities need to be designed with multiple parallel cables, rigid bus bar system or flexible bus bar systems. There has been significant attention given to these systems, now as these have advantages and limitations. There has been progress on the system and component design of these systems as well as attention given to the maintenance and operation.

This paper discusses the advantages and limitations of cable connections, rigid bus bar connection and flexible bus bar connections for high current density applications.

UL standards for the certification of these systems are being developed. The systems are tested to several IEC standards for attributes like insulation resilience, cable fixing suitability, electrical characteristics, flame resistance.

Flexible bus bar systems offer an excellent solution for point to point connections in power distribution. Future developmentson these system may see its application extended to provide load distribution capabilities.

Introduction

The reliability of high and low-voltage electrical systems is impacted by the quality of the connection system including cable and cable lugs and crimps or bus bar systems. This systems act as the main vessel of power distribution and is used for connections on the primary and secondary sides of transformers as well as on the power sources like generators, battery containers, UPSs and the load distribution.

Sometimes, the importance of the connections systems can be overlooked in electrical designs, with more focus going into selecting components like transformers, switchgear and UPS. Attention to the proper design, selection, installation, commissioning and maintenance of the connection system is paramount [4], because this is the one part of the power system that may not have any redundancy. Furthermore, future failures to the connection system can be avoided with this added attention.

Advantages and Limitations of Cables in High Density Applications

Figure 1 Examples of Large Installation using Cables

The advantage of cables as the first choice of conductor is almost trivial for electrical connections. Cables are readily available, have good ductility and are easy to install in ducts and cable trays, have been tested to relevant standards, lugs can be matched to standard cable diameters and electrical installers are familiar with cable systems.

This proposition changes significantly in very high density power applications where multiple cable are needed in parallel runs and special cables need matching lugs and correct compression tooling. These two factors can be a challenge.

Paralleling large cables take up space but the bigger challenge is that triangulated or trefoil arrangements are needed to reduce cable sheath currents.

Where multiple single-core cables are applied per phase, the sharing of the currents between the parallel cables may not always be balanced. This can cause continuous currents in sheaths of cables.

Even when the load currents are balanced, that is, equal in current magnitude, each phase needs to be displaced by 120 degrees from the other two phases [3], to reduce sheath currents by using triangulated arrangement of cables, the most popular being the trefoil arrangement.
Three different cable arrangements are shown in Figure 2.

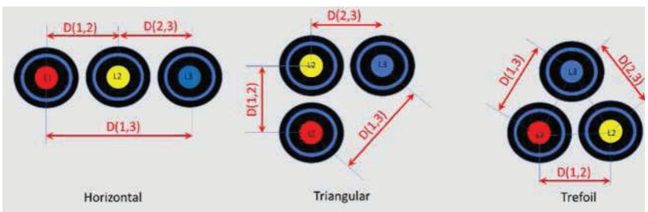

Figure 2 Different 3 Phase Cable Arrangements

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This trefoil arrangement becomes difficult to achieve when parallel conductors are used per phase. In the case of imbalanced loads, other measures like phase rotation along cable lengths may be necessary.

If this arrangement is not achieved large currents can flow in the sheaths of cables under the normal operation.

When carrying a large fault current which may be many times the normal maximum load current this open circuit voltage can be very large, which necessitates the use of special cross-bonding arrangements in long single-core cable threephase circuits as found in transmission systems. [3]

Another significant challenge is getting good connection in constricted spaces on power conversion and distribution equipment which becomes even more challenging when parallel cables and lugs are used. Failure of cable assemblies can occur at the connection point like lugs and splices. This connection point will degrade over time because of conditions like heat, humidity and dust, which leads to over-heating and a potential equipment fire.

Furthermore, standard cable insulation (PVC, XLPE) can crack resulting in short-circuits if the prescribed bending radius by cable manufacturers are not followed. This is a common occurrence in the marine and offshore applications. A remedy to these cable limitation is the use of ultra-flexible silicon cables, which have drawbacks in terms of cost and difficulty is finding type tested matching lugs and terminations.

Finally, cables are often fastened with cable ties instead of short-circuit rated cable cleats which can lead to either a pullout at connection level or lug failure during a short-circuit event which results in high mechanical stresses and movement in cables and on the connection. Mechanical damage of the insulation is also common during such events if movement of the conductor is not restricted.

The Skin Effect Discussion

Skin effect is the tendency of an alternating electric current (AC) to become distributed within a conductor such that the current density is largest near the surface of the conductor, and decreases with greater depths in the conductor. [8]

According to Faraday's low, a magnetic field inside the conductor that circulates around the axis of the conductor is induced when AC current flowing in the inner parts of a conductor. This alternating magnetic field induces an electric field that drives currents to outer parts of the conductor. These induced recirculating currents are referred to as eddy currents. Eddy currents generate resistive losses that transform some forms of energy into heat. [8]

The resistance of a conductor is strongly proportional to its cross sectional area. If the cross sectional area decreases, theresistance goes up. The skin effect causes the effective cross sectional area decreasing. Hence the skin effect increases the effective resistance of a conductor. The ratio of the apparent D.C. and A.C. resistances is known as the skin effect ratio (it's also named current displacement factor or the extra loss coefficient). Large skin effect ratio means less cross sectional area. In this article, the skin effect ratio is used to evaluate the skin effect for different shapes of conductors. [8]

For cylindrical conductor the skin effect ratio, Ra/Rc can be calculated relatively easily and accurately using empirical formulas given below:

$$\gamma = \frac{a}{\delta}$$

$$\frac{R_a}{R_c} = \begin{cases} 1 + \frac{5\gamma^4}{240+4\gamma^4} & \gamma \le 1.6 \\ 0.84 - 0.13\gamma + 0.22\gamma^2 - 0.0246\gamma^3 & 1.6 < \gamma < 3.9 \\ \frac{2\gamma+1}{2} + \frac{3}{32\gamma} & \gamma \ge 3.9 \end{cases}$$

Where a is the radius of the conductor and δ is the skin depth (The skin depth is related to the material resistivity and frequency, at 50 Hz, copper has a skin depth of 9.27 mm).

For rectangular conductors it is more difficult to calculate. In the skin effect ratio but Standard IEC 61439.1:2011, Annex N provides these for a large range of cross sectional areas. [9]

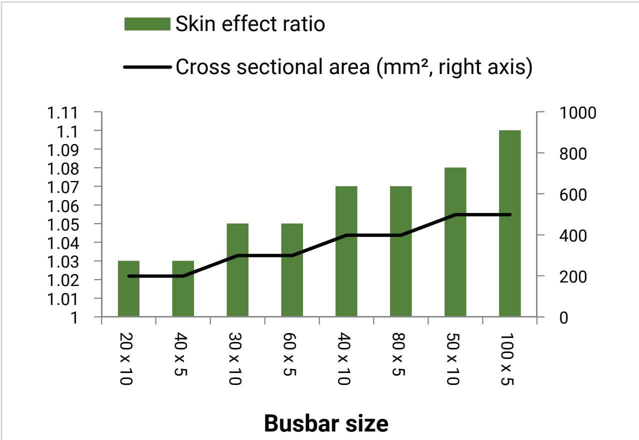

Figure 3 Comparison of skin effect ratio [9]

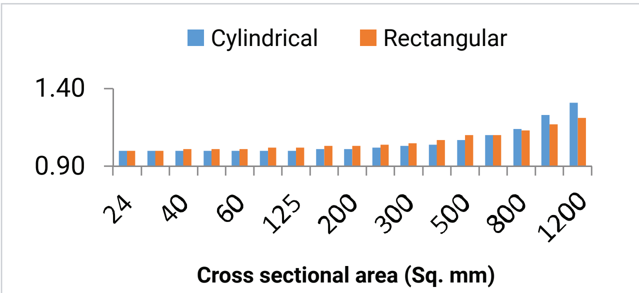

Figure 4 Comparison of skin effect ratio between cylindrical and rectangular conductor [9]

Figure 3 above shows the comparison of the skin effect ratio for cylindrical vs rectangular conductors.

As showed in Figure 4, when the cross sectional area is smaller than 150 mm², there are small ampacity differences between cable and busbar; but when the cross sectional area is larger than 150 mm², busbar can carry more current.

When the cross sectional area is smaller than 150 mm², Cable maybe a better conductor than busbar from the current carrying capacity standpoint.

The proximity effect of conductors is not considered in the discussion in this paper.

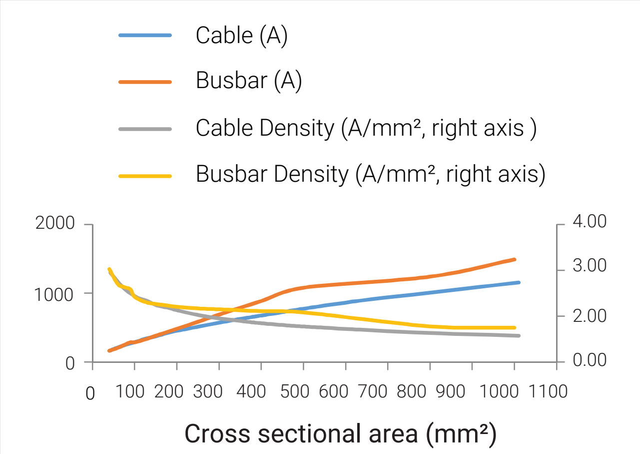

Figure 5 Ampacity comparison between cable and busbar(NEC VS DIN)

Note 1: The cable ampacity value is extracted from NEC Table 310.15(B)(17) and the busbar ampacity value is extracted from DIN 43671, the curve is obtained by data fitting.

Note 2: The temperature rise is 30°C.

Advantages and Limitations of Rigid Bus Bar Failures in High Density Applications

When it comes to transmitting and distributing dense power currents, rigid bus bar systems has been the other alternative to cables. Due to much better skin effect ratio and heat distribution, rigid flat busbar systems offer several advantages over cables in high power density applications. These systems are well developed and there is significant type testing done on the conductors and terminations. They utilize thinner insulations than cables and usually these are also type tested.

However, there have been noted and documented failures of rigid busbar system in nuclear and datacenter applications.

Some of the more common failures noted on rigid bus bar systems include:

- Multiple short lengths of rigid busbar is connected to achiever longer runs. This results in multiple connection point along the run. System failures can result from just one connection point failure along a run of bus bar.
- If the insulating material with low price and poor quality is used in the production of bus duct, and the insulation material has pinholes and uneven thickness, it will lead to the fault of bus bar in use.
- If the copper bar of bus bar contains impurities, and there are bumps and burrs, welding this will break the insulation layer after the bus bar is put into operation for a period of time, which will lead to the occurrence of bus bar short circuit.
- Fire resistant bus bar systems may have water spray function. If the fire-resistant bus duct has no water spray function, the bus duct will be short circuited in case of fire-fighting water spraying or other water encounter.
- When installing the bus duct, if there is dust into the shell of the bus duct, this will cause short circuit of the bus duct when it is damped.

Other common problems noted include poor installation, racked insulators, localized overheating, loose connections, loose, missing or inappropriate hardware, dust or dirt build up, debris or foreign material and poor system design.

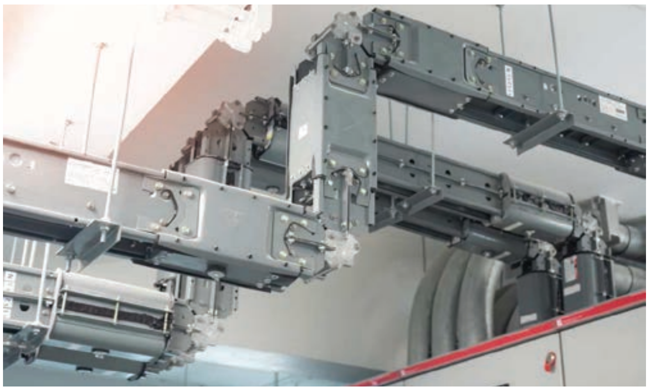

Figure 6 Examples of Rigid Bus Bar Connections

The bus system is the plant's main vessel of power distribution, carrying large amperage currents from the generator to a step-up transformer. In other words, the bus system acts like a giant extension cord. Although the value of the electrical bus duct system may seem minimal when compared to that of the generator or the transformer, the bus duct system plays a vital role in the plant. Consider it the lifeline between both high value components; if a failure occurs, there is a good chance that the connected components will be impacted. Electrical bus duct systems do not have redundancy. Because they are custom designed for each plant, they also do not have a quick fix or replacement solution readily available. [5]

Advantages and Limitations Flexible Bus Bar Sytems in High Density Applications

Flexible bus bar systems designed to provide point to point connections in high current density applications is a relatively new technology. Flexible bus bar system is made of: conductors, supports, connection components and accessories.

The conductor is made of a rectangular-shaped (flat) copperplated aluminum braid which drives two immediate benefits for designers and contractors: a flat conductor has an optimized power density (skin-effect) which leads to configurations where only two conductors per phase can carry more than 4000 A of current per phase as in a 3150 kVA transformer connection. For the sake of comparison, a cable installation would use up to 10 runs of 240 mm^2 cables per phase.

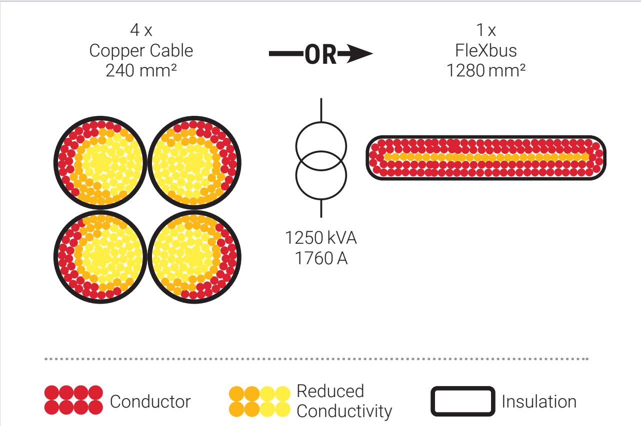

Figure 7 Conductivity Comparison with Round Cables

From a contractor standpoint, a flat braided conductor allows for greater flexibility (no minimum bending radius) and therefore an easier installation, especially since one end of the conductor is prefabricated and allows for direct connection onto the busbar system of a switchboard or onto the back of an ACB. This easier installation is further facilitated by the fact that the conductor is mostly made of lightweight aluminum and because the number of conductors to install is reduced as previously mentioned.

This braid is insulated with a TPE insulation with the following characteristics: reinforced properties, impact resistance, low-smoke, halogen-free, flame retardant (LSHFFR) features and a 115°C maximum continuous operating temperature. Figure 8, 9 and 10 show the flexible bus bar conductor and its flexibility while Figure 7 illustrates the current density benefits of flat conductors over round conductors.

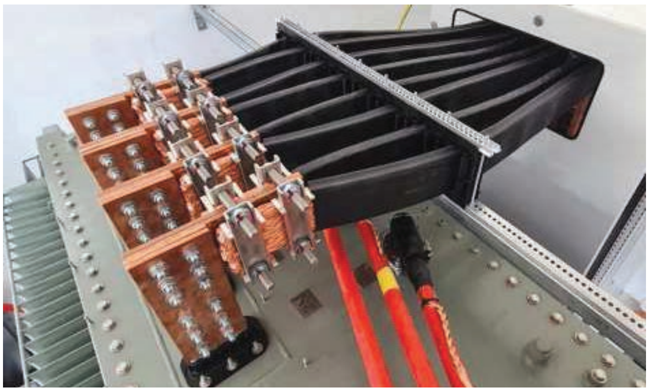

Figure 8 Flexible Bus Bar Installation

Figure 9 Flexible Bus Bar Installation

The support systems for flexible bus bar systems arepurpose designed for the conductors to be arranged in different ways. For example these could be horizontal, vertical or stacked. They can also be phase rotated along long runs to cancel out effects associated with cross coupling. The use of such supports, if installed properly at regular intervals, will prevent the conductor from pulling out and the insulation from being damaged as commonly seen in cable installations.

Figure 10 Flexible Bus Bar Installation

The flexible bus bar system overcome these common problems faced by cable and rigid bus bar solution in high current density applications:

- The terminations are either integral or purpose designed and type tested with the conductor being used. This avoids typical failures that occur in cable systems associated with termination,
- There is no minimum bend radius. Hence the conductor can be twisted and bent using appropriate hardware in any configurations without any derating.
- Heat dissipation is better than cables and rigid busbar through the use of flat configured multi stranding. Hence higher current ratings resulting is fewer conductors required.
- Insulation is significantly better than most rigid bus bar systems.
- Copper clad aluminum construction results in a lower weight per meter of the conductor in comparison with copper conductors.
- A single unjointed conductor in point to point applications avoiding risks of multiple joint and associated failure mode in rigid bus bars.
- There is no risk of impurities, and there are bumps and burrs causing insulation damage.

- The system is water resistant for outdoor application and during any water spray during fire events.
- Use of low-smoke, halogen-free, flame retardant insulation.
- The support systems are type tested with the conductor against vibrations and large fault currents to ensure mechanical integrity during and after fault events. The support systems can also be configured to provide phase rotation and horizontal and vertical single and parallel runs.
- Full system design does not have to have accuracy to the millimeter as required in rigid bus bar systems. There is flexibility is some movement in equipment position due to flexibility in the conductor.

Some of the limitations of flexible bus bar systems include:

- The conductor is available for point to point application and cannot offer distribution tee offs as rigid bus bar systems can provide.
- Other common problems that also exist with rigid busbar systems can exist including poor installation, loose, missing or inappropriate hardware, and poor system design
- The provision of the flexible bus bar conductors in long reels like cable reels is not possible hence they have to be pre-cut to size plus the expected installation tolerances.

Nec Article 371 Update on Flexible Bus Bar Systems

In the 2023 NEC®, New Article 371 was added to provide requirements for Flexible Bus Systems. [1]

According to Article 100 definitions, flexible bus systems are an assembly of flexible insulated bus, with a system of associated fittings used to secure, support, and terminate the bus. [1]

Flexible bus systems use a flat braided insulated conductor that provides greater flexibility than busduct without the bending radius limitations typical cables have. Flexible bus systems are engineered systems designed for a specific site location and are ordinarily assembled on site with the components furnished or specified by the manufacturer. [1]

Highlights from new Article 371 include:

- New Section 371.6 requires flexible bus systems to be listed but at the time the new article was created, the associated product standard and outline of investigation was still under development. [1]
- New Section 371.10 permits flexible bus systems for the following uses:
  - For services, feeders, and branch circuits
  - For indoor use
  - For outdoor use if identified for outdoor use
  - For installation in corrosive, wet, or damp locations where identified for such use
  - Exposed
  - Behind access panels where the space behind the access panel is not used for airhandling purposes
  - To penetrate through walls and floors in accordance with 371.18 [1]
- New Section 371.12 does NOT permit flexible bus systems to be used in hoist ways, in air handling spaces, where exposed to physical damage, or in hazardous locations unless specifically allowed in NEC® Chapter 5. [1]
- New Section 371.14 requires flexible bus systems to be designed for jobsite specific applications by a qualified engineer in accordance with the limits of the listing and manufacturer's installation instructions. [1]
- New Section 371.30(C) permits flexible bus systems to be installed in support trays supplied as associated fittings for the listed flexible bus system. Support trays for flexible bus systems are not required to be continuous. [1]

UL1886 Edition 1-2022 Outline of Investigation for Flexible Bus Systems

A new UL outline of investigations is being published with the intention of making this a full UL Standard after the investigation of these systems.

These UL1886 EDITION 1-2022 requirements cover

- Flexible Bus Systems having ratings up to 1000 V.
- Equipment intended for use only in ordinary locations (locations other than those identified as "Hazardous" or "Classified Locations").
- Flexible Bus Systems for installation above ground for indoor use and outdoor use, installed under engineering supervision.
- Flexible bus systems that are intended for use through fire rated assemblies are additionally evaluated to the Standard for Fire Tests of Penetration Firestops, UL 1479.

These requirements do not cover

- The use of flexible bus systems in spaces used for environmental air handling as provided in 300.22 of NFPA 70.
- Cover Cablebus, which are covered by Article 370 of NFPA 70, or Busways, which are covered by UL 857 and Article 368 of NFPA 70.

Conclusion

Use of single core cables in large power density has its limitations. Many of these limitations can be overcome through the use of rigid bus bar systems. However these later systems have new inherent failure and installation risk. Flexible bus bar systems promise to offer a new alternative that overcomes many disadvantages of cable and rigid bus bar systems in high current applications.

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