Induced Voltages and Power Losses in Single-Conductor Armored Cables

Y. Du, X. H. Wang, and Z. H. Yuan

***Abstract*—Single-conductor armored cables are often used to carry high currents in buildings. This paper presents an experimental investigation into both induced voltages and cable resistances associated with the installation of these cables within the buildings. Both induced armor voltages and cable resistances under different installation practices were measured at both power frequency and its harmonic frequencies. The impact of cable formation, bonding arrangement, and cable supporting method on these issues was addressed and illustrated experimentally via 185-mm^2 (365-kcmil) single-conductor armored copper stranded cables. The standing voltage is generally small for the armored cables used in the buildings. The power losses increase significantly when the cable armor is bonded at two cable ends, particularly in the case of rich harmonic currents in the cables. Recommendations are finally provided for the installation of single-conductor armored cables in buildings.**

***Index Terms*—Cable, induced voltage, metallic tray, power loss.**

I. Introduction

SINGLE-CONDUCTOR cables are frequently used in buildings for high-current distribution due to their large current-carrying capacity and easy installation. These cables are armored with a concentric layer of aluminum wires for mechanical protection and fault current return as well. When ac current flows through cable conductors, induced voltages are generated on cable armor. Although cable oversheath (jackets) permits a high standing voltage on the armor, excessive voltage is generally not allowed. For example, the practice in the U.S. appears that a steady-state sheath/armor voltage of 65–90 V is permitted [1], while in the U.K., the 25-V level is used for the cables installed in buildings to prevent corrosion as a consequence of electrolysis and other factors [2].

The armor of single-conductor cables may be bonded and grounded at their two ends to eliminate the induced voltage on the armor. Different bonding arrangements were introduced and illustrated in [1]. Some other publications [2]–[5] also presented the application and selection of bonding arrangements and the calculation of induced voltages and currents and of power losses in the cables at power frequency. In these cases, the single-conductor armored cables were laid either in free air or underground.

Armor bonding provided at two cable ends is the simplest solution to the problem of induced voltages and is highly recommended in [2] for the cables used in buildings. However, circulating currents are induced in the armor by the ac current flowing in the cable conductors. The induced current on the armored single-core cables is not negligible. It generates additional power losses in the cables and reduces the current-carrying capacity of the cables. It was estimated in [5] that the ampacity of three single-conductor 500-kcmil cables at power frequency was reduced by approximately 20% by the armor current when they are laid parallel on 8-in centers with 20 spiral copper armor wires. In Hong Kong, the Code of Practice for Energy Efficiency of Electrical Installations [6] sets out the minimum requirements on power losses of electrical installations in buildings (e.g., less than 1.5% of power delivered in a rising main circuit). Therefore, it is necessary to have a critical review of both induced voltages and cable resistances of the single-conductor armored cables under different installation practices.

This paper presents an experimental investigation into both induced voltages and cable resistances associated with the installation of low-voltage single-conductor armored cables within buildings. Both induced voltages and cable resistances were measured in the laboratory at power frequency as well as its harmonic frequencies. The single-conductor cables were laid either in free air or on perforated metallic tray. These issues, which have not been addressed in literature significantly before, are discussed extensively in this paper. Typical installation practices of the single-conductor armored cables adopted in buildings were considered in the experiment and are presented in Section II. It is followed by the description of measurement setup in the laboratory. Both induced voltages and cable resistances of the sample cables under different installation practices are presented at the order of up to 11. The impact of cable installations on induced voltages and cable resistances is addressed. Finally, recommendations are provided for the installation of single-conductor armored cables in buildings.

II. Cable Installation

XLPE-insulated cables with stranded copper conductors to BS/IEC standards are widely used for low-voltage high-current

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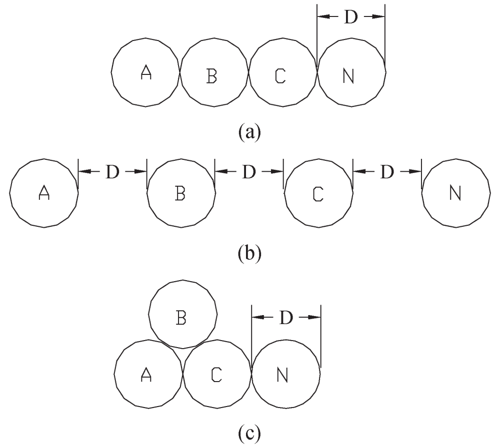

Fig. 1. Cable formation for a three-phase four-wire distribution system. (a) FT. (b) FS. (c) TF.

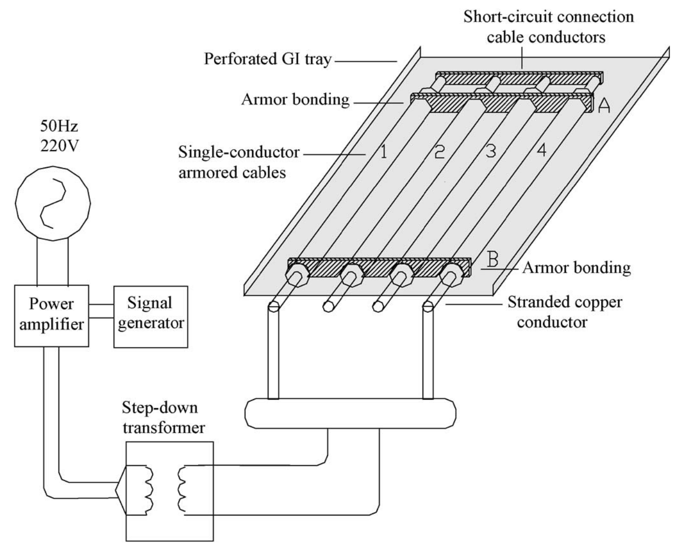

Fig. 2. Experimental setup for measuring induced voltages and cable resistances.

distribution in local buildings. The stranded conductor in the single-conductor cables is covered by an insulation material. In ac circuits, in order to reduce magnetic losses, single-conductor cables are normally protected by the armor made of a concentric layer of aluminum wires. This armor is considered as an exposed conductive part in the cabling system and has to be connected to earth at the supply end as required by the local code [7].

As the TN-C-S grounding system is adopted in local buildings [7], a separate circuit protective (grounding) conductor is provided to run in parallel with the power cables and is connected to the ground in the buildings. The standing voltage in buildings therefore refers to the induced voltage on cable armor with respect to the adjacent circuit protective conductor (e.g., a single-conductor cable or copper tape). The single-conductor armored cables are normally deployed on metallic tray (e.g., galvanized iron tray) or directly mounted on wall, floor, or ceiling in free air. When the metallic tray is used in the cable installation, the standing voltage is the induced armor voltage with respect to the metallic tray as the metallic tray normally serves as a protective conductor [7].

The power distribution system in buildings is a three-phase four-wire system. With the considerations of space or heat dissipation, three types of cable formation are applied in the installation of single-conductor armored cables. These are flat and touching (FT), flat and spaced (FS), and triangular or trefoil (TF) configurations, as shown in Fig. 1. In the FS configuration, the cables are separated with one cable diameter to improve the heat dissipation process. However, this formation could increase induced voltages and power losses.

For the cables with metallic armor, a bonding arrangement should be adopted in the cable installation. Generally, solid bonding, which bonds the armor of the cables at both ends, as shown in Fig. 2, is required to diminish the voltage induced along the cable armor. Special bonding arrangements, such as single-point bonding or cross-bonding, are used in view of economics or minimizing the heat generation by induced current. Single-point bonding means that the armor of cables in the same circuit is connected and grounded at one end only. Cross-bonding consists in sectionalizing the armor into minor sections and cross-connecting them to neutralize the total induced voltage in three consecutive sections. Both solid bonding and single-point bonding are normally for the short-length cables used in buildings and are addressed in the following sections.

III. Experimental Setup

Shown in Fig. 2 is an experimental setup for the measurement of both induced voltage and cable resistance with the single-phase current injection. The cables under test were four low-voltage single-conductor armored cables to BS6724 [8]. These cables have a conductor size of 185 mm^2 (365 kcmil) and a length of 10 m. In the experiment, the cables run in parallel in free air or on perforated galvanized-iron (GI) tray. They were arranged in the cable formation according to Fig. 1, i.e., FT, FS, or TF configuration. The single-conductor armored cables were connected together at one end with a copper bar and connected to a current source at the other end. The armor of these cables was bonded either at one cable end (point A) or at two cable ends (points A and B), depending whether the single-bonding or solid-bonding system is employed. When the cables were installed on the GI tray, the cable armor was bonded to the tray at point A, as shown in Fig. 2.

The current injected into the cables was generated from a harmonic current source. It was made of a harmonic signal generator, a power amplifier, and a step-down transformer, as shown in Fig. 2. In the measurement, the current in the cables was either an ac component at 50 Hz or its harmonic component at the order of up to 11. The magnitude of the injected current was determined by the output of the power amplifier, which remained unchanged in the measurement of induced voltage or cable resistance at all orders. The injected current therefore decayed with the inverse of harmonic order. The output voltage from the power amplifier was selected in such a way that the fundamental current was approximately equal to 50% of the cable current-carrying capacity.

TABLE I
LARGEST INDUCED ARMOR VOLTAGE ON THE CABLES INSTALLED IN FREE AIR

Cable Formation	Meas. (mV/A/m)	Cal. (mV/A/m)
(a) Flat & spaced	0.187	0.185
(b) Flat & touching	0.147	0.147
(c) Trefoil	0.091	0.089

A PM3000A power analyzer, together with three current transforms (CTs), was employed to measure voltage, current, and power in the cables under test. The analyzer had 12 voltage ranges from 0.5 to 2000 V (peak) and was capable of measuring small cable voltage, which was in the range of 1–2 V in most of the cases. This instrument had a basic accuracy of 0.1% under the condition of full analyzer ranges. The CTs had a magnitude accuracy of 0.2% and a phase accuracy of 0.3° in the frequency range of 5 Hz–2.5 kHz.

IV. INDUCED VOLTAGE ON CABLE ARMOR

In this experiment, single-point bonding was arranged for the single-conductor armored cables. The armor of these cables was connected together with a protective conductor at point A. The induced voltage is the voltage on the cable armor with respect to the circuit protective conductor.

A. Cables Installed in Free Air

For simplicity, the armor of the fourth cable was used as the protective conductor (reference conductor) when the cables were installed in free air. Table I shows the voltage gradient induced on the cable armor at 50 Hz under three different cable formations shown in Fig. 1. It was observed that the largest induced voltage appeared on cable 1, which had a large separation distance to the reference conductor. The largest value in each cable formation is presented in the table.

As the cables were installed in air without any large conductive part nearby, analytical formulas of induced voltages can be derived directly using the mutual inductance between the source loop an and the armor loop XP [9] and are given by

$$V_{XP} = jI_a 2\pi f \cdot 0.2 \times 10^{-6} \log\left(\frac{S_{Xn}S_{aP}}{S_{nP}\ D_a/2}\right) \tag{1a}$$

for the configuration shown in Fig. 3(a) and

$$V_{XP} = jI_a 2\pi f \cdot 0.2 \times 10^{-6} \log\left(\frac{S_{Xn}S_{aP}}{S_{nP}S_{aX}}\right) \tag{1b}$$

for the configuration shown in Fig. 3(b). By using (1) for all phase cables, theoretical values of the induced voltage with respect to the fourth armor were obtained and are presented in Table I. The measured and calculated results match very well with a difference of less than 2.2% in these cases.

Fig. 4 shows the ratios of the harmonic voltage at order h up to 11 over the fundamental voltage, which are induced on the cable armor under balanced load conditions (positive-/negative-sequence current conditions for $h = 1, 5, 7$, and 11 and zero-sequence current conditions for order $h = 3$ and 9). These voltage ratios in Fig. 4 are the normalized values with the harmonic order. It is noted that the normalized induced voltage under each cable formation does not decay significantly (e.g., less than 10% at the 11th order). This indicates that the induced voltage is generally proportional to harmonic order. In other words, the induced voltage V_h at order h is approximately equal to $V_1 \times h$. It is therefore necessary to evaluate the standing voltage in the design stage to ensure that it does not cause any problem in operation.

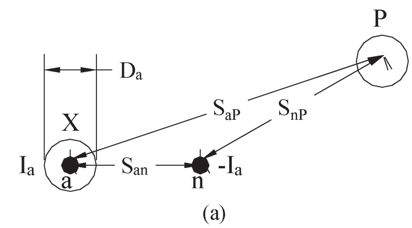

Fig. 3. Configurations of the cable conductor and armor loops. (a) Configuration I. (b) Configuration II.

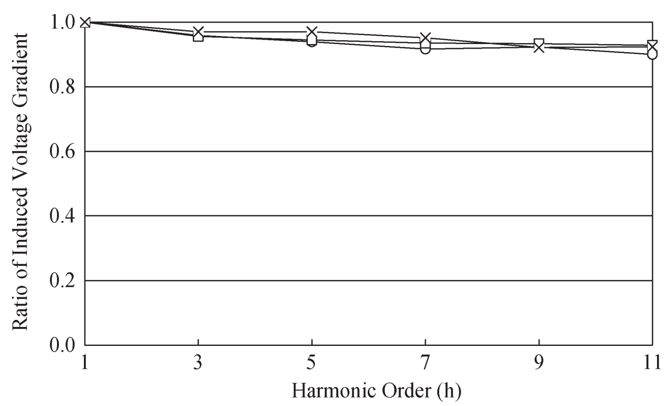

Fig. 4. Induced armor voltages for the cables in free air. □ FS configuration. ○ FT configuration. × TF configuration.

B. Cables Installed on GI Tray

When the cables are laid on the GI tray, the induced armor voltage with respect to the tray was measured as the tray was used as the protective conductor. The induced voltage on the cable armor is primarily determined by flux linkage in the armor loop formed by the cable armor and the tray. As the armor loop is perpendicular to the source current loop made by cable conductors, the mutual inductance is generally small, and the corresponding induced armor voltage would be low. However, the ferromagnetic material of the GI tray can enhance the magnetic field near or on the tray and increases the induced voltage on the armor. Table II shows the voltage gradient induced on the cable armor at 50 Hz.

TABLE II
LARGEST INDUCED ARMOR VOLTAGE ON THE CABLES INSTALLED ON TRAY

Cable Formation	Meas. (mV/A/m)
(a) Flat & spaced	0.172
(b) Flat & touching	0.115
(c) Trefoil	0.128

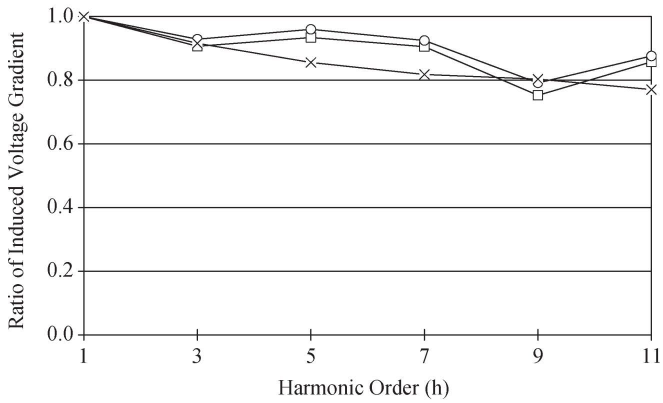

Fig. 5. Induced armor voltages for cables on GI tray. □ FS configuration. ○ FT configuration. × TF configuration.

It is noted that the induced voltage is comparable to that for the cables installed in free air. This is primarily due to small spacing and unique orientation of the armor loop. It would be possible to estimate the induced voltage for the cables on the tray using (1). Similar to the cables installed in free air, the induced armor voltage reaches the greatest under the FT configuration.

Fig. 5 shows the induced armor voltage normalized with the fundamental voltage and harmonic order against harmonic order. It is noted that the induced voltage generally decreases with increasing harmonic order but in a much faster manner than that in free-air cases under the same sequence current conditions. This is probably due to the eddy current generated within the GI tray. The eddy current on the tray is generated in such a way to reduce the source field from the currents on cable conductors. The resultant magnetic field thus becomes less. As the compensation effect turns stronger at a higher frequency, the flux linkage in the armor loop is small. The corresponding induced voltage decays quickly with the harmonic order. Induced voltage V_h at order h can be estimated using $k \times V_1 \times h$. Parameter k varies with harmonic order h but can be set to be one for the worst case estimation.

V. CABLE RESISTANCE

In the experiment, cable resistance was measured using the method of single-phase current injection. The cables under test were installed in free air or on the GI tray under three different cable formations, as shown in Fig. 1. Two bonding arrangements, i.e., solid bonding and single-point bonding, were adopted for these armored cables in the experiment.

During the measurement, voltages, currents, and active powers in all phase conductors at each harmonic order were collected. Self-resistance and mutual resistance of each phase conductor with respect to the neutral (fourth) conductor are calculated using the following equation:

$$R_{11} = \left. \frac{P_{11}}{I_1} \right|_{I_2=0} \tag{2a}$$

$$R_{21} = \left. \frac{P_{21}}{I_1} \right|_{I_2=0} . \tag{2b}$$

By repeating this procedure for all cases, a database of full resistance matrix is obtained.

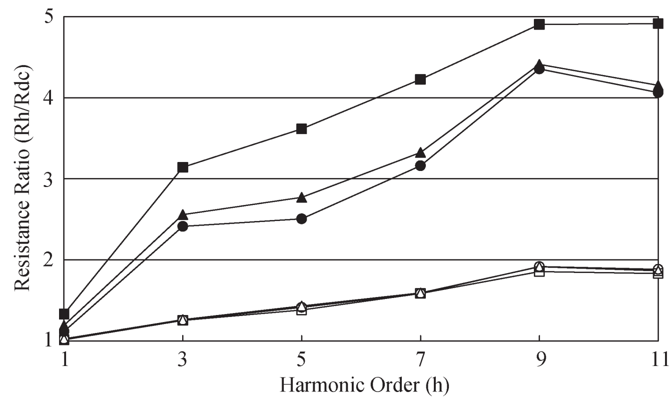

Fig. 6. Harmonic resistances of the cables installed in free air. □ and ■ FS configuration with SPB and SB. △ and ▲ FT configuration with SPB and SB. ○ and ● TF configuration with SPB and SB.

A. Cables Installed in Free Air

Fig. 6 shows the resistances of the cables installed in free air against harmonic order h at the temperature of 20 °C. The resistances presented in the figure are the values normalized with cable resistance obtained under dc conditions. These values were obtained under balanced load conditions, i.e., positive-/negative-sequence current conditions for $h = 1, 5, 7$, and 11 and zero-sequence current conditions for order $h = 3$ and 9. The abbreviation of SPB in the figure refers to "single-point bonding," while SB refers to "solid bonding."

With SPB, cable resistances are similar under three different cable formulations. They increase with increasing harmonic order because strong skin effect is observed at harmonic frequencies. When the armor of the cables is solidly bonded at two ends, the circulating currents within the armor create additional losses added on the cables. This results in a significant increase of cable resistance at harmonic frequencies. At 50 Hz, the armor losses are approximately equal to 10% and 30% of the corresponding conductor losses under two extreme cases (TF and FS configurations). However, the losses at the third order in the cables with SB are increased to 90% and 140% of the corresponding conductor losses under these two extreme cases.

It is also noted that the cable resistance is the greatest when the cables are arranged in FS configuration. This is because the greatest currents were induced within the armor under this configuration. Usually, the induced current is great when the cable spacing is large.

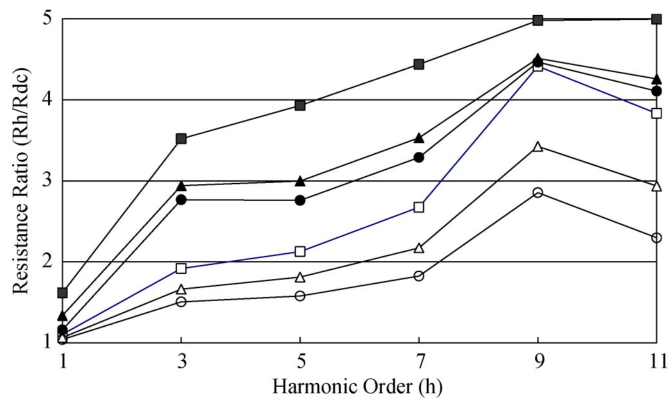

Fig. 7. Harmonic resistances of the cables installed on tray. □ and ■ FS configuration with SPB and SB. △ and ▲ FT configuration with SPB and SB. ○ and ● TF configuration with SPB and SB.

B. Cables Installed in GI Tray

When the cables are installed on the GI tray, eddy current is generated within the tray and creates additional losses on the cables. This eddy-current effect is primarily determined by the magnetic field generated from the cables. Therefore, the cables with large spacing have great resistance. Fig. 7 shows the resistances of the cables installed on the GI tray, which were normalized with the dc resistance of the cables in free air.

As shown in Fig. 7, the cable resistances at 50 Hz are generally greater than those of the cables installed in free air. The increase of resistance is not so significant for the cables with single-point bonding, for example, a 10% increase is observed in the worst case of FS configuration. The resistance, however, increases significantly for the cables with solid bonding. The circulating currents can cause an increase of cable resistance by 45% in the worst case of FS configuration. It is noted that the resistance increase is the least for the cables with TF arrangement and is approximately 5% with SB and less than 2% with SPB.

At harmonic frequencies, it seems that there is no much difference of cable resistances for the solid-bonding cables installed in free air and on metal tray. This indicates that the eddy current on the GI tray is not significant at the harmonic frequencies as the induced armor currents cancelled the partial magnetic field generated by the source current in the cable conductors. Nevertheless, the cable resistance with SB is higher than that with SPB due to additional loss on the armor. At low harmonic orders (e.g., $h = 3, 5$, and 7), the cable resistance with SB is approximately 118% of the resistance with SPB.

VI. Discussion

When single-conductor armored cables are selected for power distribution in buildings, the issues of standing voltages on armor and power losses in cables should be fully addressed. As described in the previous sections, both the induced voltages and power losses are significantly affected by installation practice of the cables, such as cable formation, bonding arrangement, and cable supporting method.

In buildings, protective conductors normally run in parallel with the power cables. Considering a typical separation distance of 2 m, induced armor voltages for the cables installed in free air were calculated by using (1) and are presented in Table III. For comparison, induced armor voltages for the cables installed on the tray, which were calculated by using the measurement results, are included in the table as well. In such a case, the tray is selected as the circuit protective conductor.

TABLE III
Standing Voltages and Max. Length of Cables With 50-Hz Currents

Installation method	Cable Formation	I_{FL} (A)	$V_{standing}$ (V)	Length (m)
Cables in Free Air	FS	618	0.081	309
	FT	574	0.051	489
	TF	529	0.031	815
Cables on GI Tray	FS	524	0.090	277
	FT	524	0.060	415
	TF	524	0.067	373

TABLE IV
Standing Voltages and Max. Length of Cables With Harmonic Currents

Installation method	Cable Formation	I_{FL} (A)	$V_{standing}$ (V)	Length (m)
Cables in Free Air	FS	618	0.120	209
	FT	574	0.082	305
	TF	529	0.057	438
Cables on GI Tray	FS	524	0.126	199
	FT	524	0.092	271
	TF	524	0.089	281

The table shows the largest standing voltages of the armor when the cables carry the rated currents [2] in different cases. The maximum length of the cables for the permissible voltage of 25 V is given in the table as well. It is found that the maximum of the cables can be over hundred meters in any of these cases. In high-rise buildings, the cables are normally less than 150 m due to voltage drop and other constraints. It is therefore unlikely to have the standing voltage over the permissible level in the buildings.

When the power supply circuit carries harmonic currents in the cables, the resultant standing voltages would increase, particularly the triplen-order harmonic currents. Assume that the current in the circuit has the total harmonic distortion of 18.7% ($HD_3 = 15\%$, $HD_5 = 10\%$, and $HD_7 = 5\%$). The standing voltage, as well as the maximum length of cables, is presented in Table IV. The standing voltage in the worst case is increased to 0.126 V/m. The maximum length of the cables is now reduced to 199 m, which is again longer than the length actually found in buildings.

When the induced voltage or the single-point bonding is not allowed, solid bonding should be applied in the installation of single-conductor armored cables. The induced currents circulate within the armor of these cables and produce additional power losses in the cables. At 50 Hz, the TF configuration could increase the power loss by 10% with solid bonding in the case of cables on the tray, while the FS configuration could increase the power loss by 60%.

The power losses of the cables at harmonic frequency increase significantly, particularly at triplen-order harmonic frequencies. Figs. 8 and 9 show the percentage of losses on the cables against the magnitude of the third-order component in

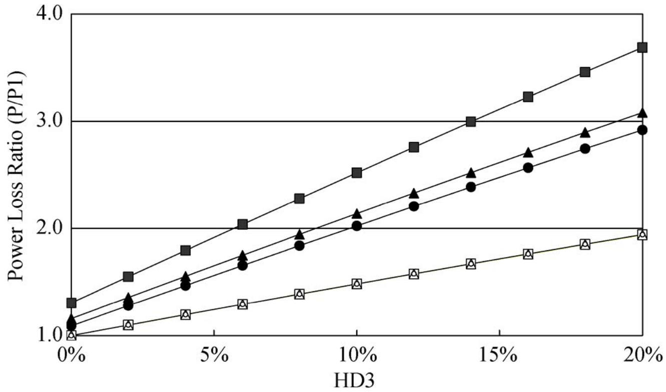

Fig. 8. Power losses of the cables installed in free air. □ and ■ FS configuration with SPB and SB. △ and ▲ FT configuration with SPB and SB. ◯ and ● TF configuration with SPB and SB.

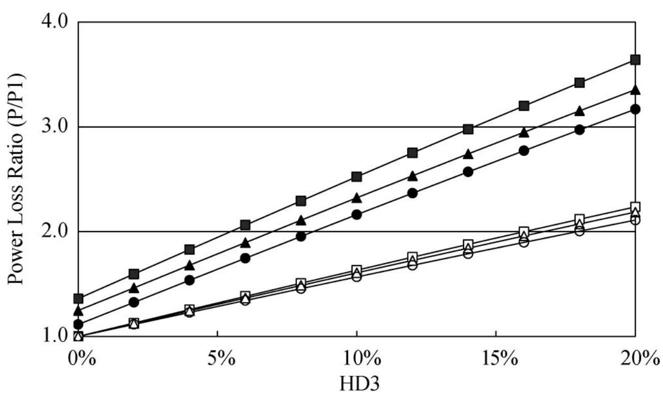

Fig. 9. Power losses of the cables installed on tray. □ and ■ FS configuration with SPB and SB. △ and ▲ FT configuration with SPB and SB. ◯ and ● TF configuration with SPB and SB.

two cases of cables in air and cables on tray, respectively. The 50-Hz losses in the cables installed in free air with SPB were selected as the reference.

As shown in the figures, at 10% harmonic distortion, the total power loss in the case of cables with SPB is increased approximately by 50%, while in the case of cable with SB, the power loss is increased by 100%–150% for cables in air and 120%–160% for cables on tray. This indicates that solid bonding could significantly reduce the current-carrying capacity of the cables; hence, large-size cables should be selected for such a circuit.

VII. Conclusion

This paper has presented the experimental results of induced voltages and power losses in the single-conductor armored cables under different installations in buildings. The impact of cable formations, bonding arrangements, and cable supporting methods was addressed at 50 Hz as well as at its harmonic frequencies.

To reduce the armor losses, single-point bonding is highly recommended for the installation of single-conductor armored cables in buildings. The induced voltage on cable armor may be of concern in a long-cable system. However, because of short length of the cables used in buildings, the standing armor voltage is generally less than the permissible voltage. It is also found that the standing armor voltage on cables installed on metallic tray is comparable to that on cables installed in free air and could be even less when the cables carry harmonic currents. The standing armor voltage can be roughly estimated using the impedance at 50 Hz or even using (1) for the worst case evaluation.

Cable resistance is significantly increased if the cable armor is bonded at two cable ends, as a result of circulating currents in the cable armor. The situation becomes worse when the cables are installed on metallic tray with large separation distance. It has been identified that the FS configuration is the worst formation in terms of both power losses and induced armor voltage and should not be adopted if possible.

The TF configuration is the best formation as this minimizes the armor currents and eddy current on the tray produced by magnetic flux from the cable conductors. The power losses under this formation increase slightly by 10% at power frequency when the cable armor is solidly bonded. However, the power losses in the cables increase significantly when the cables carry the currents with rich harmonics, particularly the third-order harmonic. Additional capacity of the cables is required for the circuit to handle the losses generated by current harmonics. Detailed evaluation needs to be carried out to ensure that the cables are not overloaded and the requirement of energy efficiency given in [6] is fulfilled.

References

[1] *IEEE Guide for the Application of Sheath-Bonding Methods for Single-Conductor Cables and the Calculation of Induced Voltages and Currents in Cable Sheaths*, ANSI/IEEE Std. 575, 1988.
[2] *Requirements for Electrical Installations*, 17th Edition, BSI, London, U.K., 2008. BS7671.
[3] G. J. Anders, *Rating of Electric Power Cables: Ampacity Computations for Transmission, Distribution, and Industrial Applications*. New York: IEEE Press, 1997.
[4] *Electric Power Systems in Commercial Buildings*, IEEE Std. 241, 1990.
[5] K. Ferkal, M. Poloujadoff, and E. Dorison, "Proximity effect and Eddy current losses in insulated cables," *IEEE Trans. Power Del.*, vol. 11, no. 3, pp. 1171–1178, Jul. 1996.
[6] *Code of Practice for Energy Efficiency of Electrical Installations*, Mech. Elect. Dept., Gov. Hong Kong Special Admin. Region, Hong Kong, 1998.
[7] *Code of Practice for the Electricity (Wiring) Regulations*, Mech. Elect. Dept., Gov. Hong Kong Special Admin. Region, Hong Kong, 2003.
[8] *Electric Cables—Thermosetting Insulated, Armoured Cables for Voltages of 600/1000 V and 1900/3300 V, Having Low Emission of Smoke and Corrosive Gases When Affected by Fire*, BS Standard 6724, 1997.
[9] Y. Du and J. Burnett, "Current distribution in single-core cables connected in parallel," *Proc. Inst. Elect. Eng.—Gener. Transm. Distrib.*, vol. 148, no. 5, pp. 406–412, Sep. 2001.

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