BUSBARS

WHAT IS A BUSBAR?

An early encyclopedia defines busbars as “the common connections to which several generators deliver their current, and from which several feeders draw their supply” (1). A later definition that relates to power switchgear states that a bus (busbar) is “a conductor, or group of conductors, that serves as a common connection for two or more circuits” (2). More generally speaking, a busbar is one or more electrical conductors that are used to distribute electrical power from one place to another or from one electrical or electronic device to another. A busbar or busbar assembly serves the same function as a wire or group of wires in a cable, that of carrying electrical current, but it is physically different from a cable in that it is usually more dimensionally stable.

Except for a special type of busbar called a flexible busbar, most busbars are intended to have a certain fixed size and shape. The fixed shape of a busbar may provide many advantages that an ordinary insulated wire, which is usually flexible, cannot. These advantages include smaller thicknesses for a given current rating, improved airflow in the area around the busbar, lower parasitic inductance, higher distributed capacitance, and reduced electromagnetic interference (EMI) generation (3). Other advantages of using busbars to carry electrical currents include mechanical support for components mounted to the busbar, simplified manufacturing assembly and reduction of assembly time, nearly complete elimination of possible assembly mistakes, and higher overall product reliability (4). Like wires and other types of electrical conductors, busbars need to be sized by cross-sectional area to carry the required amount of electrical current, in amperes, while operating at or below a certain required temperature. This maximum operating temperature is dictated by the allowable operating temperature of the insulating material on or near

J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*.

the busbar or of the maximum allowable temperature of the surrounding air near the busbar, whichever is lower.

WHERE ARE BUSBARS USED?

Busbars are used to carry electrical current within many types of electrical and electronic equipment. They are also used as a means to make external connections to bring power into and out of many types of electrical equipment, such as power-converters, for example. Power-converters modify or convert one type of electrical power, such as direct current (dc), into another form of electrical power, such as alternating current (ac), or they change the frequency of ac power by using power-switching devices. Busbars are generally used in higher current applications for which other current-carrying methods, such as laminated circuit boards or medium-gauge wires, are not as appropriate because of the high temperatures, usually between 105°C and 150°C, that the conductors would reach during normal continuous operation. These high temperatures can cause damage to the insulating material such that the insulation may melt, a short circuit could occur, or a fire could result. The current levels for which it is generally more practical to use busbars rather than circuit boards is above the 50 A to 150 A range, where a circuit board would require copper that is thicker than 0.014 in. or 10 oz. (per square foot), or where the interconnecting wires would have to be larger than #8 or #6 American Wire Gauge (AWG) (5). To reduce the operating temperatures, the cross-sectional area of the conductors is increased by using a busbar, which can be made much thicker than the conductor layers on a circuit board. Since cross-sectional area is the width of the conductor multiplied by its thickness, large cross-sectional areas of the conductors can be achieved by making them quite wide, but still relatively thin. Busbars are also capable of providing much larger cross-sectional area than large gauge wires.

Besides being desirable from a packaging standpoint, the use of thin and wide conductors in the busbar is desirable when the currents involved are ac and of high frequencies. Under these conditions, a phenomenon called the “skin effect” occurs, whereby the current only passes through a portion of the actual thickness of the busbar, called the skin depth (6). This may result in a condition whereby the busbar temperature reaches too high of a level, as if the busbar were deliberately undersized by making it too thin for the amount of current involved. This effect is counteracted by properly choosing the thickness of the busbar to be approximately 2.0 to 3.5 times larger than the skin depth of the current, for the highest ac busbar operating frequency or harmonic frequency. Because busbars are usually relatively thin and wide, the surface area for air to flow around them is significantly improved over using large-gauge wires.

Busbars can also be made with high temperature insulating materials that allow them to operate at much higher temperatures than the 120°C to 125°C limit for the typical FR-4/G-10 circuit board material used in most circuit boards and at very high current levels (7). Many busbars are uninsulated so that the only insulating material present is the air between the busbars, allowing them to run at temperatures of 300°C or more. This approach is unacceptable, however, when the voltages involved are so high that corona arcing would occur through the air space between the busbars, which can occur when the applied voltage exceeds approximately 1000 V, depending on the exact chemical composition and humidity of the air. A suitable choice of insulating material allows the busbar to support working voltages of many thousands of volts. Unfortunately, the use of insulating materials on busbars reduces their ability to give off heat to the surrounding air via convection and radiation heat transfer. This increased heating requires the cross-sectional area of the busbar to be increased and/or additional airflow provided around the busbar to cool it off.

The types of equipment in which busbars are used includes high-power substations for electrical utilities, various types of power-converters including motor drives and controls, inverters for electric vehicle drives, uninterruptible power supplies (UPSs) for computers, and power-supplies for medical electronics and large mainframe computers. Nearly all equipment of a high power rating, above 1 kW to 25 kW of power handled, uses some type of busbars for carrying electrical currents in the equipment. A list of typical equipment that uses busbars either internally or for external connections or both is shown below, although this list is by no means an exhaustive one.

Equipment that uses busbars:

1. Ac–ac power-converters (cycloconverters and frequency changers)
2. Ac–dc power-converters (rectifiers and buck/boost converters)
3. Ac motor drives (induction, synchronous or switched reluctance)
4. Dc–ac power-converters (inverters)
5. Dc–dc power-converters (choppers and switching power-converters)
6. Dc motor drives (brush type and brushless)
7. Fuel-cell power plants
8. Gas turbine power stations
9. High-power amplifiers
10. High-voltage dc (HVDC) power-converters
11. Induction heating equipment
12. Large audio amplifiers
13. Large computer power-supplies
14. Large radio-frequency amplifiers and transmitters
15. Magnetic resonance imaging (MRI) and medical equipment power-supplies
16. Photovoltaic, solar, and wind power systems (8)
17. Power factor correction circuits and active filter circuits (9)
18. Power line conditioners and uninterruptible power supplies (UPSs)
19. Power switchgear
20. Resonant power-converters
21. Utility substations and transformers (10)
22. Welding and cutting equipment

TYPES OF BUSBARS

There are three basic types of busbars: conventional, flexible, and laminated. The uses and advantages of each type of busbar will be described in detail in the following sections.

Conventional Busbars

Conventional busbars are typically uninsulated bars that are stamped or machined out of a highly electrically conductive material like copper or aluminum. High electrical conductivity is important because this reduces the resistance of the busbars and the power dissipated in the busbars, keeping the operating temperature lower than if a less conductive busbar is used to carry the same amount of current. Lower busbar resistance also results in a smaller voltage-drop across the busbar than would occur with a higher resistance conductor. The conventional type of busbar usually relies on air spaces for insulation between the exposed conductor and any other busbars or other conductive materials, such as the equipment cabinet or adjacent printed circuit boards. Insulation around the busbar is usually avoided because it acts as a thermal insulator as well as an electrical insulator, reducing the normal transfer of heat from the busbar to the surrounding air via the heat-transfer mechanisms of convection and radiation. Conventional busbars are typically of a rigid design so that they hold their predetermined shape, and so that they will not short out to nearby electrical conductors. Rigidness is also important so that the busbar can mechanically support various components of substantial mass within an equipment cabinet. These busbars typically have various features built into them such as special custom shapes, variations in width, holes of various sizes and locations, and captive fasteners, such as studs or retaining nuts, to aid in the assembly of the busbars into the equipment. The fasteners are also used to provide a high-pressure, low-resistance connection between the busbar and the interconnected electrical devices. This is important so that the busbar operating temperature will be low and there will be no possibility of an intermittent connection that could arc, heat excessively, and cause damage during equipment operation. This condition is possible when aluminum busbars interface to terminals made of copper and other non-aluminum materials. Preventing intermittent connections is especially important when semiconductors are used for power-switching, as they are particularly susceptible to damage from the effects of arcing and excessive heating. If copper is used as the busbar material, the busbar is often plated with a very thin layer of a protective metal such as silver, nickel, tin, or cadmium to reduce oxidation of the busbar. Plating is especially desirable when the busbars will be operated at very high temperatures or in highly corrosive environments, such as near ocean salt water. Figure 1 is a photograph showing several examples of various types of conventional busbars.

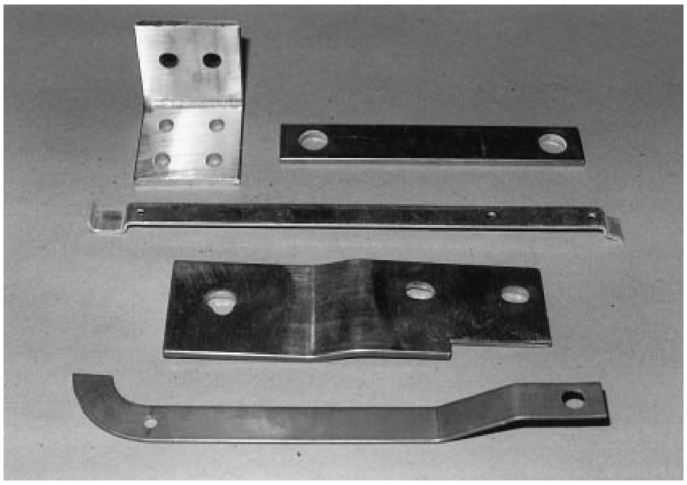
Figure 1. Several examples of various types of conventional busbars.

Flexible Busbars

Many busbars are designed without mechanical rigidity so that they are flexible. Here again, the conductor is usually made out of a highly electrically conductive material such as copper, but in this case the conductors must be soft and flexible like copper that has been fully annealed. Two or more layers of an insulation material are usually used to insulate the conductors from other nearby electrically conductive features. A low-current example of this type of busbar is the flexible printed circuit or "flex cable" used in most dot matrix computer printers. Here the copper conductors are made thin and soft enough to withstand many thousands of flexures, due to the movement of the printhead, without breaking or fatiguing. The width and thickness of the conductor are chosen so that the cable can carry the proper amount of current without overheating. Two or more layers of an insulating material such as Mylar (polyester), Kapton, or Kevlar are used to surround the circuit so as to insulate it from any conductors it could come in contact with, due to the moving and bending motion of the flexible circuit. These insulating materials are typically very thin layers of a polyimide type (Kapton or Kevlar) material that is mechanically tough and abrasion resistant and has a high dielectric strength to resist voltage breakdown and short-circuiting (11).

An example of a flexible busbar with high current capability is a material called Flexibar®. Rather than being made by machining or stamping like rigid busbars, the material comes on a long roll, and it is cut to length and holes are drilled into it to make the connections. As with the lower current flexible circuits, the flexible busbar uses a bendable conductor material like copper, but it typically uses several thin layers instead of just one thicker layer. The use of multiple layers allows for much higher current capacity, due to the layers being connected in parallel with each other, and it allows for good flexibility because the individual layers can slide across each other when the busbar material is bent into various shapes. The flexible busbar material is quite bendable, but it could also be considered semirigid because it maintains the shape it has been formed into until it is bent further. The overall insulation is typically a flexible, heat-shrinkable tubing such as a polyvinylchloride (PVC) or polyolefin-type material, which is easy to form, provides the material with some added rigidity or position "memory," and can withstand temperatures up to 150°C (12).

Laminated Busbars

The conventional and flexible busbars described so far are typically designed to handle a certain amount of current, while operating at a specific maximum busbar and ambient air temperature. These types of busbars work very well for dc or low-frequency ac circuits that operate at frequencies below approximately 1000 cycles/s or hertz (Hz). Unfortunately, these types of busbars are not as appropriate for use at higher ac power frequencies because their ac resistance to current flow, also called impedance, is many times higher than their resistance to the flow of dc current. Two effects account for this: the intrinsic or parasitic inductance of the busbar and an effect called the skin effect, which will be described later. Any conductor has a certain inductance, called its parasitic inductance, which is largely dependent on the length of the conductor, somewhat dependent on its cross-sectional area, and very dependent on the spacing of the conductor from other conductors. This inductance, also called self-inductance, causes some of the energy carried by the busbar to be stored in a magnetic field around the busbar, instead of all of it being electrically conducted or passed through the busbar. This effect can be counteracted by using mutual inductance to cancel out most of the self-inductance. Mutual inductance is created by designing the busbar assembly so that one busbar section or layer, that carries a certain amount of current, is positioned very close to another busbar layer that carries approximately the same magnitude of current, but in the opposite direction. This way the magnetic field produced by one busbar layer is nearly cancelled out by the magnetic field produced by the other layer, because of the current flowing in the adjacent conductors in opposite directions. The distance between layers is minimized by using high-voltage insulating materials, such as Kapton, Tedlar, Nomex, or epoxy-glass laminates instead of air, so that the mutual inductance effect is maximized and the self-inductance is minimized (13). This concept can be extended to more than two layers, so laminated busbar assemblies can be made with as many layers as necessary to carry all of the different large-magnitude currents in a system, and the self-inductance of each circuit can be substantially reduced over using wires or cables. Only the conductors that need to have their inductance minimized really need to be included in the busbar assembly, but it usually increases the overall cost only slightly to add extra layers to the assembly. Often these extra layers will be added to the assembly for the purpose of simplifying the assembly of the equipment and also for reducing the possibility of the connections being made incorrectly. Extra layers can be added to the busbar while still keeping the assembly relatively thin, allowing for increased airflow around the busbar and the entire cabinet that the equipment is housed in. The space occupied by the busbar is considerably less than that of a comparably sized wiring harness. Overall system reliability is improved because fewer components are required, which results in fewer components that could be assembled improperly, and fewer components that may ultimately fail in the equipment. Figure 2 shows a photograph of a typical low-inductance, laminated busbar assembly.

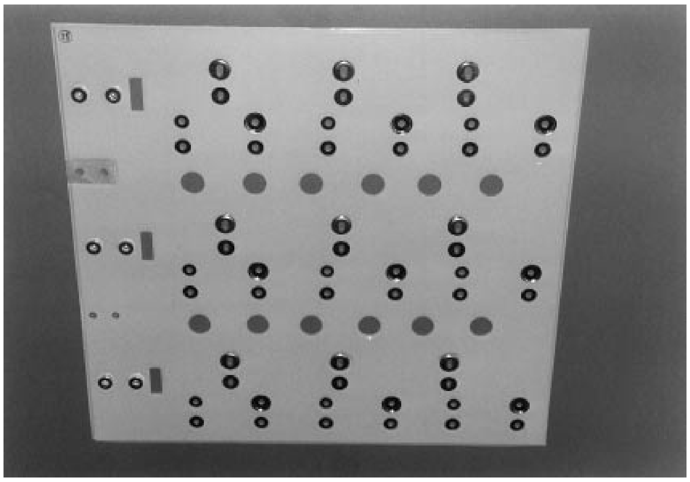

Figure 2. An example of a low-inductance, laminated busbar assembly (courtesy of Eldre Corporation).

Another reason for using a laminated busbar assembly to lower inductance in a piece of equipment is to protect the power switches in the equipment, which are usually semiconductors. Keeping busbar impedance low is important to minimize busbar losses, but keeping the inductance low is more important in controlling the transient voltages to which the power semiconductor switches are subjected. These solid-state switches are used to convert power from one form to another or to change the frequency of the power, in power-conversion equipment, for example. The problem of excessive transient or overshoot voltages on semiconductors occurs primarily during the turn-off operation of the switches, and the problem is magnified by the parasitic inductance of the busbars. The reason for this is evident when the definition of inductance is considered in detail:

$$V = -0.001L\,(di/dt) \tag{1}$$

where V is the transient voltage generated across the busbar, in volts, L is the busbar inductance, in nanohenries, and di/dt is the rate of change of current with respect to time, in volts per microsecond.

The minus sign indicates that the voltage generated is of the opposite polarity to the rate of change of the current. When the current decreases, which happens during power switch turn-off, the voltage increases, and when the current increases, which happens during power switch turn-on, the voltage decreases. The magnitude of the voltage is determined by the inductance in the circuit, a large amount of it being contained in the busbar assembly, and the rate at which the power switch changes state, which the equipment designer has little or no control over. Modern power semiconductor switches, such as insulated gate bipolar transistors (IGBTs), can switch at rates of 2500 V/μs to 10,000 V/μs, so it only takes several nanohenries of busbar inductance to generate a large voltage across the busbar conductors. Modern metal-oxide semiconductor field-effect transistors (MOSFETs) can switch 5 to 50 times faster than IGBTs. This generated transient voltage across the total inductance of the busbars is added to the dc link or dc bus voltage being switched by the power semiconductors. This causes the actual voltage appearing across the power semiconductor during turn-off to be many hundreds of volts higher than the steady-state dc link voltage. If this transient voltage gets high enough, it will exceed the maximum voltage rating of the power semiconductors. The reliability of the switches may be reduced and, in extreme cases, the devices can be damaged after only a short operating period (14).

Snubbers Used with Busbars. Besides reducing the parasitic inductance of the busbars by making them into a laminated assembly, often snubbers are used across the power semiconductors to further control this transient voltage further during turn-off, also called overshoot voltage. Snubbers are typically made of capacitors, resistors, and sometimes diodes, in various circuit configurations, in which the capacitors, called snubber capacitors, are bolted directly to the busbar assembly. This is also done to minimize the circuit inductance. There are four main types of snubber circuits used for protecting various power semiconductors such as power transistors, MOSFETs, IGBTs, silicon-controlled rectifiers (SCRs), and gate turn-off thyristors (GTOs). These snubber circuits are called the bus-capacitor type, the resistor-capacitor-diode (RCD) type, the resistor-capacitor (RC) type, and regenerative snubber types.

The bus-capacitor type snubber is constructed using one or more capacitors, which are typically polypropylene film, multilayer ceramic (MLC) or other types of high-frequency capacitors, mounted on a low-inductance, laminated busbar, which connects them across each power pole in a piece of power-conversion equipment. The laminated busbar assembly provides significant distributed capacitance, which is desirable to reduce parasitic oscillations and adds to the snubber capacitance, but its capacitance value is usually quite small compared to the total capacitance of the snubber capacitors, which is usually 0.33 μF to 1.0 μF per 100 A of power-switching device current rating. The power pole consists of one or two power switches connected in series across the dc link or bus, in equipment that either switches the dc power on and off, called a chopper, or in equipment that converts the dc to ac by reversing its polarity, called an inverter. Bus-capacitor type snubbers are usually used in low-power equipment, typically rated at 10 kW or less, which uses very high-speed power-switching devices such as power MOSFETs. Examples of this type of equipment are the high-frequency power-supplies used in larger mainframe computers, power line conditioners, uninterruptible power supplies, medical equipment, and large audio amplifiers. This type of snubber configuration is also used in medium-power equipment, typically rated at 100 kW or less, such as ac motor drives and inverters, which use the somewhat slower IGBT as the power-switching device. Other examples of this type of equipment are power factor correction circuits, resonant power-converters, and alternative fuel power-converters, such as those used in fuel-cell power plants, gas turbine power stations, and photovoltaic, solar, and wind power systems.

The RCD type of snubber configuration consists of a resistor, a capacitor, and one or more diodes. The diodes, which are usually fast-recovery or high-frequency types, connect the snubber capacitor across the power-switching device and may also connect the capacitor to the dc link or dc bus in the equipment. By connecting the snubber capacitor to the dc link voltage, the turn-off voltage across the power semiconductor is also "clamped" or limited to a voltage slightly above the value of the dc link or dc bus voltage. To improve snubber effectiveness, often stud-mounted type diodes are used, which are installed directly into the busbar assembly to minimize the parasitic inductance of the snubber circuit. This serves to reduce the overshoot voltage across the power-switching device to a lower level than can usually be achieved with the bus-capacitor type snubber. The resistor serves to damp out ringing in the snubber circuit and to discharge the snubber capacitor between turn-off switching cycles of the power switch, so that snubber effectiveness is maintained. The RCD snubber is typically used with conventional busbars in medium-power equipment, when high- or medium-speed switching devices such as MOSFETs or IGBTs are used. This type of snubber is also used with low-inductance laminated busbars in high-power equipment, which is typically rated at 125 kW or greater, when IGBTs are used as the power switches. Very high-power GTO-based equipment also uses the RCD type snubber, and this equipment can have power ratings into the megawatt (MW) range.

The RC type of snubber is a combination, usually connected in series, of a resistor and a high-frequency capacitor, connected directly across each power switch in the equipment. It is usually used in conjunction with a bus-capacitor or resistor-capacitor-diode snubber to "fine tune" the performance of the complete snubber. The addition of the resistor in the RC snubber provides damping that can serve to damp out high-frequency oscillations and ringing. It also "tunes" the RC snubber to a higher operating frequency than the other snubber(s), so that the overall reduction in high dV/dt transient overshoot voltage across the power switches during turn-off is improved (15).

All snubbers dissipate some power while protecting the power switches from excessive voltages. Regenerative snubbers are more complex types of snubbers using resistors, capacitors, diodes, and inductors or transformers to recover some of the energy that is normally lost in the conventional types of snubbers. Unfortunately, while the regenerative snubbers dissipate less power, they also tend to be less effective at controlling overvoltages than the other types of snubbers, such as the RCD snubber, for example. This limits their use, therefore, to lower power equipment and equipment that uses low- to medium-speed switching devices, such as power transistors, power Darlington transistors, and IGBTs (16).

DESIGNING THE BUSBAR

There are three basic considerations that need to be made when a busbar is designed. The designer needs to consider the busbar type needed—conventional, flexible, or low inductance—and how it is to be manufactured. He or she also needs to address the mechanical considerations of the busbars or busbar assembly. The electrical design aspects of the busbar must also be considered. Information will be presented showing the reader how to make the decision in choosing the proper type of busbar and also how to engineer the busbar to result in a successful design.

Choosing the Busbar Type

Choosing the busbar type is somewhat straightforward. If your application does not require mechanical flexibility, does not need low inductance due to the use of high-speed semiconductor switches, and small space is not a major consideration, then the conventional busbar is usually the easiest to design and the most cost-effective to manufacture. If your design needs mechanical flexibility, then the flexible busbar is the choice. Finally, if high-speed semiconductor switches are used in the design, then a laminated, low-inductance busbar is indicated. If the ease and speed of assembly and the reduction of possible assembly errors are important, a laminated busbar assembly would also be appropriate. Use the selection algorithm of Fig. 3 as an aid in choosing the proper type of busbar for your application.

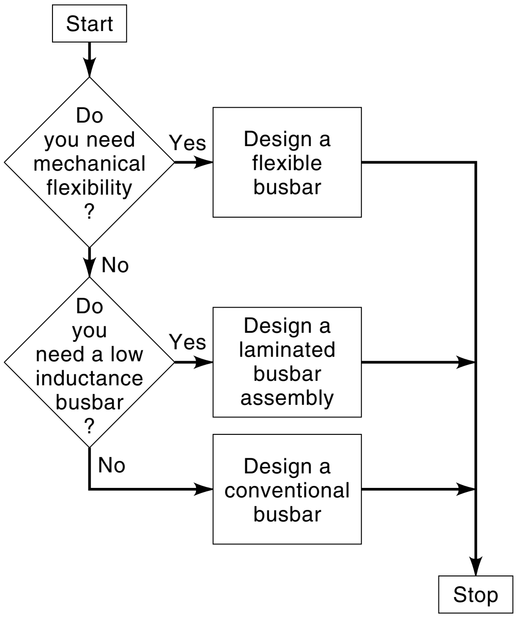

Figure 3. A selection algorithm for determining the proper type of busbar for a particular application.

Designing a Conventional Busbar

Conventional busbars are relatively simple to design. Materials such as Copper Development Association (CDA) 110 alloy half or full-hard copper, various hardnesses or tempers of aluminum and steel are used, which provide sufficient rigidity to maintain their shape and support the components that they are connected to. The busbars incorporate the mechanical features needed to connect two or more components together and they need to have sufficient cross-sectional area to carry the maximum amount of current involved while limiting the temperature rise of the busbar to the desired level. The mechanical features include the proper length and width to accommodate the bolted connections of the components being connected to, and holes and/or fasteners such as captive nut inserts, captive screws, or quick-connect terminals to ease assembly and reduce the chances of losing hardware. The thickness is then chosen so that the cross-sectional area, the product of width and thickness, is sufficient for the amount of current, in amperes, to be handled. A good rule of thumb for copper busbars is to make the cross-sectional area such that there is a minimum of 267 circular mils of area (0.135 mm^2) per ampere of maximum current flow. This assumes a temperature rise above ambient of 20°C, that the busbar is made of copper, and that it is open to the air on all sides. Larger cross-sectional areas will be required when higher-resistivity materials such as aluminum or steel are used for the busbar conductor or if insulation is used around the busbar. For example, aluminum has only 61.0% of the conductivity of copper, so 1.64 times the cross-sectional area will be required to carry the same amount of current with the same temperature rise. A circular mil is a measure of cross-sectional area equal to the area of a round-shaped wire that is 1 mil (0.001 in. or 0.0254 mm) in diameter and is equal to 7.854×10^{-7} in.^{2} or 5.067×10^{-4} mm^2. These square units of area are more applicable for rectangular shapes such as busbars. Once the length and width of the busbar have been determined by the mechanical constraints, the thickness is chosen to achieve the proper cross-sectional area. Busbar material is available in certain standard thicknesses so the required minimum thickness is determined by calculation and the next larger standard thickness is chosen. CDA 110 alloy copper busbar, for example, is available in 1/16 in. (1.59 mm) increments from 1/16 in. (1.59 mm) to 1/2 in. (12.7 mm) in thickness (17). If a maximum resistance or voltage-drop, at a specified current, is the limiting factor rather than the temperature rise, then the thickness of the busbar is further increased to achieve the desired dc resistance. The dc resistance, in ohms, is determined by dividing the desired maximum voltage-drop, in volts, by the current, in amperes, at which the voltage-drop is measured. The thickness of the busbar is then determined by using a modified version of the formula for determining the busbar resistance:

$$t = \rho l / Rw \tag{2}$$

where t is the minimum required busbar thickness, in cm, ρ is the conductor resistivity, in $\Omega \cdot$cm, l is the busbar length, in cm, R is the maximum allowable dc resistance, in Ω, and w is the minimum busbar width, in cm.

Busbars that are made in simple, straight shapes can be made from standard strip stock that is cut into the proper length. After the required holes for the mounting screws are drilled or punched into them, the busbars are then bent into the proper shape. Necessary hardware inserts such as captive nuts or captive screws are then pressed into the busbar. More complex shapes are typically machined or stamped out of sheet stock of the appropriate material. Then the required holes are drilled or punched into the busbar and any necessary bending is performed. Inserts, if used, are then pressed into the busbar. Often machining of the material is utilized for prototypes and small quantities of busbars, while stamping and punching of the busbars is done when larger production quantities of a particular type of busbar are required. Utilizing manufacturing processes such as continuous-feed stamping, bending, and punching usually results in lower costs per busbar than machining and drilling, but usually requires some tooling investment. The tooling can be either "soft" tooling, which is limited to a maximum material thickness of about 0.040 in. (1.02 mm) and wears out relatively quickly after approximately 1000 to 10,000 pieces are made, or "hard" tooling, which can usually make hundreds of thousands of parts before it is worn out and needs to be rebuilt or replaced.

Conventional-type busbars do not typically have any insulation applied to them because this increases the operating temperature of the busbars. Loss of heat from a busbar due to convection and radiation is inhibited when insulation is applied to its surface. Heat loss due to conduction is not reduced significantly by adding insulation, but this is usually not the primary heat-loss method, except at low temperatures. Usually air spaces between the busbars and other bare conductors are designed so that the air itself acts as the insulation medium between the busbars and other bare electrically conductive materials. Specifications such as Underwriters Laboratories specification UL 508, for example, describe the minimum voltage clearances that are required between conductors and other conductive surfaces for industrial equipment and power-converters, depending on the operating voltages involved in the equipment (18). Other specifications apply to other types of equipment. Occasionally, insulation such as heat shrinkable PVC or polyolefin tubing is added to the busbar in certain critical locations where airspaces do not meet the required clearance values. Insulation such as this is used very sparingly since it causes the busbar to run hotter than it would without any insulation. In extreme cases, where most of the busbar would need to be covered by insulation, for voltage-clearance reasons, a busbar with a larger cross-sectional area would be chosen to reduce the electrical resistance and the resulting temperature rise.

Designing a Flexible Busbar

A flexible busbar is designed using essentially the same procedure as described previously for conventional busbars. The main differences between conventional busbars and flexible busbars are the techniques by which they are made and the presence of insulation over most of the conductor in flexible busbars. Flexible busbars are made flexible by using "soft" materials, such as fully annealed copper, placed in a stack of several thin sheets that are free to slide across each other so the busbar bends easily. The stack of several thin sheets has a combined cross-sectional area that can be treated as a single cross-sectional area for the purpose of determining the required total thickness. Using multiple thin layers also reduces the resistance of the busbar to high frequency ac currents, which is caused by the "skin effect." This effect causes current to concentrate near the surface or "skin" of a conductor, increasing the effective resistance of the busbar to ac currents. This effect will be described in greater detail in the next section on designing laminar busbars. Usually, insulation such as PVC or Kapton is placed over the copper sheets so that the busbar can be placed near other conductors without requiring an air space for voltage clearance or to prevent short-circuits. The insulation also provides a small amount of stiffness or "memory" so that the flexible busbar retains the shape it is bent into. Flexible busbar material is available premade in various widths and thicknesses. The material is available in rolls so that flexible busbars can be made into the desired lengths by cutting the material, usually with a shear. Then the holes for connecting the busbar to the various components in the equipment are added by drilling or punching. Finally, the busbar is bent into the desired shape.

Designing a Laminated Busbar

A laminated busbar is appropriate when it is desired to reduce the inductance, reduce the voltage-drop, and increase the capacitance between the terminals of the busbar and/or to make the equipment faster and simpler to assemble and to reduce assembly errors. As described earlier, busbar inductance causes some of the energy put into the busbar to be stored in a magnetic field rather than all of it being completely transferred to the devices connected to the busbar. Also, the inductance causes an additional voltage-drop when the current changes in the busbar rapidly, which applies additional voltage to the switches used in inverter equipment, such as power semiconductors, when they are turned off. Use of a laminated busbar instead of a similarly sized conventional busbar typically reduces the inductance, also called self-inductance, by approximately a factor of 10. This is done by using the mutual inductance of closely coupled conductors, with their currents flowing in opposite directions, to nearly cancel out the magnetic field and also most of the self-inductance. Two or more parallel plates of a laminated busbar behave like a parallel-strip transmission line or "strip line" (19). A laminated busbar assembly also provides some shielding, like a coaxial cable, but with somewhat less effectiveness.

To design a laminated busbar, all of the concepts presented so far are used and some additional ones are required. The mechanical design needs to address the features required to connect the various components connected by the busbar together. The overall size of the busbar assembly is chosen to be wide and long enough to reach the terminals of the most widely separated devices to be connected together, and the overall shape is usually rectangular or square. The length-to-width ratio should be limited to 2.0 or 3.0 to minimize the parasitic inductance and to utilize the materials most efficiently (20). Bushings or embossments with holes of the proper size to accommodate the terminal bolts, and located in the proper position to connect to the components, are included in the busbar. Often fasteners such as captive nuts, captive screws, quick-connect terminals, or flexible leads are included to prevent hardware loss when the busbar is being assembled into the equipment. Although less desirable from a manufacturing standpoint, flexible leads that are already attached to the busbar assembly may be provided for connection to various devices. The busbar is often custom designed to have components like snubber capacitors, diodes, and resistors bolted directly to it prior to installation into the equipment. Fuses can even be incorporated into the busbar assembly without adding a large amount of parasitic inductance to the assembly. The fusing can be used to protect the busbar assembly, the components connected to the busbar, or both (21).

As with all busbars, the electrical design needs to provide the required cross-sectional area to carry the maximum current involved with the maximum desirable temperature rise. Here fault and overload currents and their possible time durations must be considered. The forces applied to the busbar by the large magnetic fields that are generated when the assembly is carrying large fault currents must also be considered in the design. This is particularly important for busbars that are used in utility substations, where fault currents can reach hundreds of thousands of amperes. The rule of thumb for copper-based laminated busbars is to provide a minimum of 400 circular mils (0.203 mm^2) of cross-sectional area per ampere of maximum current flow. As before, this is based on a desirable temperature rise of 20°C above ambient temperature (22). The increased cross-sectional area, over that of a comparably rated conventional busbar, is required because the busbars in a laminated busbar assembly are insulated, and the heat loss due to convection and radiation is thereby reduced. The insulation is necessary because it is important to place the busbars close together to maximize the mutual inductance effect, reducing the self-inductance to the lowest possible value. Usually, no air space is provided between layers so that the distance between the busbars is minimized. The insulation material and thickness must be chosen to provide the proper insulation voltage rating required for the equipment, based on its operating voltage or the dielectric (high-potential) test voltage, whichever is greater.

Since the inductance of the busbar is of concern, ac or rapidly changing dc currents are usually involved in equipment utilizing laminated busbar assemblies. Busbars carrying ac currents are subject to skin and magnetic proximity effects. In other words, ac currents tend to crowd near the surface of a conductor and are not carried throughout the entire thickness of the conductor. Ac currents are carried in a portion of the busbar thickness called the skin depth. Making the busbar thicker than 2.0 to 3.5 times the skin depth provides little improvement in ac resistance, voltage-drop, or temperature rise of the busbar. Therefore, laminated busbars designed for ac currents are not designed by choosing the width based on mechanical considerations first, and then choosing the thickness to achieve the proper cross-sectional area required for the current involved. Instead, the skin depth is calculated for the highest frequency of current that the busbar must carry. The thickness of the busbar is chosen to be 2.0 to 3.5 times the skin depth for the highest frequency of ac current involved, or slightly thicker, to reach the nearest standard thickness. Standard conductor thicknesses for copper laminated busbars range from 0.005 in. (0.13 mm) to 0.031 in. (0.79 mm), but larger thicknesses are available. After a practical thickness has been determined, the width is chosen to provide the proper cross-sectional area for the magnitude of the current involved. If mechanical considerations do not allow enough room for the required busbar width, then the busbar is redesigned using two or more layers in parallel to achieve the high-frequency current capacity required. Each individual busbar layer must not be thicker than 3.5 times the calculated skin-depth thickness; otherwise the extra thickness will not provide any benefit. The skin depth for ac currents of various frequencies is calculated by using:

$$\delta = (\rho/\pi f \mu)^{1/2} \tag{3}$$

where δ is the skin depth in the conductor, in cm, ρ is the resistivity of the conductor material, in $\Omega \cdot$cm (for copper $\rho = 2.2661 \times 10^{-6}\ \Omega \cdot \mathrm{cm}$ at 100°C), $\pi = 3.141592654 \ldots$, f is the frequency of the ac current, in Hz, and μ is the permeability of the conductor material, in H/cm (in copper, which is approximately the same as free space, $\mu = 1.2566 \times 10^{-8}$ H/cm).

Table 1 shows typical skin depths for ac currents of various frequencies in copper conductors at 100°C operating temperature.

Table 1. Typical Skin Depths for ac Currents of Various Frequencies in Copper Conductors at 100°C Operating Temperature

Frequency (Hz)	Skin Depth in Copper at 100°C (in.)	Skin Depth in Copper at 100°C (cm)
1	2.98	7.58
10	0.943	2.396
30	0.545	1.383
50	0.422	1.071
60	0.385	0.978
100	0.298	0.758
500	0.133	0.339
1 k	0.094	0.240
5 k	0.042	0.107
10 k	0.030	0.076
20 k	0.021	0.054
50 k	0.013	0.034
100 k	0.0094	0.024
500 k	0.0042	0.011
1 M	0.0030	0.0076

The busbar thickness is chosen to be between 2.0 and 3.5 times the skin depth at the highest ac frequency at which the busbar must operate. In systems with harmonic currents at multiples of the power frequency, an estimation or measurement must be made to determine which number of frequency multiples, or harmonics, carry significant currents. Usually significant current is not present beyond the tenth or fifteenth harmonic of a power line frequency, and the highest practical harmonic is then considered to be the highest frequency for calculating the skin depth and the maximum practical thickness of the busbar (23).

Often it is useful to determine the ac voltage drop due to the individual harmonic currents. This is done by first calculating the dc resistance of the busbar. The ac resistance of the busbar is calculated by determining the ratio of the ac resistance at the frequency of interest to the dc resistance and multiplying this ratio by the dc resistance. Equations (4) and (5) are used to calculate the ratio $R_{\mathrm{ac}}/R_{\mathrm{dc}}$.

$$x = t/\delta \tag{4}$$

where x is the number of skin depths, dimensionless, t is the conductor thickness, in inches or cm, and δ is the skin depth, in inches or cm.

$$R_{\mathrm{ac}}/R_{\mathrm{dc}} = x[\sinh(2x) + \sin(2x)/\cosh(2x) - \cos(2x)] \tag{5}$$

where $R_{\mathrm{ac}}/R_{\mathrm{dc}}$ is the ratio of ac resistance to dc resistance, dimensionless.

The derivation of these equations is beyond the scope of this article, but it is based on Maxwell's equations and uses the theory on which skin and magnetic proximity effects are based on. Magnetic proximity effects consider how the path that current takes in a conductor is affected by the magnetic field from another nearby conductor that is carrying current. Time-varying magnetic flux generated by the ac current flowing in a nearby wire causes eddy currents to flow in the first wire, altering the distribution of current in the wire. Once the ac resistance is known, the ac voltage-drop can be determined by multiplying the resistance by the ac current at that frequency. The ac resistance and voltage-drop may be calculated at all of the harmonic frequencies of interest to make sure that the ac voltage-drop is not excessive for the application. Usually it is desirable to keep the ratio of ac resistance to dc resistance below approximately 1.2 at all of the ac frequencies of interest, to limit the skin effect to a reasonable level (24). The worst-case voltage-drop is the highest voltage-drop determined from the voltage-drop calculations at dc and all of the ac harmonic frequencies.

Laminated busbars are constructed much differently from conventional busbars. Since many layers of conductors are involved rather than one, each layer is stamped or machined separately. The conductor layers are stacked together with thin layers of insulation between them. The insulation layers can be FR-4/G-10 fiberglass sheets, Kapton or other polyimide materials, Mylar, Tedlar, Nomex, or powder coatings, which are applied to the individual conductor layers before assembly. Powder coatings are typically applied to the conductors via electrostatic attraction, and then the conductor layer is heated up to convert the powder to a liquid that covers the conductor completely. The layers are typically joined together by sealing under heat, time, and pressure, using a process called heat-machine sealing. Exposed conductor edges that need additional insulation are typically coated with an epoxy edge-coating. This edge-coating needs to be only 0.007 in. (0.18 mm) thick for a dielectric voltage capability of 2500 VAC, for example. Due to the number of conductor and insulation layers involved, the thickness of the busbar assembly can be quite significant. Because of this, connections are not usually made by simply drilling or punching holes in the conductors. To bring the conductive areas to the surface of the busbar, above the level of the insulation layers and the other conductor layers, a bushing or embossment that goes completely through the busbar assembly is used for most connections. Holes are made in the busbar that are large enough to accommodate the bushings, and the bushings are connected to the conductor layers using metal-to-metal bonds. Depending on the conductor and bushing materials used, metal-to-metal bonding methods such as soldering, brazing, or welding are used. The other conductor layers that do not connect to a particular terminal bushing have a larger hole to provide room for insulation between these layers and the bushing. This is how short-circuits between conductive layers are prevented, and the proper voltage capability for the busbar assembly is achieved. Another method of making connections to the laminated busbar assembly is to design the conductor layers so that they each extend beyond the edge of the insulation in different places and form uninsulated tabs. Holes can then be punched or drilled into these tabs to accommodate a connecting bolt, or a pressed-in insert such as a captive stud or nut. Exposed conductor areas such as these are typically protected from the environment by electroplating with a tin plating or dipping in tin-lead solder. For low-resistance contacts in high-reliability applications, a gold flash is sometimes used.

Determining the Inductance of Laminated Busbars. Often it is important to estimate the inductance of a busbar by calculation or modeling. While it is possible to determine the inductance of a conventional or flexible busbar, inductance is usually not a major consideration for these types of busbars. The laminated busbar, however, is usually designed and applied to minimize self-inductance, so it is useful to estimate the inductance of the busbar assembly before expending the effort and cost to build and test it. Equation (6) shows how to estimate the inductance between two terminals on a laminated busbar assembly, where the busbar is relatively short, being less than approximately 6 in. (15.2 cm) in length (25).

$$L = 0.005l\{[\log(d/w + t)] + 1.5\} \tag{6}$$

where L is the busbar self-inductance in microhenries, l is the length of the busbar conductor in cm, d is the distance between the busbar conductors in cm, w is the width of the busbar conductors in cm, and t is the thickness of the busbar conductors in cm.

When the busbar assembly involved is relatively long, being approximately 6 in. (15.2 cm) or more in length, Eq. (7) provides a more accurate estimate of the inductance between two terminals on the busbar (26)

$$L = 0.002|\{2.303[\log(2l/w + t)] + 0.5 + 0.2235(w + t/l)\} \tag{7}$$

where L is the busbar self-inductance in microhenries, l is the length of the busbar conductors in cm, w is the width of the busbar conductors in cm, and t is the thickness of the busbar conductors in cm.

Since a laminated busbar assembly may have many terminals, it is of interest to know the inductance between each pair of terminals. Rather than repeating the preceding calculations many times, computer models have been developed to calculate all of the inductance values between all pairs of terminals on a laminated busbar. A model has been developed by engineers from the Laboratoire d'Electrotechnique de Grenoble (Laboratory of Electronics) in Grenoble, France using a simulation tool called InCa. This model calculates the inductance, resistance, and current density between all connections on a laminated busbar assembly. It takes into account the skin effects of ac currents by decomposing each conductor layer into several elementary segments. Each segment is made small enough so that the current density can be considered constant throughout the segment. Analytical formulas have been developed that are used to calculate the inductance, resistance, and current density of each of the segments. Linear matrix mathematical techniques are then used to combine the results determined for each of the segments into the values for the complete busbar conductor layers. Using the simulation model, it is possible to modify the physical characteristics of the laminated busbar assembly and determine from the model if an improvement in the inductance between certain pairs of terminals has been made, without actually building and testing the laminated busbar assembly. This modeling serves as a very useful design tool for designing laminated low-inductance busbar assemblies (27).

FUTURE APPLICATIONS OF BUSBARS

This article has defined what busbars are and the types of equipment in which they are used. The common types of busbars that exist have been detailed, methods for their fabrication have been discussed, and their advantages and disadvantages have been described. Methods for determining the proper type of busbar for a particular equipment application have been presented, and general design approaches used for designing each type of busbar have been outlined. Several types of snubber circuits, used with busbars to protect power-semiconductor switches in electronic power-conversion equipment, have been presented and their advantages and disadvantages have been described. The question might now be asked, as to where we might go from here? Research is being done in several new areas that relate to this topic and might be of interest to the reader.

Custom Power Distribution Systems

The Electric Power Research Institute (EPRI) is developing a new concept for improving the reliability of utility power systems called custom power distribution. Rather than providing conventional solutions to power-quality problems by operating on the low-power or load side of electric power systems, custom power distribution operates on the high-power or source side of the utility power system. Power electronic devices called dynamic voltage restorers (DVRs) have been developed that rapidly compensate for nonlinearities and harmonics introduced on the power lines by customer loads, within a few microseconds. This equipment is actually a dc to ac power-converter device that provides an ac-compensating voltage, which is added to or subtracted from the power grid voltage, restoring the voltage at a specific user's node to the proper pure sine wave voltage. The DVR, like a very high-voltage, high-power active filter circuit, uses a source of dc voltage storage such as a large capacitor, battery, superconducting magnetic energy storage device, or a combination of these devices to provide the energy for delivering the compensating voltage to the power grid. Solid-state circuit breakers (SSBs) are also being used to switch the customer's sensitive loads rapidly from a feeder that has lost power due to a fault, such as a lightning strike, to another that has normal power. This way the customer's power is lost for only a few milliseconds, rather than for the one to three full seconds or longer that is typical when an electromechanical recloser interrupts the feeder power to the customer's load (28). As with most power-conversion equipment, laminated low-inductance busbars are being used to advantage to transfer power and protect the semiconductor-switches in these DVRs and SSBs. The future promises to utilize more solid-state power-conversion equipment to solve power-quality problems and improve power-supply reliability, with the help of special busbars that transfer power within and outside this equipment.

High-Temperature Superconductivity

A large amount of research is also being done by several companies in the area of superconductivity of materials. One very exciting area of this work is that new metal-oxide ceramic materials are being developed that become superconductive at much higher temperatures than metals do. Pure metals become superconductive at temperatures of 4°K (−269°C), while these new materials, called high-temperature superconductors (HTS), become superconductive at much higher temperatures of 20°K to 85°K (−253°C to −188°C). This makes it much more practical to cool these conductors, because relatively inexpensive liquid nitrogen can be used instead of liquid helium. These ceramic materials are being made into wires of various shapes so that electromagnetic devices such as magnetic energy storage devices, fault-current limiters, generators, motors, distribution transformers, and shielded and unshielded power cable systems can be made using superconductivity principles. Using these superconductors instead of standard copper wire reduces the losses in these devices to about one-half of what they normally are with copper conductors (29). In the future, it may be possible to build special high-current, low-inductance busbars using these superconductive materials to significantly reduce the resistive energy losses in busbars and in the equipment in which they are used. This could reduce the energy losses within much of our electronic equipment to between 1/2 to 1/6 of present levels, having very positive effects on electric power utilization efficiency, the world's total energy consumption, and the long-term preservation of our environment.

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