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Experimental and numerical evaluation of busbar trunking impedance

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Experimental and numerical evaluation of busbar trunking impedance

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Abstract

This paper reports on experimental and numerical evaluation of the impedance of busbar systems with ferromagnetic enclosures (trunking). A linear model is developed in which the ferromagnetic material is approximated by a 'linear' material with an 'equivalent' relative permeability. The validation of this linear model is carried out through laboratory measurements on a sample system, and a reasonable level of accuracy is demonstrated. With this model, system impedance can be computed by employing the BEM software. The impact of design parameters, such as relative permeability, separation of bars, trunking size, etc on system impedance is discussed. Finally, the impact of these parameters on magnetic shielding is presented for the comparison.

Keywords: Busbar impedance; Impedance measurement; Boundary element method; Trunking

1. Introduction

Busbars are traditionally used in switchgear and controlgear assemblies and for power distribution in buildings. As the energy consumption in high-rise buildings increases, busbars are often employed in the main or feeder circuits for distribution to various floors or load centres. These busbar systems are housed in metallic enclosures (trunking) for safety and structural reasons. In Hong Kong buildings with such systems can carry currents up to the full-load rating of supply transformers, typically 2280 A for 1500 kVA, 11 kV/380 V transformers.

The impedance of busbar trunking systems is an important parameter in LV distribution system design. It is used to predict system performance, such as, voltage drop, voltage balance, power loss, etc. Traditionally, busbar system impedance is modelled by averaging phase resistance and effective reactance obtained by measurements [1]. This model gives general characteristics of a busbar system, but it is inadequate in detailed assessments (e.g. thermal performance, current sharing in multi-conductor systems [2]). Metallic trunking is a cost-effective measure in shielding magnetic fields from the busbars. It is found that trunking parameters, such as the material, thickness and size, have a significant influence on its shielding performance [3]. However, the effect of these parameters on system impedance does not appear to have been adequately addressed in published literature.

As indicated elsewhere [1,4], data on busbar impedance is normally ascertained through measurement. However, there are limitations using this approach. The major one is the inadequacy for determining the impedance for various busbar system configurations and sizes. There is the associated problem of making simultaneous measurements of high currents and small voltage values, unless the sample is rather long. Analytical calculation and computer simulation are alternative approaches for determining busbar impedance. These approaches have been investigated for several decades, and have been successfully applied to bare busbars without any metallic enclosure. The analytical calculation approach deduces a matrix of impedance based on a coupled circuit model [5,6]. In this model the resistive part is deduced from the approximation of skin effect and proximity effect formulation neglecting the eddy current effect.

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The inductive part is deduced from self and mutual inductance computation using geometric mean distances. These approaches are suitable for simple configurations of bare bars.

The computer simulation approach employs a numerical method to solve the diffusion equations for the magnetic field and eddy currents. The impedance matrix is deduced from these quantities. Both finite-element method (FEM) and hybrid finite-element-boundary-element method (FE-BE) have been successfully applied to calculating the impedance of busbar systems [2,7,8]. However, the application of numerical methods for steady-state impedance of busbar trunking systems is not discussed significantly although short circuit currents of such systems were mentioned [7]. The complication in the analysis results from the presence of ferromagnetic material in the busbar system.

This paper presents the results of investigation into steady-state power-frequency impedance of busbar trunking systems practically used in buildings, where the trunking is made of galvanised iron, a low-μ, ferromagnetic material. Both computer simulations and laboratory measurements are carried out to investigate the impedance. The commercial software for simulations is based on the boundary-element method. In this paper, a linear simulation model of busbar trunking systems is identified. The model is validated by laboratory measurements, the procedure is described in Section 3. Critical issues are discussed for model development and validation, that is, determination of equivalent relative permeability for galvanised iron trunking for a given current carried. With the validated linear model, system impedance can be computed by employing the BEM software. The impact of trunking parameters (e.g. busbar spacing, trunking material, thickness, and size, etc) on system impedance is determined. Finally, the impact of these parameters on trunking performance in magnetic shielding is presented for a comparison.

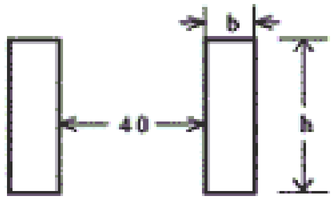

Fig. 1. Go-and-return rectangular busbar system (unit: mm). (b) busbars housed by galvanized iron trunking.

Table 1
Impedance calculated with BEM and FEM methods

Ratio b/h	Resistance ($\mu\Omega/m$)		Inductance ($\mu H/m$)	
	BEM	FEM	BEM	FEM
6/60	103.9	104	0.4953	0.489
60/6	109.5	109	0.7319	0.718
18/20	105.7	106	0.7661	0.753
12/30	105.2	105	0.6904	0.681
30/12	107.2	107	0.7915	0.778
8/45	104.5	105	0.5806	0.574
45/8	108.6	108	0.7674	0.752

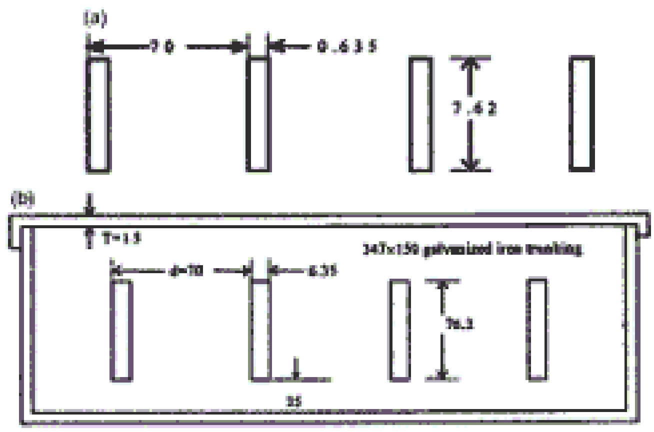

Fig. 2. Configurations of two busbar systems (unit: mm).

2. Computation approach and busbar models

Computer simulations for busbar system impedance are performed with the aid of the commercial software employing a two-dimensional boundary element procedure [10]. It solves for magnetic vector potential first, then calculates other derived quantities such as, magnetic field, induced current, the per unit length self-impedance and the mutual impedance of conductors as required.

The applicability of this software for impedance calculation was investigated on a simple go-and-return rectangular busbar system, as illustrated in Fig. 1. Its accuracy was investigated by comparing the results with those calculated according to the finite-element method [3]. For the purpose of comparison, conductivity of the conductors was taken to be 0.55×10^8 S/m, the same as that used by others [3]. Both resistance and inductance at 50 Hz were calculated at several values of the height-to-width ratio h/b. The simulation results are presented in Table 1, together with those calculated [3]. It is found that the discrepancy of impedance is very small and is generally less than 2%.

This BEM procedure was applied to calculate impedance of busbar systems commonly found in large buildings. Fig. 2 shows configurations and geometry of three-phase busbar systems. Illustrated in Case A is the system of four copper busbars without any metallic enclosure, in Case B is the busbar system enclosed by galvanised iron (GI) trunking. The busbar system in Case B is rated 800 A. Conductivity of busbars and galvanised iron used in the busbar systems was ob-

Table 2
Properties of materials in busbar systems

	Conductivity (σ) (S/m)	Relative permeability (μ_r)
Copper	0.563×10^8	1
GI	0.759×10^7	1000

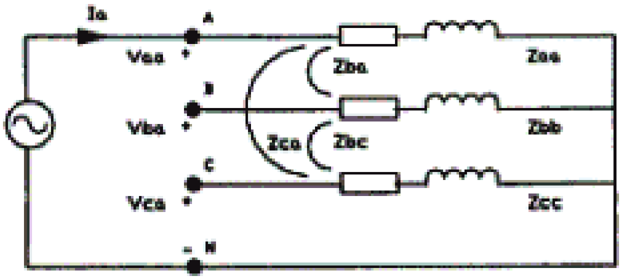

Fig. 3. Circuit model with the A-N current injection.

tained via laboratory measurements. The measurements for each material were repeated several times, and an average value was selected for computational models, as shown in Table 2. Because galvanised iron is a ferromagnetic material its relative permeability varies with the field level within the material. In the computation of busbar impedance, this material is treated to be linear with an equivalent relative permeability of 1000. It is based on the assumption that magnetic saturation of the trunking enclosure does not occur under normal operating conditions. The validation of this linear model, as well as the selection of equivalent relative permeability, is discussed in Section 3 and Section 4.

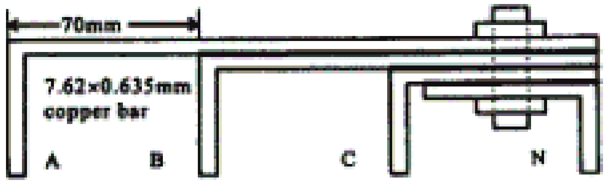

Fig. 4. End connector for busbar systems.

3. Validation procedure

Given that all phase conductors are mutually coupled, impedance of the busbar system is characterised by a 3-by-3 matrix in the steady state, as described below:

$$\mathbf{Z}=\begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} \\ Z_{ba} & Z_{bb} & Z_{bc} \\ Z_{ca} & Z_{cb} & Z_{cc} \end{bmatrix} \tag{1}$$

As demonstrated in Section 4, busbar impedance is generally independent of the current applied even in the presence of GI trunking. The single-phase current injection method illustrated in Fig. 3, then, is employed to determine impedance elements in (Eq. (1)). Fig. 3 shows the lumped-parameter model of a tested system under the A-N current injection. In the experiment, the single-phase current corresponding to the rating of the tested system was injected. Voltage V_{an}, V_{bn}, V_{cn} and current I_{an} were measured. Self and mutual impedance for Phase A, then, was calculated with these measured voltages and currents, as shown below:

$$Z_{aa}=\left.\frac{V_{an}}{I_a}\right|_{I_b=I_c=0}$$
$$Z_{ba}=\left.\frac{V_{bn}}{I_a}\right|_{I_b=I_c=0}$$
$$Z_{ca}=\left.\frac{V_{cn}}{I_a}\right|_{I_b=I_c=0} \tag{2}$$

Other elements of this impedance matrix were obtained by using this procedure repeatedly for both Phase B and C.

The busbar systems under test were 6 m long, and terminated at one end by an end connector, as illustrated in Fig. 4. This copper connector introduced additional small but non-trivial impedance in the circuit. It was necessary to subtract this impedance, which was measured on this connector, from values given in (Eq. (1)) to minimise the influence of the end connector.

In the measurements, the single-phase current was injected by a step-down transformer, and controlled by an auto-transformer. This current injected during tests was measured via current transformers. These CTs were verified to have a resolution of 0.12 A, an accuracy of ±0.05%, and a phase accuracy of 0.2°. The CT outputs were recorded by a digital recorder/analyser system having a resolution of 14 bits. The digital analyser was also used to measure the voltage signals. It was noted that the strong magnetic field produced by heavy-current busbars could affect the voltage measurement. To minimise measurement errors caused by field coupling, leads of the voltage probe were twisted. Given that the current in the busbars generated magnetic fields in the transverse plane (cross sectional plane), the phase voltage was measured between phase and neutral conductors in the same cross section plane.

Harmonics were observed in the experiments. They resulted from the supply circuit and/or were generated by the circuit non-linearity, as a consequence of the ferromagnetic material in the trunking. In the absence of GI trunking, voltage harmonic distortion (THD_V) and current harmonic distortion (THD_I) were less than 2 and 0.8%, respectively. When galvanised iron trunking is present in the circuit, they were less than 3 and 2%, respectively for the injected current up to its rated value. As the harmonic level was very small, busbar models as well as busbar impedance at 50 Hz were

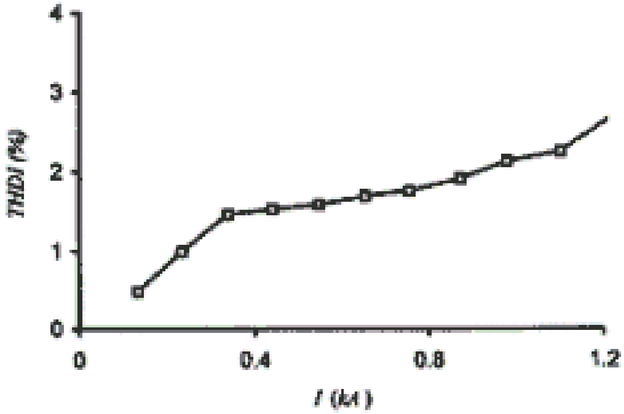

Fig. 5. Harmonic distortion against injected current.

Table 3
Calculated and measured impedance for Case A (μΩ/m, 20°C)

	Computed	Measured
Z_{aa}	78.9+j304.0	77.3+j303.5
Z_{bb}	78.6+j254.8	77.7+j255.6
Z_{cc}	77.4+j175.7	76.1+j177.6
Z_{ab}	40.1+j191.6	39.4+j190.7
Z_{bc}	39.3+j127.3	38.8+j130.1
Z_{ca}	38.8+j112.5	37.8+j113.1
Z_0	157.1+j532.4	154.2+j534.8
Z_1	38.9+j101.0	38.5+j100.9

Table 4
Calculated and Measured Impedance of Case B (μΩ/m, 20°C)

	Computed	Measured
Z_{aa}	157.2+j465.9	167.7+j497.9
Z_{bb}	117.2+j349.6	119.0+j364.2
Z_{cc}	875+j206.7	87.5+j208.7
Z_{ab}	93.5+j303.3	98.8+j326.7
Z_{bc}	58.4+j174.6	58.7+j182.0
Z_{ca}	63.7+j162.5	66.4+j171.2
Z_0	264.4+j767.1	274.1+j810.3
Z_1	48.8+j126.6	50.1+j130.2

discussed only. Nonetheless, voltage V_1 and current I_1 given below were used for impedance calculation at 50 Hz.

$$V_1 = V_{rms}/\sqrt{1+(THD_V)^2}$$

$$I_1 = I_{rms}/\sqrt{1+(THD_I)^2} \quad (3)$$

Fig. 5 shows a curve of total harmonic distortion plotted against the RMS current in Phase A. The significant harmonic distortion of current was observed when the Phase A conductor in Case B carried a current above 2 kA.

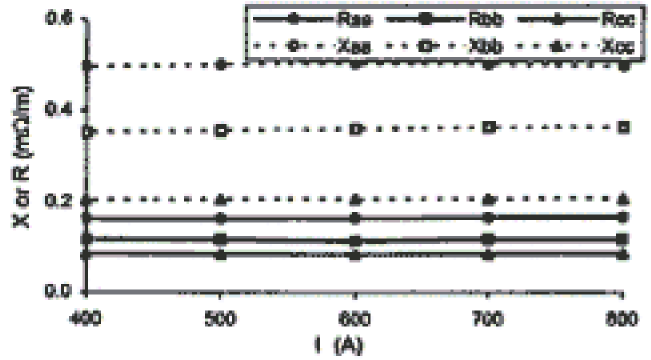

Fig. 6. Measured impedance against injected current.

4. Comparisons of results

Impedance of the busbar systems shown in Fig. 1 was measured in the laboratory. In the experiment for Case A, a current of 1000 A was injected into the test system. Both voltage and current were recorded to calculate the impedance matrix (Eq. (1)). The measurement was repeated several times, and an average value of impedance matrix is presented in Table 3. The resistance shown in the table has been normalised with respect to the reference temperature of 20°C. Theoretical impedance for the model of Case A was calculated by using the boundary element method, and is presented in Table 3 for the comparison. It is found that the measured values of resistance and reactance are very close to the computed values. The relative error is generally less than 2%. Given that the busbar system of Case A is a linear circuit, impedance of this circuit is independent of the supply current. An experiment with the injected current of 600 A was performed to check the linearity. It is noted that the relative error caused by the difference of the injected current is insignificant and generally less than 1%.

The sample system corresponding to the model of Case B is the duplicate of an 800 A busbar trunking system installed in a large building. This system has an enclosure made of galvanised iron. In the experiment, both voltage and current measurements were carried out with an injected current of 800 A. The average value of impedance matrix was calculated using (Eq. (2)), and is presented in Table 4. To validate the single-phase method, impedance variations were investigated when the injected current varied from 800–400 A. The measurement results are presented in Fig. 6. It is observed that all the resistance almost remains constant, and its change is within 3% generally. A similar observation is found for the reactance. Actually the impedance did not change significantly until the injected current exceeded 2000 A, which was far above the rating. The average resistance and effective reactance per phase defined in [1] were also measured under a balanced three-phase current of 800 A. Compared

Table 5
Average impedance of Case B (μΩ/m, 20°C)

Measurement method	R_{av}	X_{av}
Three-phase	49.6	136.6
Single-phase	50.1	137.6

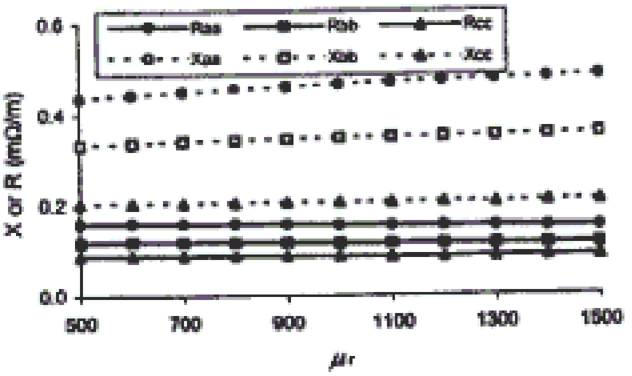

Fig. 7. Calculated impedance against relative permeability.

with the values obtained from the single-phase method, the difference is very small, as seen in Table 5.

As system impedance is independent of the applied current generally, the busbar trunking system can be substituted for impedance computation by a linear system or model. The computational model is already described in Section 2, in which the equivalent relative permeability of GI trunking is considered to be 1000. This value is considered reasonable by comparing with relative permeability of other similar low-μ_r, materials [9], measured in the laboratory. The calculation results are also included in Table 4 for the comparison. It is found that an agreement between measured and computed results is achieved. The average error of resistance or reactance is around 5%. Such error is acceptable from the viewpoint of electrical installation design. All these indicate the impedance influence of the nonlinearity of galvanised iron is insignificant, and the linear model is applicable for busbar trunking systems from the viewpoint of engineering. The predicted impedance has an adequate accuracy (e.g. less than 10%) if the current varies in a reasonable range.

It is observed that the selection of equivalent relative permeability for galvanised iron is subjective. In fact, the value of equivalent relative permeability is not so critical, as illustrated in Fig. 7. Fig. 7 depicts the impedance of this trunking system for equivalent μ_r in the range of 500–1500. It shows that the system impedance is insensitive to the variation of equivalent μ_r. The difference is within 2.8% for positive sequence impedance Z_+ or 5% for zero sequence impedance Z_0 if the impedance $\mu_r = 1000$ is used for the reference. The difference is even smaller if the trunking has a larger size (e.g., 1.4% for Z_+ and 2.7% for Z_0 if trunking height is increased to 250 mm), as its influence on reluctance in the magnetic circuit for inductance evaluation is reduced. The value of 1000, then, may be used for equivalent μ_r of GI trunking in other practical sizes. Practically, because of physical constraints (e.g. installation constraint, overheating problem, etc), the size of GI trunking is not too small. It should be mentioned that equivalent μ_r does not have any direct relationship with actual μ_r within the GI. The 'equivalent' means the equivalence of impedance between GI trunking and its linear substitute.

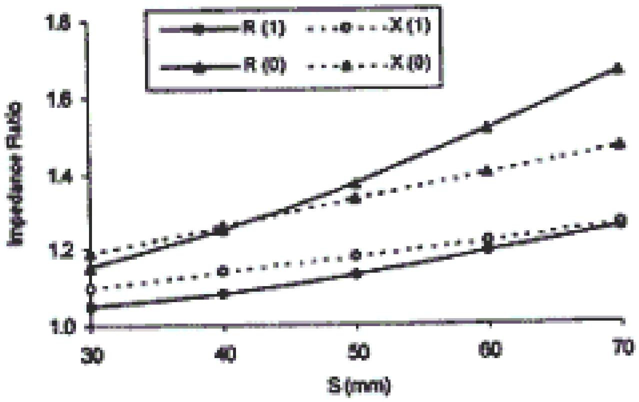

Fig. 8. Busbar trunking impedance against busbar spacing.

5. Impedance impact of trunking parameters

Impedance of busbars housed by a metallic enclosure can be computed by numerical methods using commercially available software. However, it requires substantial experience with the software and substantial time for modelling and computation. To carry out cost-effective design of busbar trunking systems, it is necessary to have knowledge about the influence of design parameters on system impedance. These design parameters include busbar size, separation, trunking size and thickness, material properties, and so on. In this section, computer simulations with the validated model are performed to reveal impedance characteristics in relation to busbar separation, trunking size and thickness. The influence of relative permeability for GI trunking was addressed in the previous section. In all computed cases the linear model is assumed with a relative permeability of 1000. For a comparison, trunking performance in magnetic field shielding is also evaluated with the said software. Its performance is characterised by shielding effectiveness (SE), a ratio of the magnetic field with trunking present to that with trunking absent. As seen from this definition, a small value of shielding effectiveness indicates good shielding performance.

Impedance in relation to busbar spacing is illustrated in Fig. 8. The data given in the figure are expressed as the ratio of: impedance with trunking present to that with trunking absent. It is observed that the ratio of resistance or reactance rises with increasing busbar separation. This increasing ratio indicates that the trunking has a significant effect on its impedance when the busbar separation is large. This gives rise to an increase in eddy-current losses within the trunking and enhances flux linkage of the busbars. However, shielding effectiveing effectiveness of trunking does not change significantly if the observation point is away from the trunking (1 m from the trunking centre), as seen in Table 6.

Table 6
Shielding effectiveness against spacing

S (mm)	30	40	50	60	70
SE	0.23	0.22	0.21	0.20	0.19

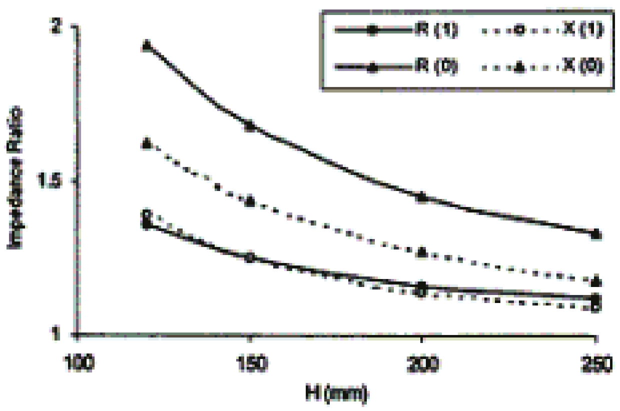

Fig. 9. Busbar trunking impedance against trunking height.

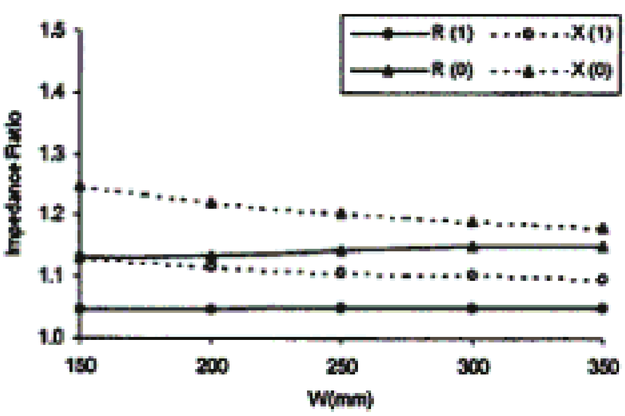

Fig. 10. Busbar trunking impedance against trunking width.

Trunking size is characterised by width and height, which affects the impedance in a different manner. Fig. 9 and Fig. 10 show the variation of impedance against height and width of trunking, respectively. It is found that trunking height has a significant influence on the busbar impedance, while trunking width does not. When the height of trunking is increased, the trunking experiences low magnetic fields. Accordingly eddy-current losses are reduced, and enhancement on busbar flux linkage becomes less significant. On the other hand, the change of trunking width hardly affects the field distribution between busbars, as the dominant parts of the trunking (top and bottom parts) are fixed. Consequently, the impedance does not change significantly, as shown in Fig. 10. It is worthwhile to note that both height and width affect shielding performance of trunking in the opposite way. As illustrated in Table 7 and Table 8, shielding effectiveness is sensitive to trunking width, but insensitive to trunking height.

Table 7
Shielding effectiveness against height

H (mm)	120	150	200	250
SE	0.20	0.19	0.18	0.18

Table 8
Shielding effectiveness against width

W (mm)	150	200	250	300	350
SE	0.12	0.15	0.18	0.21	0.23

Practically trunking thickness varies within a range of a few millimetres. Fig. 11 shows the influence of trunking thickness on the busbar impedance. It is noted that the impedance tends to saturate when trunking thickness reaches a certain value. According to the curves given in the figure, both resistance and reactance remain constant if thickness is greater than 1.5 mm. Generally this value is determined by skin depth of trunking, because the induced current is primarily concentrated near the inner surface of the trunking due to the skin effect. Changing trunking thickness will not affect the system impedance much if the thickness is large compared with skin depth of the trunking. As a comparison, thickness of trunking for heavy-current conductors in buildings is usually greater than 1.5 mm. Shielding effectiveness of trunking, however, is greatly affected by its thickness. Generally, shield-

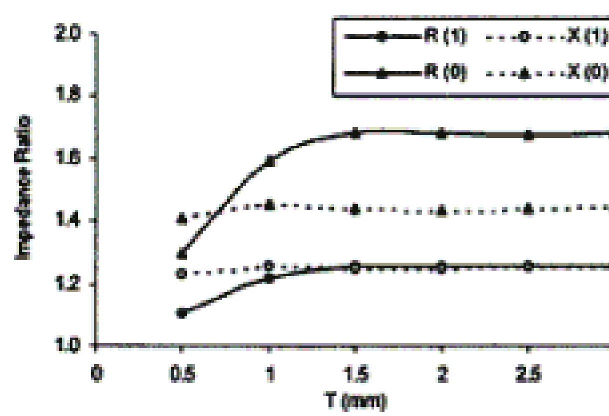

Fig. 11. Busbar trunking impedance against trunking thickness.

Table 9
Shielding effectiveness against thickness

t (mm)	0.5	1.0	1.5	2.0	2.5	3.0
SE	0.58	0.34	0.19	0.10	0.06	0.03

ness decays exponentially with the ratio of its thickness over its skin depth if this ratio is greater than 1 [3]. The exact results of shielding effectiveness are shown in Table 9.

6. Conclusions

Impedance characteristics for busbar systems practically used in buildings were investigated experimentally and numerically. Busbar systems without any ferromagnetic material present are successfully modelled using the boundary element method. The results from the measurements indicate that the model can be used to predict impedance of any such busbar system with a good accuracy. When a ferromagnetic material (e.g., galvanised iron) is present in the busbar system, the impedance varies within a small range. A linear model with a constant value of equivalent relative permeability is practically possible for predicting the impedance. A reasonable accuracy of 10% can be achievable if the current is close to its rated value. The linear model may not be valid if the GI trunking is saturated, which usually occurs under short circuit or earth fault conditions.

The impedance of busbar trunking systems is greatly affected by system design parameters, such as busbar separation, trunking size and thickness, relative permeability. As stated previously, the impedance is insensitive to relative permeability in the normal operating conditions. Both busbar separation and trunking height have a great influence on its impedance. However, both trunking size and thickness have an insignificant influence on the impedance. From the viewpoint of impedance, it is not recommended to use large and thick trunking if small impedance is desired. However, as far as the performance of magnetic shielding is concerned, it is better to make the trunking thicker or less in width.

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References

[1] IEC 439. Low Voltage Switchgear and Controlgear Assemblies: Part II: Particular Requirements for Busbar Trunking Systems (Busways), 1987.

[2] O. Battauscio, M. Chiampi, D. Chiarabaglio, Experimental validation of a numerical model of busbar systems, IEE Proc. Gener. Transm. Distrb. 142 (1) (1995) 65–72.

[3] Y. Du, J. Burnett, ELF Magnetic Shielding of Rectangular Shields for HeavyCurrent Conductors, IEE Proc.-Gener. Transm. Distrb. 146 (3) (1999) 223–228.

[4] D. Birtwhistle, P. Oearl, Measurement of impedance, power loss and current distribution in three-phase busbars, J. Electr. Electron. Eng. Aust. 8 (1) (1988) 38–46.

[5] H.B. Dwight, G.W. Andrew, H.W. Tileston, Temperature rise of busbars, Gen. Electr. Rev. 43 (5) (1940) 213–216.

[6] O.R. Schurig, Engineering calculation of inductance and reactance for rectangular bar conductors, Gen. Electr. Rev. 36 (5) (1933) 228–231.

[7] O. Battauscio, M. Chiampi, D. Chiarabaglio, M. Tartaglia, Comparison between finite-element and traditional procedures for the prediction of busbar behaviour, ETEP 5 (4) (1995) 233–238.

[8] O. Battauscio, M. Chiampi, D. Chiarabaglio, M. Tartaglia, Numerical and experimental evaluation of magnetic field generated by power busbar systems, IEE Proc. Gener. Transm. Distrib. 143 (5) (1996) 455–460.

[9] J. Hoburg, Material Characterization, in: Handout of Project Meeting of EPRI Contract 3335-08, Los Angeles, 1993.

[10] OERSTED Users and Technical Manual, Integrated Engineering Software, 1994.