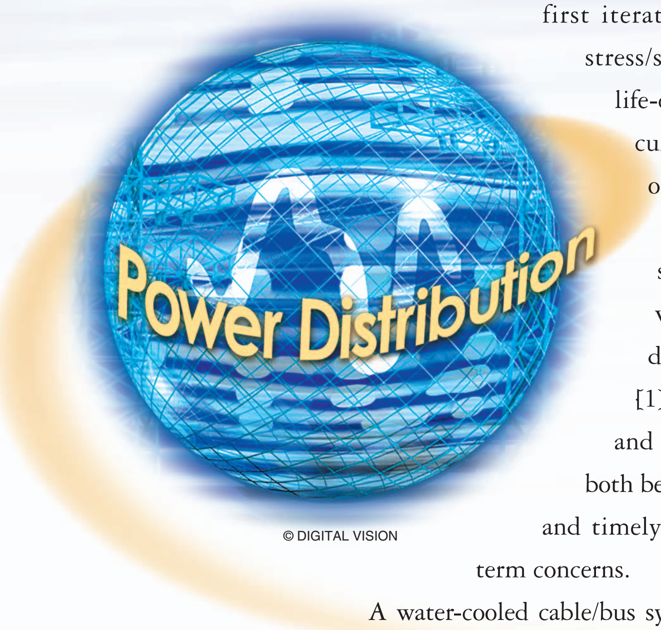
BUS CALCULATIONS

A practical approach for sizing a water-cooled bus.

BY SOUMITRA K. GHOSH

THE SIZING OF AN ELECTRICAL BUS IS AN ITERATIVE EXERCISE. The process logically starts with the selection of materials based on performance requirements, budget, design standards, and fabrication/installation codes to be met. The design of multiple forced-cooled buses within a space-restricted envelope at a public regulated facility has its own challenges. The first iteration in sizing is critical for subsequent calculations like stress/seismic analysis, electromotive force (EMF) effect, cooling, life-cycle cost, etc. This article provides a baseline bus-sizing calculation that can also be used as a tool for procedural validation of calculations performed by software, if any.



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Most electrical engineers at some point routinely make decisions on bus or cable sizing. The ampacity of copper bus and various recommended adjustment factors causing derating/uprating could be derived from the IEEE Brown Book [1], the CDA Guide [2], the National Electric Code (NEC) [3] and manufacturer's data. Over/undersizing of conductors could both be of serious concern, depending on applications. Comprehensive and timely evaluation of factors of significance can avoid short-/long-term concerns.

A water-cooled cable/bus system from a transformer secondary to an electric furnace can significantly reduce the footprint than a natural air-cooled cable/bus. The water-cooling of cable/bus is not a new concept. For example, Fermilab report TM1372 mentioned a water-cooled bus designed by Argonne National Lab in 1967. The earlier applications were driven mainly by high-current welding needs. Water-cooled cables were often run as temporary installations without any conduits or confinements and had no regulatory approvals. The NEC and Underwriters' Laboratories (UL) have started permitting the use of such cables, however, the great welding cable debate still continues.

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This article will demonstrate the design of bus system for a single-phase electric furnace (Figure 1) with multiple pairs of electrodes.

The prototype glass furnace in production.

Material

Workability Matters

The bus will be constructed of copper pipes (not tubes). Copper pipe grades with superior conductivity come at a cost of reduced mechanical strength and corrosion resistance. For example, UNS C11000 electrolytic grade copper has 101% of International Annealed Copper Standard (IACS) conductivity while that of C12200 DHP only 85%, but with superior workability for brazed or welded construction.

Satisfying Standards

ASTM B188 might be a popular standard for copper bus pipes, but one has to be careful as to which fabrication code the buswork has to meet. For example, B31.1 ASME Power Piping code does list B188 pipes, while B31.3 Process Piping code, more common in industry, does not; ASTM B42 pipe can be used instead.

SYMBOLS

CM = circular mil
Cp = 1 Btu/lb-°F
d_1 = bus pipe ID
d_2 = bus pipe OD
D = length of jumper conduction path
E = voltage
F = force
f = frequency
G_S = bus reactance
I = current
K = thermal conductivity
L_S = self-inductance
L = inductance
L_A = Phase A inductance
M = mass
MCM = wire size in 1,000 CM
OD = outside diameter
P = hydrostatic pressure
Q = rate of heat generation
R = resistance
R_{AC} = ac resistance
R_{DC} = dc resistance
R_{ac}/R_{dc} = skin effect ratio
S = allowable stress
t_w = bus pipe wall thickness
ΔT = temperature change
T_1 = terminal temperature
T_X = maximum strand temperature
VD = voltage drop
VD_{dc} = dc voltage drop
VD_{ac} = ac voltage drop
W = power in kW
X_L = ac reactance
Z = impedance

Durability

It could be argued that in case of loss of water circulation, the piping may be required to withstand steam temperature and pressure, even if only for a short period. ASME Boiler and Pressure Vessel Code Section VIII, Division 1 considers the margins for deterioration of such pressure vessels during service. Internal bursting pressure could be calculated from Barlow's formula for Hoop Stress for a 2-in nominal, double extra-heavy-duty (OD: 2.375 in, thickness: 0.436 in), C12000, O61 temper, ASTM B42 pipe as

$$\begin{aligned}\mathrm{P} &= 2\,St_w/(d_2 - 0.8\,t_w)\\ &= 2 \times 3,000 \times 0.436\,(2.375 - 0.8 \times 0.436)\\ &= 1,300\ \mathrm{lb/in}^2.\end{aligned}$$

Thermal reserve capacity of the system would not be sufficient to raise the steam pressure to 1,300 lb/in^2. The flanges and O-rings/hardware will give way much sooner than the pipes under such a circumstance.

Pipe flanges, connectors between flexible braids and pipe/electrodes, might require reinforcing or be made of harder alloys, such as bronze, in order to meet NEMA CC1 or SAE standard torque specification. Appropriate Belleville (disc spring) or similar washers are to be used at the joints that are subject to vibration or thermal movements.

Water Issues

Water temperature, purity, and continuity of supply are important for obvious reasons. Erosion (impingement) of copper pipe depends on various factors including the water velocity (shear), 3–5 ft/s. have been considered to be in safer range. An evaporative closed-loop water system with the primary side conductivity range of 100–300 μ-mhos/cm has been considered adequate for a coreless induction furnace [4]. However, if the water treatment system is not maintained/operated properly, deionized water could cause more corrosion than regular demineralized water.

Insulators

Asymmetrical short circuit (AIC) for the power system was 48,000 A. The electromagnetic force developed between two pipes 6-in apart with 2-ft unsupported span is

$$(\mu 1/2\pi)\,I^2/d = \frac{\frac{4\pi\times10^{-7}\times2}{2\pi\times3.28}\times 48,000^2}{0.5}$$
$$=562\ \mathrm{lbf}.$$

Allowing a safety factor of two on this force for rigidity, resonance conditions, etc., will be 1,124 lbf.

Stress on a 1-in thick standoff insulator is, $1405/(\pi \times 1.287) \times 1 = 348$ lb/in^2, which could easily be handled by NEMA GPO-3 fiberglass-reinforced plastic insulators whose tensile/compression strength are in the range of 10,000–15,000 lb/in^2.

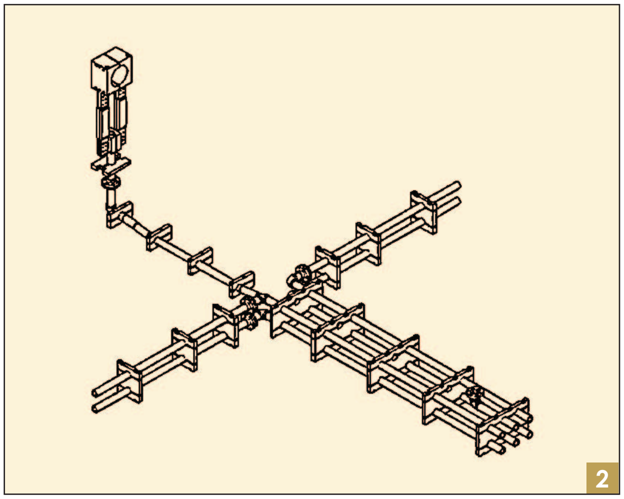
Maximum deflection per Euler beam bending equation

$$0.2 \times 5\, w \times L^4/(384EI),$$

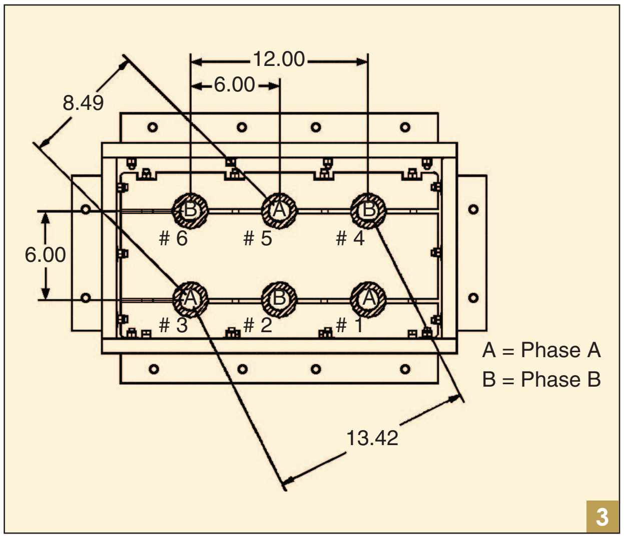
where
w = weight per unit length
L = length
E = modulus of elasticity
I = moment of inertia $= \pi(d_1^2 - d_2^2)$.

It's found to be in the order of 1 mm and is accommodated by design tolerance of 1/8-in clearance provided between the pipe and insulator for constructability and thermal movements.

The insulators were rigidly clamped to the housing (enclosure) with sufficient clearance between the bus and insulators for thermal growth/movement that offered some challenges in seismic restraint of the buswork.



A portion of bus layout.



Bus conductors.

Assumptions and Boundary Conditions

Assumptions

Each electrode pair under normal operation draws about 4,300 A, with a total load of 12,905 A for all three pairs. In the worst case of uneven current distribution (assuming one pair is lost), the peak current loading per pair is 6,452 A.

Each bus (Figure 2) is made of a 2-in nominal, double extra-heavy-duty copper pipe without any coatings and assumed to carry up to 3,000 A/in^2 (rule of thumb). The buses run parallel to each other to minimize inductive drops and finally branch out to their respective electrodes.

The flexible jumpers (shunt) between the bus and the electrode are made of naturally cooled, tinned-copper braids. The manufacturer's recommended ampacities widely vary from 600–1,500 A/in^2 for such braids.

The ac frequency is 60 Hz.

Spacing between bus elements of 1 in could be enough for the dielectric strength, however, 6 in is more appropriate to accommodate pipe flanges, instruments such as current transformers, or flow meters [5] planned, if any.

Boundary Conditions

The maximum allowable voltage drop cannot exceed 3% as per NEC 210-19 for branch circuits and 5% for feeders.

The maximum allowable temperature for the connections recommended by the manufacturers is 200 °F. The higher temperature can cause surface oxidation of joints, loosening of connections, and is too close to the boiling point of water in the attached pipes. For the given supply water temperature of 90 °F, the bus is designed for a 30 °F temperature rise conservatively, while 30 °C is the norm in industry.

Configuration/Calculations

Bus Size (Rule of Thumb) for 6,452 A

Assuming 3,000 A/in^2 current density, minimum cross-sectional area required, $6{,}452/3{,}000 = 2.15$ in^2.

For a 2-in pipe, from Figure 3, $d_1 = 1.503$ in and $d_2 = 2.375$ in.

$$A = (\pi d_1^2/4 - \pi d_2^2/4) = 2.656 \text{ in}^2. \qquad (1)$$

AC Resistance at 60 Hz

The bus length and reactance are required to determine the approximate voltage drop (see Table 1).

The resistivity of copper is 10.3 Ω-cmil/ft at 68 °F [6] or 10.6 Ω-cmil/ft @ 90 °F. The dc resistance of a 2-in pipe is $10.6/(2{,}375^2 - 1{,}503^2) = 3.14\ \mu\Omega$/ft or 0.00314 Ω/1,000 ft.

TABLE 1. BUS LENGTHS.

Bus #-Phase	Length (ft)
#1-A	24.5
#2-B	17.9
#3-A	24.5
#4-B	24.7
#5-A	4.8
#6-B	24.7

The pipe thickness-to-diameter ratio is $t_w/d_2 = 0.436/2.365 = 0.184$.

At 60 Hz, $\sqrt{(f/R_{dc})} = \sqrt{(60/0.00314)} = 138$.

From standard skin-effect charts [7], the corresponding R_{ac}/R_{dc} is determined as 1.18.

$$R_{AC} = R_{DC}(R_{ac}/R_{dc}) = 3.14 \times 1.18 = 3.7\ \mu\Omega/\text{ft}. \tag{2}$$

Inductance for a Six-Conductor Configuration

Bus Conductor #1 (Figure 3)

Self-inductance [8]

$$\begin{aligned} L_S &= (\mu_0 l/2\pi)[\ln(2l/a) - {}^3\!/_4] \\ &= (4\pi \times 10^{-7}/2\pi \times 3.28)[\ln(24/1.287) - {}^3\!/_4] \\ &= 0.06 \times 2.17 \\ &= 0.13\ \mu\text{H/ft}. \end{aligned}$$

Phase A to B, Mutual Inductance

$$\begin{aligned} L_{12} =& (\mu_0 l/2\pi)\{\ln((l/d + \sqrt{(1+(l/d)^2)}) \\ & - \sqrt{((1+(d/l)^2)} + d/l\} \\ =& 0.06[\ln(4.236) - 1.118 + 0.5] \\ =& 0.05\mu\text{H/ft}. \end{aligned}$$

Phase A to A: $L_{13} = 0.028\ \mu$H/ft
Phase A to B: $L_{14} = 0.025\ \mu$H/ft
Phase A to A: $L_{15} = 0.038\ \mu$H/ft
Phase A to B: $L_{16} = L_{12} = 0.05\ \mu$H/ft
Total self-inductance of Conductor #1:

$$L_1 = L_S - L_{12} + L_{13} - L_{14} + L_{15} - L_{16} = 0.071\ \mu\text{H/ft}. \tag{3}$$

Since Buses 1, 3, 4, and 6 are symmetrical, $L_1 = L_3 = L_4 = L_6$.

Bus Conductor #5 (Figure 3)

Self inductance: $L_S = 0.13\ \mu$H/ft.
Phase A to A: $L_{51} = L_{53} = 0.038\ \mu$H/ft.
Phase A to B: $L_{52} = L_{54} = L_{56} = 0.05\ \mu$H/ft.
Total self-inductance of Conductor #5:

$$L_5 = L_S + L_{51} - L_{52} + L_{53} - L_{54} - L_{56} = 0.056\ \mu\text{H/ft}. \tag{4}$$

Since Buses 2 and 5 are symmetrical, $L_2 = L_5$.

Voltage Drop

Impedance of the longest pair of conductors:

$$\begin{aligned} Z &= (R_{AC} + jX_L)\mu\Omega/\text{ft} \times (\text{length}) \\ &= (3.7 + j2\pi 60\, L_3) \times 24.5 + (3.7 + j2\pi 60 L_6) \\ &\quad \times 24.7 = 0.00133\Omega \\ V_D &= IZ = 6,452 \times 0.00133 = 8.58\ \text{V}. \end{aligned} \tag{5}$$

The above does not account for any significant contact resistance, which is controlled by using correct joint pressures, materials, and workmanship. The capacitance for such systems is negligible but could be calculated if necessary, from [9]:

$$C = \pi\varepsilon_0/\ln\left[D/2R + \{(D/2R)^2 - 1\}^{1/2}\right] = 3.63\ \text{pF/ft}.$$

With 50% contingency, the drop of 12.87 V is still within the allowable limit of 3% for a 480-V system.

Cooling Water Requirement

The I^2R loss for the longest conductor is

$$\begin{aligned} 6,452^2 \times (3.7 \times 24.7) \times 10^{-6} &= 3,794\ \text{W} \\ &= 12,949\ \text{Btu/hr}. \end{aligned}$$

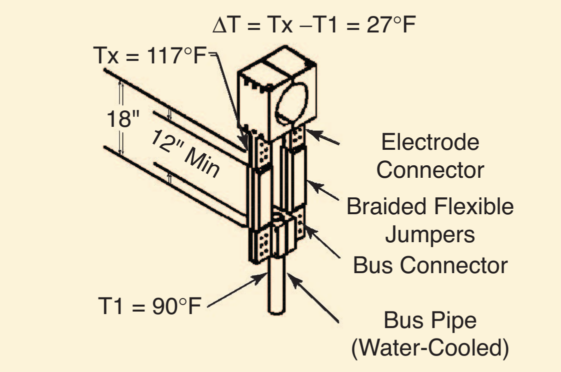
Assuming no other cooling taking place, the water quantity

$$\begin{aligned} &= Q/(Cp \times \Delta T) \\ &= (12,949\ \text{Btu}/30\ ^\circ\text{F}) \\ &\quad (\text{hr}/60\ \text{min})(\text{ft}^3/62.4\ \text{lb}) \\ &\quad (7.5\ \text{gal/ft}^3)\ \text{or}\ 0.864\ \text{gal/min}. \end{aligned} \tag{6}$$

The recommendations will be for 100% safety margin with a 1.75 Gal/min flow to take care of pressure drop, hot spots etc.

Sizing of Flexible Jumper (Shunt)

The flexible jumpers (shunt) arrangement is shown in Figure 4.



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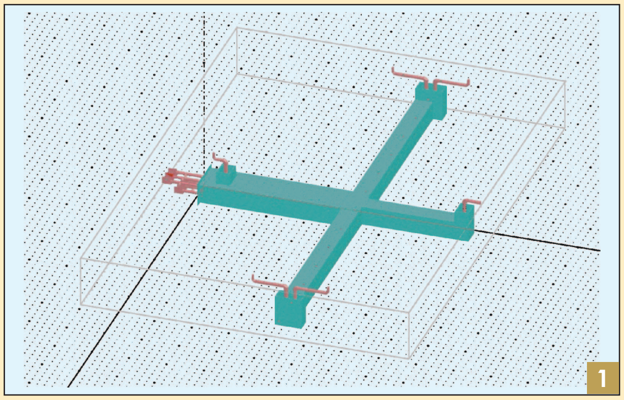
A flexible jumper (shunt).

THE BUS ENCLOSURE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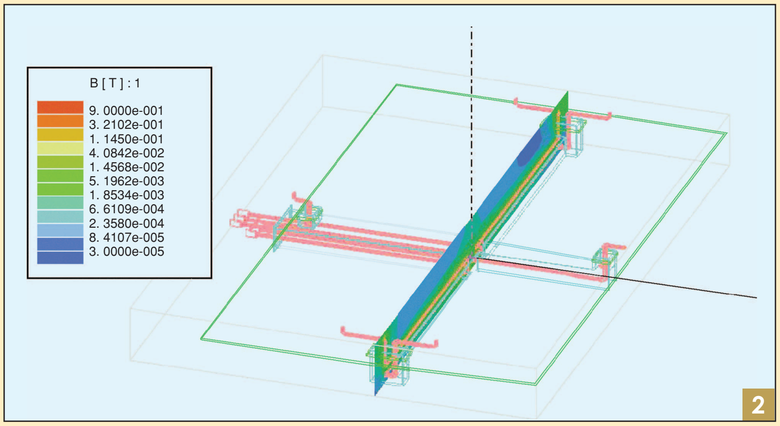
Shaded isometric of the buses with enclosure.

The design of bus enclosure certainly had its own challenges and is beyond the scope of this article. The following information is provided to do justice to curious readers. The aluminum enclosure for the buswork used 6061-T3 grade. A calculation was performed to determine if any adverse temperature increases imposed on the enclosure or surrounding A36 carbon steel structural components from electromagnetic heating that would prevent the structure from performing design requirements.



2

Magnetic field B through the east-west section of the bus enclosure.

At the bottom of the range using 600 A/in^2, the cross-section required is 6,452/600 = 10.75 in^2 = 13,686 MCM, while at the top of the range using 1,500 A/in^2, the cross-section required is 6,452/1,500 = 4.3 in^2 = 5475 MCM.

Using a somewhat middle range of current density of 1,050 A/in^2, the required cross-section = 6,452/1,050 = 6.14 in^2 = 7,823 MCM.

Standard braided wire rope sizes are 1,000 1,500, 1,750, and 2,000 MCM. Therefore, four 2,000-MCM flexible braids per connector need to be used for a total cross-section of 6.288 in^2.

Space constraints near a furnace electrode often dictate using shorter braid while the desired mechanical flexibility and restriction of dissipation by conduction would limit how short it could go. A safe current limit calculation is often required instead of designing by conventional wisdom. A 12-in long jumper may provide mechanical flexibility while an additional 6 in is required for overlap on connectors for NEMA CC1 bolting.

Fourier's Law is simplified to one-dimensional steady-state heat conduction [10], and, assuming electrode extension end to be adiabatic, uniform volumetric heat generation rate

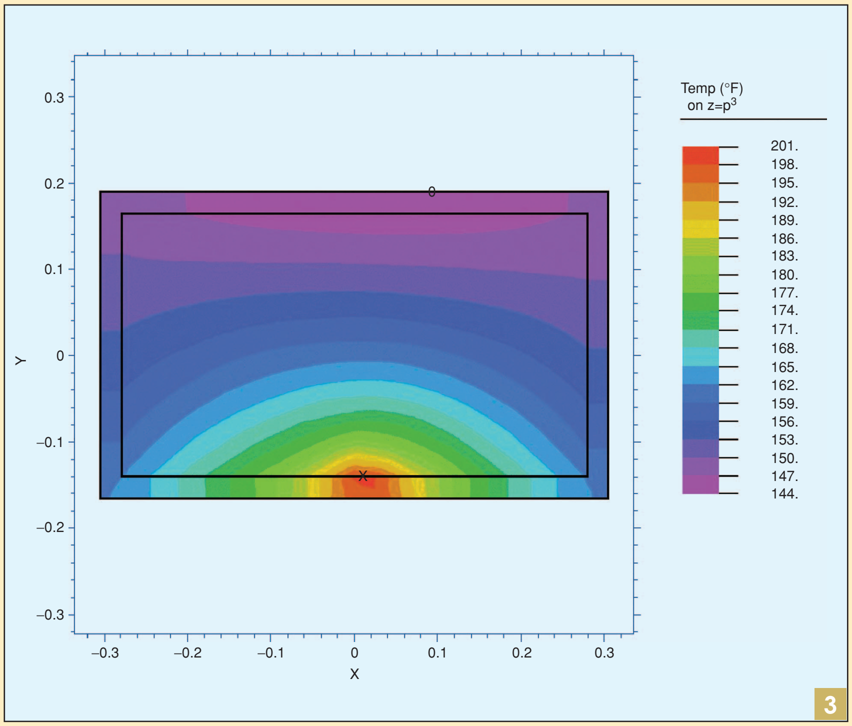
$$q' = (T_X - T_L)\, 2\, k/L^2. \tag{7}$$

The cold end (T_L) of the jumper is assumed to be at a bus temperature of 90 °F, the electrode extension end (T_X) could not go over the temperature rise limit of 120 °F, while the amps value also has to be acceptable. Equation (7) is solved iteratively for T_X of 116.95 °F ≈ 117 °F, for which, $q' = (116.95 - 90)2 \times 0.304/18^2 = 0.05$ Btu/min-in^3 = 0.887 W/in^3, which permits 6.288/0.887 or 5.579 W/in to be carried by the braids.

The dc resistance of the braid is (10.6 × 1,000/8,000)/12 $\mu\Omega$/in. Hence, $R_{AC} = R_{DC}(R_{ac}/R_{dc}) = 0.1104 \times 1.18 = 0.1303$ $\mu\Omega$/in. Current through the jumper wire $= \sqrt{(W/R_{ac})} = 6,543$ A, which verifies that the jumpers would be able to carry the requiredd 6452 A without overheating.

Maxwell-3D FEA software is used to compute the electromagnetic field intensity values and an ohmic loss array associated with running the rated current through the bus in intended design location. The array thus generated was then analyzed within another package FlexPDE using heat equation, $\mathrm{div}[k \times \mathrm{grad}(T)] + Q = 0$ to compute the expected temperature rise of the members of the structure. The hottest spots did not necessarily coincide with the highest magnetic field intensity. The structure's paint was more vulnerable to the hot spots than the metal itself.

Figure 1 shows the bus in the enclosure, Figure 2 represents magnetic flux density (in Tesla) at the enclosure and/or surrounding structure, while Figure 3 is the temperature profile.



The temperature profile of the main enclosure section.

Conclusion

Bus sizing calculation is more of a system design across discipline boundaries. It could consist simply of selecting values from tables/handbooks or significant efforts using classical analyses. The criticality and impact of sizing calculations on subsequent efforts are enormous. Commercial sizing software could have a black-box approach without disclosing the underlying methods used and, in turn, not empowering sensitivity analysis. Public regulated facilities often demand alternative analytical calculation. Effort has been given to balance the two approaches and to incorporate industry practices and assumptions as necessary.

Acknowledgment

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