Achieving (and maintaining) electrical connection tightness

Reliability depends upon the integrity between conductors

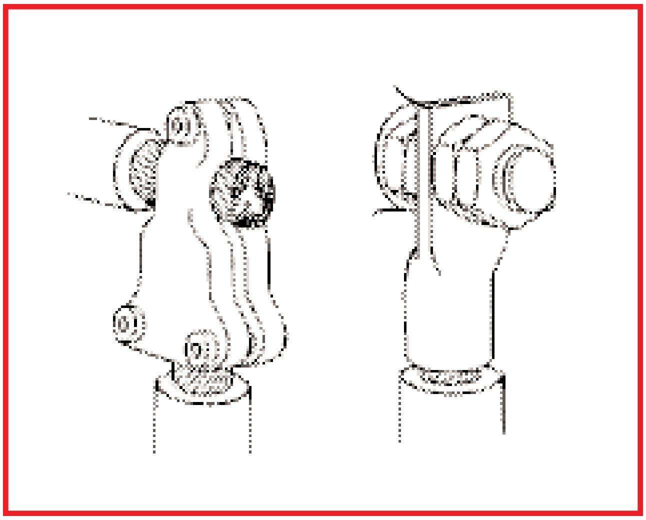


Figure 1. Two basic types of bolted connection, in which fastener tightening torque should be carefully controlled. At (a), fasteners clamp the connecting wires directly. At (b), the tightening torque acts instead on conducting surfaces of the hardware and terminal lug.

By Richard L. Nailen, P.E., *EA* Engineering Editor

CAN A CONNECTION BE TOO TIGHT? YES AND no. Supposedly, someone once asked Abraham Lincoln, "How long should a man's legs be?" His answer: "Long enough to reach from his body to the ground."

Along that same line, one might ask, "How tight should an electrical connection be?" The simple answer is, "Tight enough to carry the maximum circuit current forever without overheating, arcing, or significant voltage drop." Unfortunately, that answer is no more useful than Lincoln's.

Insofar as the contact surfaces between two conductors are concerned, "the tighter the better." The joint may involve two flat surfaces (such as terminal lugs—see Figures 1 and 2), or a wire and a pressure plate of some sort, as in a "screw lug" (Figures 1 and 3).

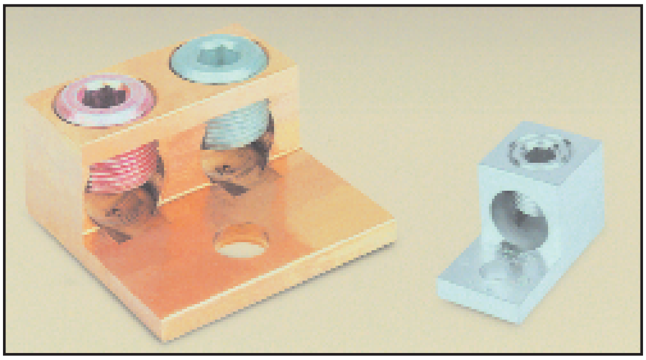


Figure 3. Bolted connectors for copper or aluminum conductors, in which a clamping screw tightens directly down on a wire or cable.

—Galvan Industries photo

Figure 2. Terminal bars in this 5 kV reactor assembly are drilled for bolted attachment of multiple cable lugs. Uniform loading and heating of all connections requires uniform tightening of all hardware.

—Photo by Richard Nailen

Both types may take many forms (Figure 4). The subject here is not crimp connectors, or spring assemblies (such as fuse clips), or joints involving brazing or soldering between conductors, but terminations held together by threaded fasteners. At one extreme is the bus bar assembly, usually clamped together by two or more large bolts and nuts (covered nearly two decades ago in "What makes bolted connections tight enough?," *EA* March 1988).

At the other extreme is the small screw terminal on a branch circuit device such as a lampholder (Figure 5). In between are compression connectors involving sockets or saddles in which conductors are squeezed by tightening a screw or bolt (Figure 1).

Problems with rough surfaces

Although flat mating surfaces may appear smooth, electrical contact is actually made through numerous tiny

Please turn to next page

CONNECTION TIGHTNESS continued from previous page

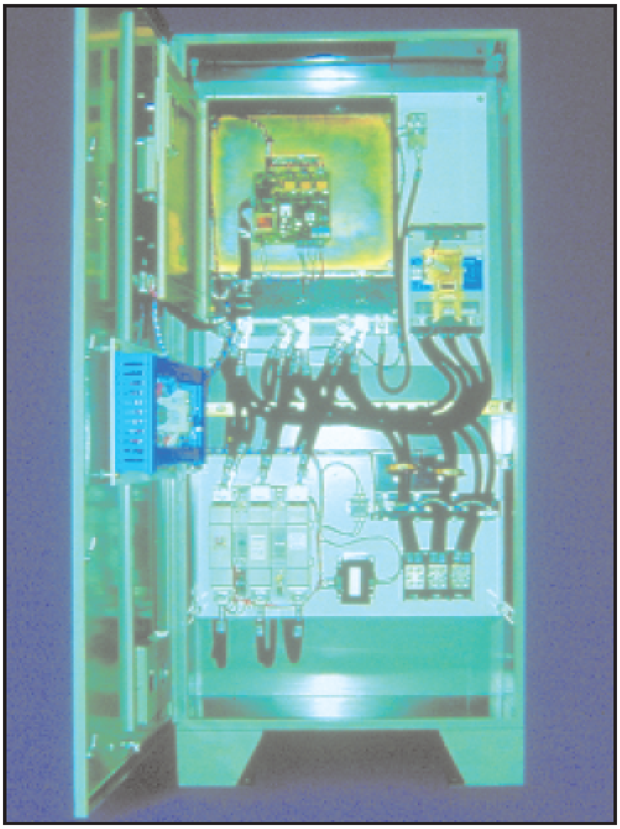


Figure 4. Variety of sizes and types of apparatus terminal connections is evident in this typical 400 hp motor starter. —Photo by Richard Nailen

peaks—individual points of contact that normally constitute only a small portion of the nominal joint surface. As those peaks are compressed against each other more and more tightly, they flatten, spreading the conducting area more widely, and lowering overall contact resistance. Also, the air space within the joint is reduced, decreasing possible access of corrosive contaminants into the joint.

Although joint tightness determines the integrity of most terminations, even surfaces that are clean and smooth can be compromised in ways that cannot be dealt with by proper tightening. In an industrial substation, termination of a ½ by 5 inch bus carrying 1,200 amperes was discovered to have been factory-assembled with a band of masking tape across the termination surface to identify the part number. Invisible outside the assembled joint, it blocked off a significant area of contact.

In the second type of termination, the individual wire strands (Figure 6) are meant to be compressed against each other such that each carries an equal share of current while exhibiting an equal share of total joint resistance. That ideal condition is sometimes difficult to achieve, however, and seldom possible to measure.

Tightening any fastener increases the stress within it. If that stress reaches the fastener's breaking point, the joint is in danger of rupture. Failure may not be immediate, unless the fastener breaks while being tightened.

Consider a simple bolted joint. If stretched beyond the material's yield point, the bolt will elongate (without immediate fracture) such that the joint is no longer tight—or at least the tightness will not increase beyond that point. At

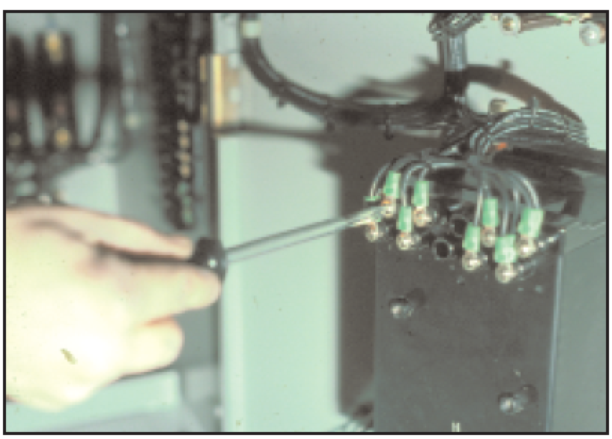


Figure 5. Tightening small screw terminals on control apparatus—a process that seldom gets close attention. —Photo by Richard Nailen

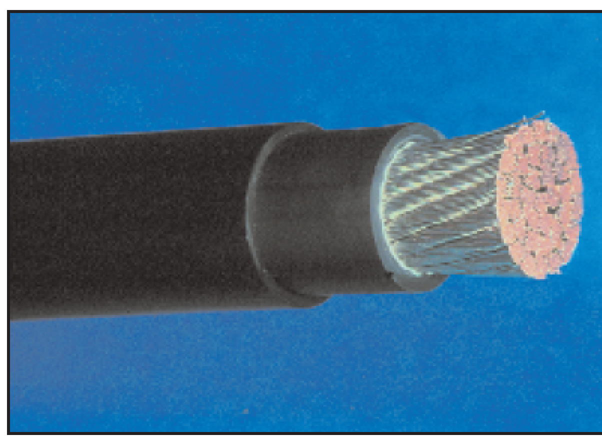


Figure 6. Special care is needed in terminating large conductors like this, in which each strand is made up of many smaller wires. Improperly tightened connections may overload some wires and underload others. —American Insulated Wire photo

some lower value of stress, the joint will be tight, yet the bolt is subject to premature breakage under any added stress imposed by weight or magnetic forces from the joined conductors. A joint found to be loose (such as by infrared imaging) may be re-tightened during routine maintenance, deforming threads or stretching fasteners still further, so that the problem worsens.

These concerns are intensified when joint components include several different materials (especially aluminum), when vibration is present, or when the environment or wide current fluctuations cause repeated heating and cooling cycles in the joint.

Even when a properly calibrated torque tool is properly used, completely consistent results can't be assured. Actual tension in a bolt—to say nothing of the actual compressive force exerted on the connection components—can vary as much as 30% from one to the next.

Proper use of thermography

Infrared thermography, useful as it is, has been widely misunderstood as a means of evaluating the integrity of connections in electrical circuits (Figure 7). When properly used, it will always reveal an overheated termination (Figure 8). "Properly used" means more than just using the

Please turn to next page

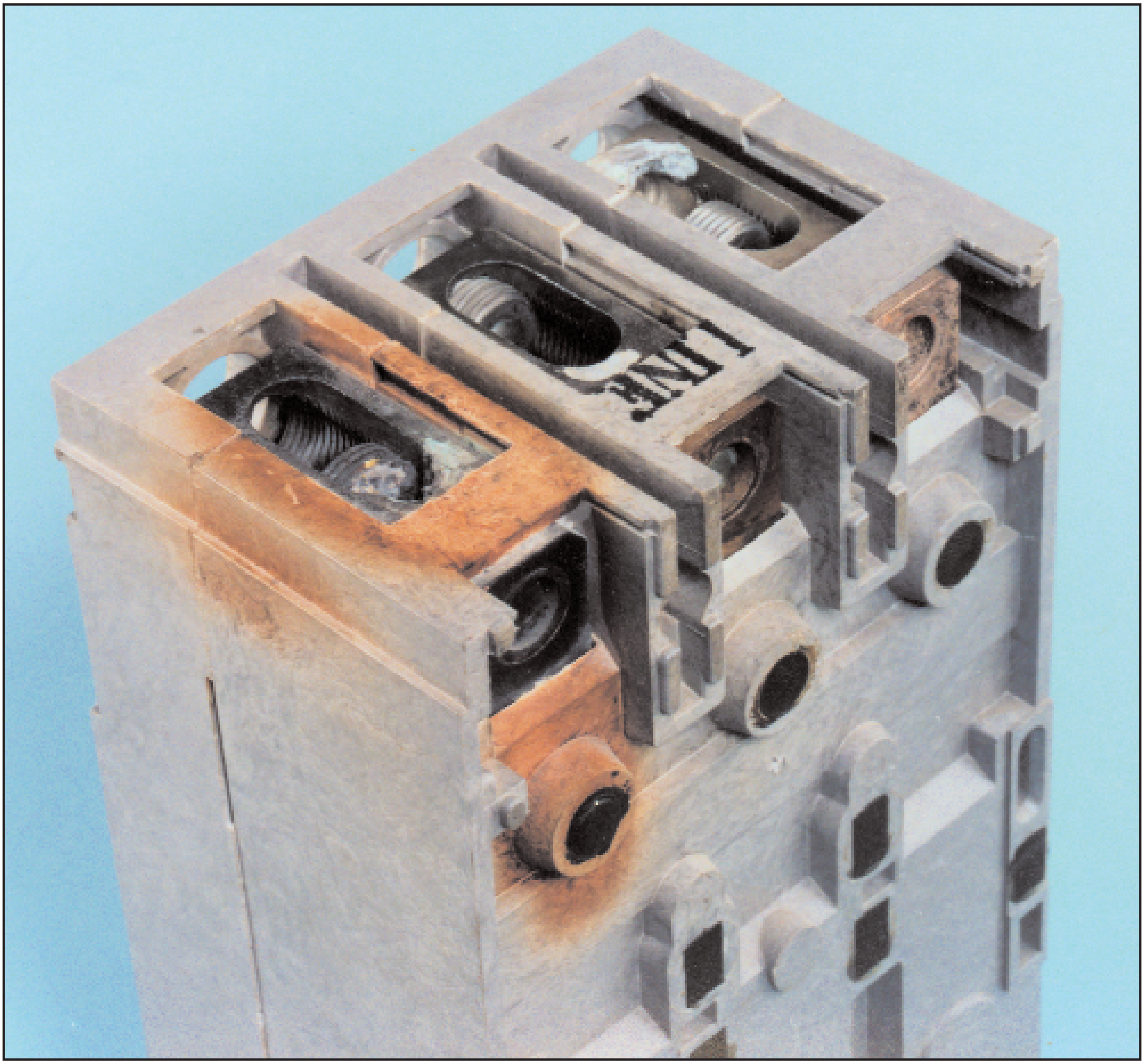


Figure 8. The result of inadequate connection tightness at a circuit breaker line terminal in a motor control center. —Wisconsin Electric Power photo

CONNECTION TIGHTNESS continued from previous page

imaging equipment within its limitations, and properly interpreting the readings. For example, in a three-phase circuit, how much difference is allowable between the temperature of one phase and that of the other two? Is total temperature the important criterion, or should it be the rise above ambient?

"Proper use" also means not jumping to conclusions as to the nature of the problem. Overheating may have more than one cause. All too often, maintenance workers have assumed that any hot connection is "loose." Their response is to re-tighten it. "Loose connections" do develop higher resistance and are likely to get hotter than they should. As indicated by Paragraph. 110.14 of the National Electrical Code, connections to "equipment terminations" are to involve conductors that won't be hotter than either 65°C or 75°C (depending upon current and conductor size), regardless of the temperature rating of the conductor insulation. A higher conductor operating temperature will add heat to conductor terminations.

Uncontrolled heating and cooling cycles, together with corrosion in a hostile environment, can accelerate deterioration in the joint. Even when that's not the case, re-tightening may still be ineffective because the problem lies in the nature of the connection rather than its tightness. If one component is a compression lug, for example, the bolted connection between lug and terminal may be tight, but the wire or cable crimp within the lug was not properly made or has deteriorated in service. Wire strands may break or be pulled loose.

Overheating can be expected when mating termination surfaces become dirty or corroded, greatly increasing the contact resistance. No matter how tight initially, joints are not airtight. Another problem, especially with repeated tightening, is damage to the fasteners involved, such as crossing or stripping of threads.

In a paper mill 25 years ago, an infrared study performed prior to a scheduled maintenance shutdown indicated numerous overheated electrical connections. After all the "loose" terminations were tightened, and the plant was back in operation, a repeat study showed that a fourth of all the problems observed in the first round were still present. Some had gotten worse.

Examination of the repair records showed that when suspect connections were taken apart, cleaned, and put back together, 92% of them exhibited acceptable temperature. But when a connection was only re-tightened, only one in five showed improvement.

What the National Electrical Code says

What does the National Electrical Code say about tightening terminations? Turning to Section 110.14 in the 1984 edition of the Code, we find the first appearance of the requirement that "devices such as pressure terminal or pressure splicing connectors . . . shall be suitable for the material of the conductor and shall be properly installed and used. . . ." A Fine Print Note adds this: "Many terminations and equipment are [sic] marked with a tightening torque."

Then and since, 110.14(A) adds that "Connections of conductors to terminal parts shall ensure a thoroughly good connection without damaging the conductors. . . ." (How "thoroughly good" differs from "good" has not been explained.)

The wording of the Code is usually taken to imply that terminations are to be tightened to the value (if any) that is marked on the equipment. But that is implicit rather than explicit. The practice has become increasingly common. Back in the spring of 1985, a leading electrical trade publication ran this headline over its lead editorial: "Torquing electrical terminals—soon, it will be mandatory!" For five years, the magazine had been advocating the practice for "all current-carrying electrical terminals and joints," to achieve "a precisely determined value of contact pressure." Either "inadequate" or "excessive" tightening was said to account for most electrical failures.

Why "mandatory"? In 1984 (the year of the NEC revision), Underwriters Laboratories publications began requiring circuit breakers and enclosed switches to be marked with a tightening torque value "for all wire connectors intended for use with field wiring." In Section 110.3(B), the NEC had already required that "Listed or labeled equipment shall be used or installed in accordance with any instructions included in the listing or labeling." Thus, the UL changes meant that installers had to comply with the torque markings provided in accordance with the UL listing.

Why, then, isn't the practice universal today? First, because the UL and NEC requirements apply only to "field wiring"—to connections made when listed apparatus is installed. No such requirements apply to internal connections—such as bus bar joints within switchgear, tap changer connections within transformers or regulators, terminal boards inside control centers or electronic apparatus, or many other factory assemblies. Secondly, the initial UL stipulations dealt only with breakers and switches, not fuse blocks, dry-type transformers, reactors, motor starters, rectifiers, battery chargers, etc.

In any event, specifying (and using) a torque value does not necessarily result in a "precisely determined" contact pressure. How much contact pressure exists within any joint depends upon the condition and nature of the contact surfaces as much as upon the force exerted by one or more tightened fasteners. No universal practice governs the size, shape, or stiffness of a terminal lug on a conductor based just on the wire gauge size. Furthermore, different conductor sizes, and therefore different lug sizes, may be attached

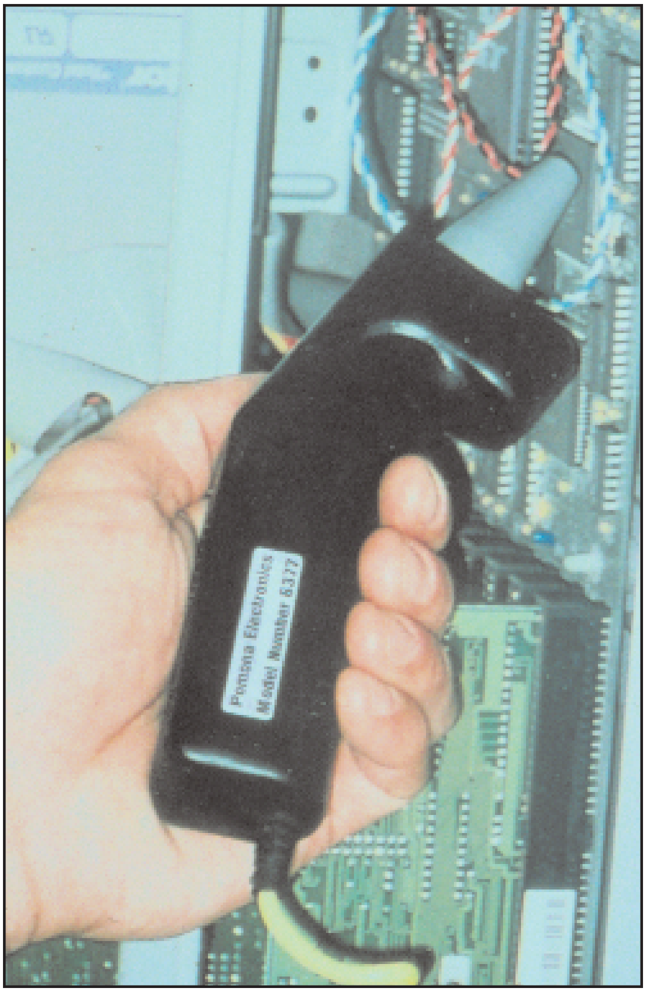


Figure 7. Infrared surveillance can be useful for electrical connections of all types and sizes, but the results must be interpreted carefully, especially when dealing with a variety of operating conditions and current levels.

—Pomona Electronics photo

to the same apparatus terminal (such as a motor lead).

Hence, when bolts are tightened to a specific pound-inch value of torque, the installer can have no idea what the contact pressure is within the joint. It can hardly be considered "precisely determined."

Questions unanswered by technology

Despite those yawning loopholes, the use of torque markings—and the use of torque wrenches and screwdrivers in field wiring—has increased. Electricians, electrical inspectors, and maintenance technicians continue to question the practice, though, not because they don't recognize the value of torque control, but because of these questions for which the technology has not provided firm answers:

1. All physical limits, such as machining dimensions, operating temperatures, and vibration levels, must involve tolerances. When tightening torque is listed or marked as "25 lb-in," for example, what's the tolerance? Is 25 a lower limit (25 minus zero), an upper limit (25 plus zero), or neither? What plus/minus variation is allowable?

2. If the correct tightness is present at installation, and (by whatever means) the joint is later found to be "loose," which of the following actions should be taken?

a. Re-tighten the joint to the original or listed value (which is of no help unless that original value is known).

b. Disassemble the joint and re-assemble using spring

Please turn to next page

CONNECTION TIGHTNESS continued from previous page

washers, a sealant, or some kind of locking device.

3. How accurate is a torque tool? How can its calibration be checked, and how often should recalibration be done?

Solid versus stranded wire

When the joint is tightened by "squeezing" a wire, an ongoing debate among electrical installers involves the relative merits of solid and stranded conductors, particularly in larger sizes such as No. 10 and above. Because it is much stiffer in handling, solid wire can be easier to push through some raceways (although harder to remove). On the other hand, the greater flexibility of stranded wire renders it easier to place inside cabinets or junction boxes where space is limited. The NEC requires most conductors in raceways to be stranded in sizes 8 and larger.

Some electricians contend that compression terminations for stranded wire tend to exhibit higher resistance because the innermost strands are compressed less tightly than those on the periphery. However, product listings and manufacturer recommendations generally sanction the use of either solid or stranded conductors.

What about wires of the same gauge but two different strandings? For the added flexibility needed in close quarters within rotating machinery, motor and generator lead cables use finer stranding—many more strands of smaller wire—than the power cable used in utility work or commercial building wiring. For the same total cross-sectional area (and therefore the same resistance and ampacity), the finer the stranding, the larger the physical O.D. of the conductor. The difference is not great. For example, comparing Figure 9(a) with Figure 9(b), for a No. 6 gauge wire, the outer diameters are 0.186 and 0.210 inch respectively.

Hence, when extra-flexible "locomotive cable" or "welding cable" is used to achieve maximum flexibility in wiring, properly fitting the conductor to terminal assemblies can be difficult. "Making it fit" by trimming strands—either from the conductor periphery, or (to make it less noticeable) from the interior, is unacceptable.

So, what are electricians saying and doing about the issue? In the trade, comments like these are not uncommon:

"I've been hand-tightening 500 mcm for years and never had any problems."

"I suggest to re-tighten aluminum connections every five years."

"The foreman of this job asked why I use a torque wrench. I replied, 'Don't you?' He said no."

"I was taught never to re-torque a connection."

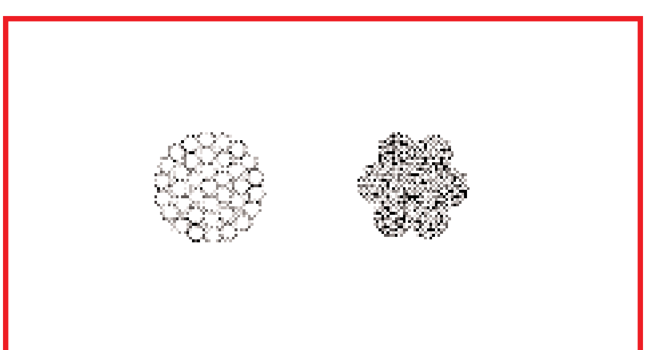
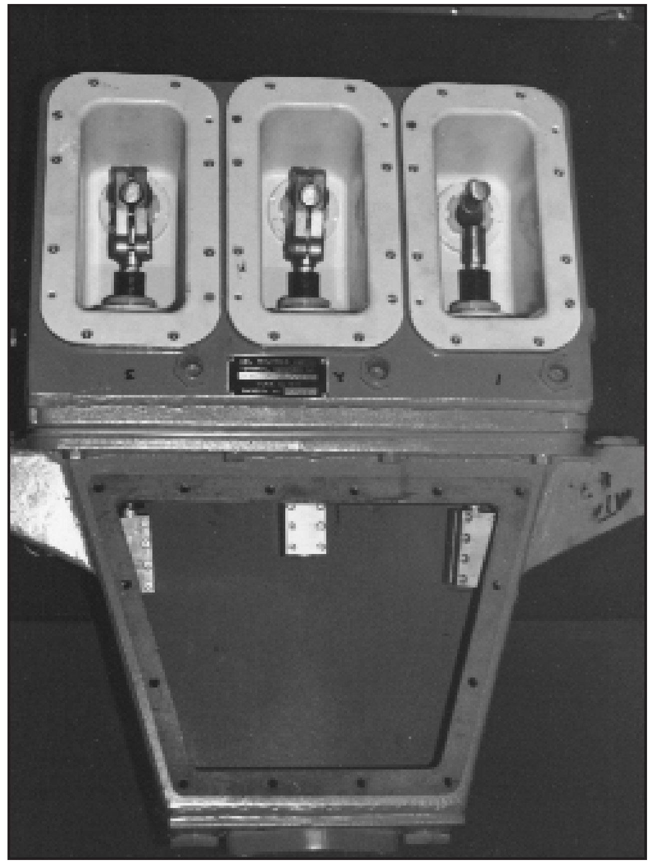


Figure 9. Although of the same wire gauge and ampacity as the conventional power cable at left, the more finely stranded wire at right necessarily has a slightly larger outside diameter. Hence, the same size terminal connector may not be a proper fit on both conductors.



Each of these motor lead connections in a European "phase segregated" terminal box includes two clamping fasteners similar to those in Figure 1(a). —Photo by Richard Nailen

"Whenever I finish a job, the inspector comes along, and gives all the connections another half turn or so, no matter how tight they were to begin with."

"I was always taught that the tighter you make a connection, the better. . . . I have split neutral bars from tightening . . . stripped out 600 kcmil split bolts. . . . I have always done this in the belief that I was doing a good job; I thought the resistance falls as the connections get tighter."

Others have said—whether facetiously or not—that they were taught to "tighten it until it breaks and then back off a quarter turn," or "torque it down till it strips then back it up a half-turn."

The right way to tighten a connection

What, then, is the "right way"? These appear to be the most useful guidelines:

1. When a termination is given a tightening torque limit by the manufacturer, work to that limit, using a properly calibrated torque tool (wrench or screwdriver). Avoid confusing "pound-inches" with "pound-feet," and distinguish properly between English and metric units.

2. Subsequently, when infrared scanning or any other form of surveillance indicates that a termination may have loosened, do not routinely re-tighten to the original torque level. Instead, take the connection apart. If one joint member is wire or cable, cut that back a sufficient length to remake the joint with undisturbed conductors; check the condition of other joint components for mechanical integrity and cleanliness; then re-assemble the joint, applying the proper torque as if it were new work. In the process, check fasteners carefully for signs of such damage as stripped threads. ■