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Electric Shock in Urban Village: Reflections from A Practical Accident

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***Abstract*—Different types of grounding systems are adopted in residential buildings due to various considerations such as location, regulation, etc. In order to reduce the potential electrical hazards, the appropriate grounding system should be selected according to the specific situation. The purpose of this study is to identify the suitable grounding system for urban villages or areas with similar situations. The discussions are based on a typical case that frequently happened in the urban village. According to our investigation, adopting TN-C-S system in urban villages is with a high risk of electric shock hazards due to the disadvantage of the system itself and the situation in the urban village. The reported case and analysis in this paper can provide a reference for selecting an appropriate grounding system.**

***Index Terms*— Grounding, bonding, electric shock, safety**

I. Introduction

Electrical safety is always an important issue in the delivery and utilization of electricity. Electric shock hazards occur every year, and fatalities caused by electric shock are reported continuously. To protect people from direct or indirect electric shock, related research has been carried out widely in this area. Various technical standards and guides have been developed to ensure a safe electricity environment.

Grounding and bonding are two important factors that can ensure the electrical safety of low voltage distribution systems. The importance of these factors has been emphasized in standards, such as the National Electrical Code [1], IEC 60364-4-41 [2]. The detailed requirements of grounding and bonding are also elaborated in these standards. In [3] the function of the equipment bonding and system grounding, as well as their difference, is introduced. Under a ground fault in a building, the fault current is returned via the grounding system. The potential on the upper floors will rise. Thus, dangerous touch voltage appears in these areas. This touch voltage depends on various factors, such as touch point, construction of structure type, floor material. The influence of these factors can be evaluated through both the experiment and theoretical analysis [4, 5]. If the touch voltage exceeds a certain level, an electric shock hazard could occur. The proper bonding can limit the touch voltage to a great extent. In [6] the issue of whether conductive objects should be bonded or not is addressed by using objective criteria. The extraneous conductive parts can easily result in dangerous touch voltage if bonding is not proper. According to the standards, all the extraneous conductor and the metal enclosure of the conductors should be connected to the main grounding terminal. However, in practical cases, it is hard to implement. In [7], the authors use electromagnetic simulation to analyze the touch voltage in the building under different bonding conditions during ground faults. It shows that the presence of widespread metallic parts in buildings helps to reduce touch voltages, but not enough to ensure safety against indirect contacts.

Apart from bonding, grounding is also a traditional topic addressed well. The grounding can provide a low impedance loop for the fault current. The impedance of the ground fault loop is a very important parameter for both evaluating the expected touch voltage and selecting protection devices [8] [9]. The touch voltage and selection of protection devices are largely determined by the grounding method.

In this paper, the safety conditions of electrical installations in a particular area — the urban village is analyzed. An electric shock accident, which happened in the urban village is investigated. The suitable grounding method for the area like an urban village is addressed.

II. Review of Grounding Methods

According to [10], the grounding systems can be divided into IT, TT and TN systems. Each system has its own advantages and disadvantages.

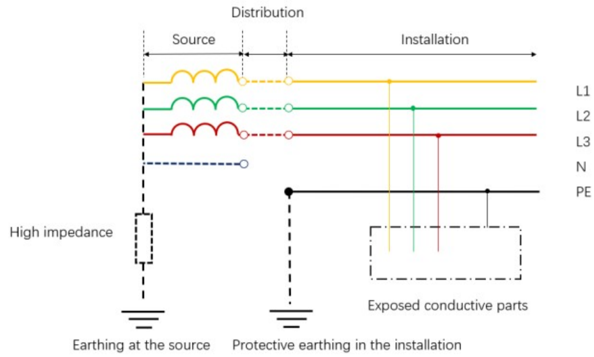


Figure 1. Grounding of IT system.

In an IT system, the neutral of the distribution transformer is grounded through a high impedance, while the metal enclosure of electrical equipment is directly grounded. When the single-phase ground fault occurs, the fault current is very small, the power supply will not be interrupted. Because of its high supply reliability, it was widely used in places where power interruption can lead to serious consequences, such as an operating room in the hospital, coal mine, steel plant, etc. The disadvantages of the system are that the voltage in the healthy line under a ground fault changes from phase voltage to line voltage so the insulation electrical equipment should be upgraded. In addition, the residual current devices cannot be used in IT system so IMD (insulation monitoring device) has to be installed to monitor the insulation condition of the system.

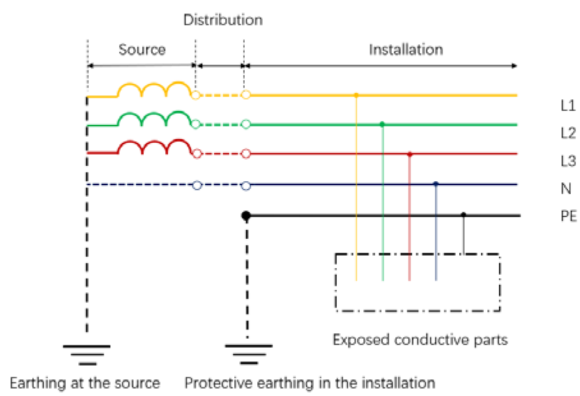


Figure 2. Grounding of TT system.

TT systems are mainly used in areas with long transmission lines, especially in rural areas. If the TN-S system is adopted in these areas, there will be a large voltage drop on PE line thus its protection effect will be affected. Since the power system was grounded through two independent grounding points, the grounding fault current is small, so over current protection cannot be used as grounding fault protection in such a system. Another disadvantage of the independent grounding point is the ground potential rise caused by a transformer high-voltage side fault or a lightning strike can lead to the voltage difference between the enclosure of equipment and neutral of equipment. This voltage difference will exceed the withstand voltage of the equipment, resulting in a breakdown or a short circuit within the equipment.

By connecting the enclosure of the equipment with the neutral line, the TN system solves the problem of insulation breakdown caused by the voltage difference. TN systems include TN-C, TN-S, TN-C-S systems.

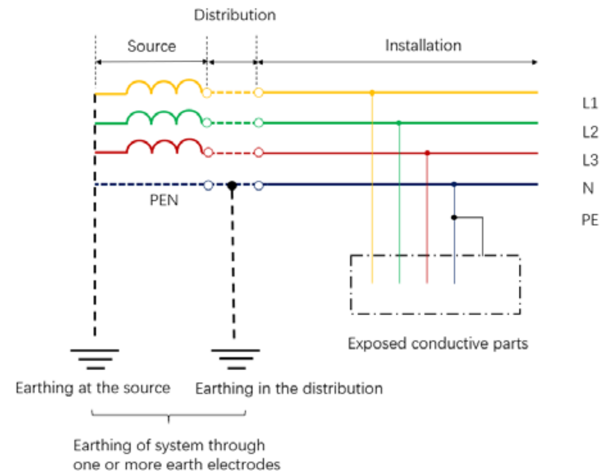


Figure 3. Grounding of TN-C system.

In TN-C systems, the neutral point of the distribution transformer is grounded. The PE and N conductors are the same conductor which is called PEN conductor. This system is only suitable for the balanced three-phase load. If the load is unbalanced, the current will appear in the PEN line. The harmonic current caused by electronic equipment will be also injected into the PEN conductor. Under some conditions, the voltage in the PEN line is very likely to be higher than 50V leading to potential electric shock hazards.

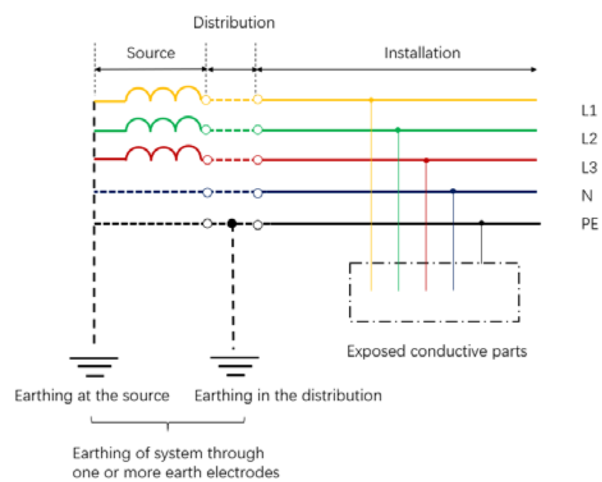


Figure 4. Grounding of TN-S system.

TN-S systems completely separate the PE conductor from the N conductor, thus overcome the shortage of TN-C systems. However, since the PE line is grounded at the same transformer, the fault voltage can be transmitted to other places along the PE line if any ground fault occurs. In addition, the investment of the TN-S systems is larger than other systems.

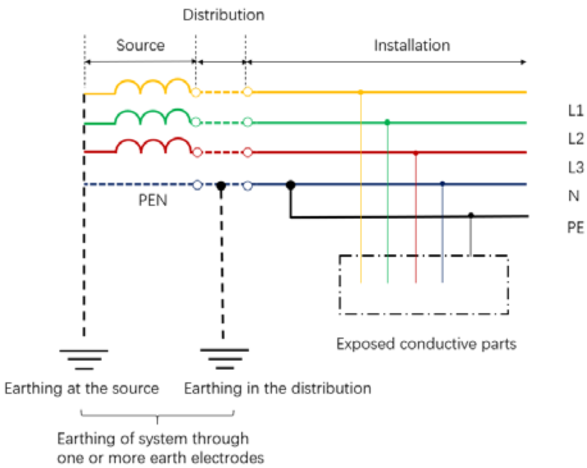


Figure 5. Grounding of TN-C-S system.

For TN-C-S systems, the neutral and protective conductor are combined in a single conductor in a part of the system and the PEN conductor can be grounded through one or more earth electrodes. The enclosure of the equipment connected by PE conductor will not be live during normal operation. Generally, a TN-C-S system is adopted when the transformer is far away. The problems of this system include a single line ground fault on the low-voltage distribution system, interruption of the neutral conductor, excessive fault-loop impedance value, etc. [11].

Different types of grounding systems are adopted in different areas and supply systems for different considerations. For example, The TT system is used in Denmark, France, Italy, Japan, Spain, Portugal and etc. The IT system is used in Norway, Albania, and Peru. The TN system is used in Canada, Germany, Sweden, and USA [9]. In some countries, adopting which grounding system is not mandatory stipulated in the National Standard. In fact, there is no optimal grounding system suitable for all, the appropriate grounding system should be selected according to the specific situation.

III. URBAN VILLAGES

Urban villages resulted from the rapid economic development of cities in China in the later 20th century. As the fastest growing and most economically developed city in China, Shenzhen also has a huge number of urban villages, providing shelter for millions of migrant workers as shown in Fig. 6. There is usually no unified planning and management in these urban villages. The crowded buildings supplied by non-standardized low-voltage power distribution systems make the urban villages become a high-risk area where electric shock frequently happens. It is noted that equipotential bonding and residual current devices are effective means to protect persons from electric shock. However, these two measures are often absent in urban villages.


Figure 6. Overview of Urban-Village in Shenzhen, China.

In most cases, the supply system in the urban villages employs a TN grounding system. The cut-off boundary of utility's system and customer installations is the meter box at the entrance of the building. The distribution system inside the building belongs to the users. The supply company owns the external distribution system, including the meter boxes, cables, low voltage switchgear cabinet, and transformer. In the past years, the government and the power supply company have made great efforts to improve electrical safety in urban villages in the city. However, the situation does not go well. This is because the site situation is complicated. In particular, the wiring system within the building is chaotic in some buildings, with great potential risks. The possible causes of electric shock in the low voltage system are various, and are listed below:

1) Insulation failure of the electrical appliances.

2) Dangerous voltage caused by insulation failure of electrical equipment in an adjacent circuit.

3) Ground fault on the medium-voltage utility distribution system.

4) Ground fault on the low-voltage utility distribution system.

5) Broken PEN Conductor in a TN-C-S grounding system.

6) Unbalanced load in a TN-C grounding system.

Among these factors, the broken PEN conductor is frequently observed in urban villages and has caused a number of casualties.

IV. AN ELECTRIC SHOCK ACCIDENT IN AN URBAN VILLAGE

On June 21, 2018, a male person died after an electric shock when using a water heater in a building of an urban village. The 6-story building is made by brick masonry structure without installing either main equipotential bonding or supplementary equipotential bonding. After the accident, engineers went to the spot to investigate the accident and try to find out the root cause of the accident. The system description and the analyzed are presented in this section.

1) Utility distribution system

The building under investigation is powered by a distribution transformer with a capacity of 1250 kVA. The distribution system adopts the TN-C grounding system. The system is grounded at the neutral point of the distribution transformer and the power is delivered to the users through an overhead transmission line.

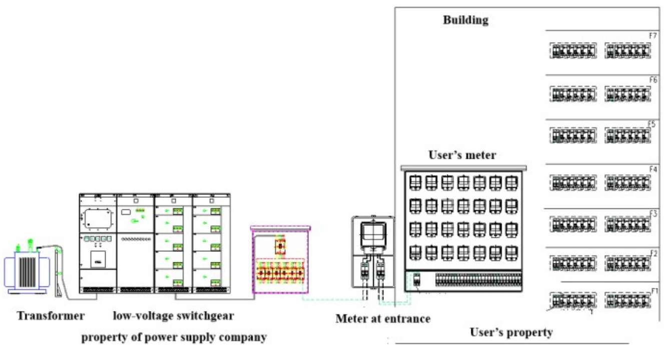


Figure 7. Configuration of the distribution system.

Two electricity meters are installed at the entrance of the building one for commercial users and the other for residential electricity used. The commercial meter box and the resident meter box are powered by the single phase of the distribution network (220V).

2) User's distribution system

After the residential meter, there is a customer meter box that contains 28 single-phase meters for individual rooms in the building. In the utility meter box, both N busbar and PE busbar are provided as shown in Fig. 8. These two busbars are connected through a short wire. The PEN is separated into PE and N at the user's meter box.

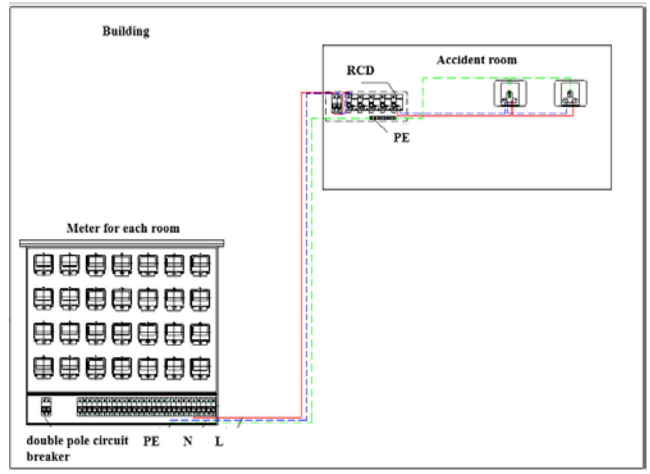


Figure 8. Configuration of User's distribution system.

The incident happened in one of the rooms on the 6th floor of the building. The room is equipped with a two-pole circuit breaker and five RCDs which protect the lighting circuit, socket circuit, and power circuit. The rated residual operating current of RCDs is 30 mA. According to test results after the accident, all RCDS function satisfactorily. The person suffered from electric shock while taking a shower in the bathroom. In the bathroom, a water heater and a booster pump were installed. The enclosure of the equipment is connected to the PE conductor and the insulation of these equipment is in good condition.

3) Cause of the accident:

This section will analyze a reported electric shock accident in the urban village. The system configuration during the accident is presented in Figure. 9.

- *The broken PEN Conductor:*

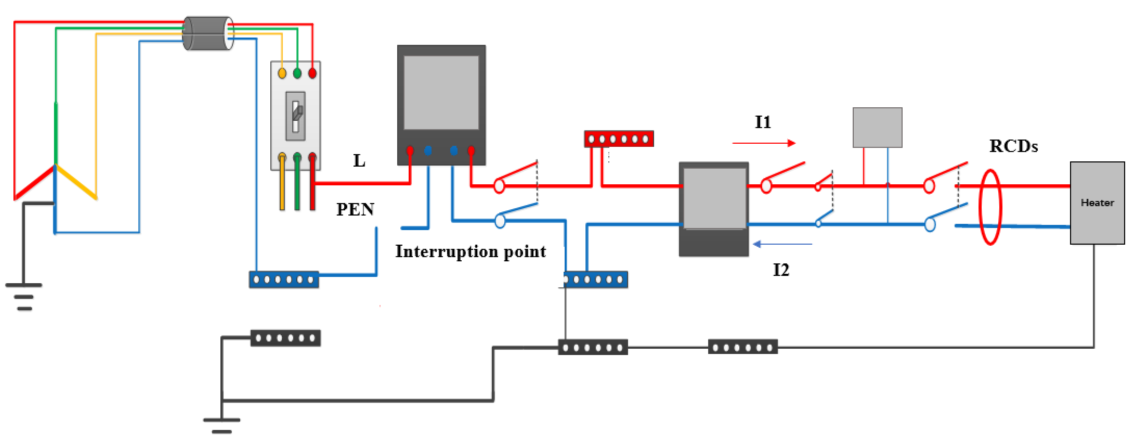
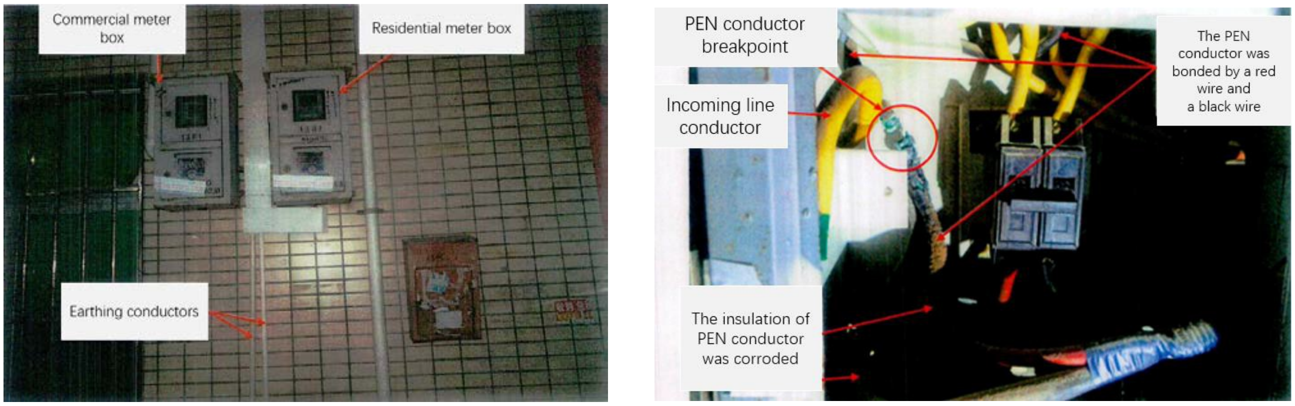


Figure 9. Electrical configuration of the building in the accident.



(a) (b)

Figure 10. Picture of the electricity meters at the entrance of the building. (a) electricity meters for commercial use and residential use. (b) interruption of PEN conductor.

The broken PEN conductor directly leads to an electric shock accident. As seen in Fig. 10, the connecting wire is completely broken due to aging. Since the PEN is separated into PE and N at the user's meter box, so the grounding system of the building can be seen as the TN-C-S grounding system. The interruption of PEN conductor makes all the metal enclosures of the equipment becomes energized.

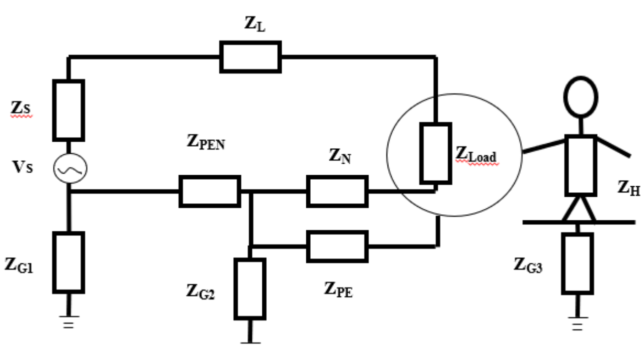


Figure 11. Equivalent circuit before the damage of the PEN conductor.

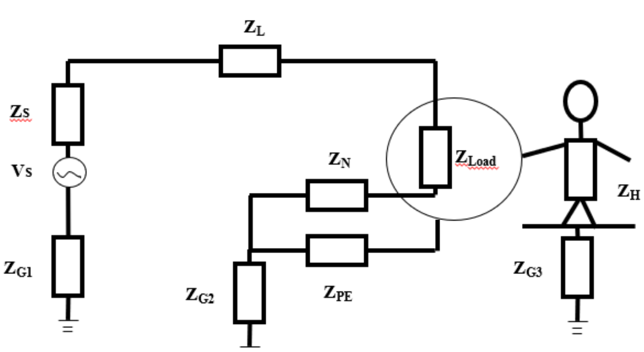


Figure 12. Equivalent circuit after the damage of the PEN conductor.

Fig. 11 shows the equivalent circuit before the PEN conductor is broken. The potential on the enclosure of the equipment is (Before people contact):

$$P_E = V_s \frac{Z_{PEN} // (Z_{G1} + Z_{G2})}{Z_s + Z_L + Z_{Load} + Z_N + Z_{PEN} // (Z_{G1} + Z_{G2})} \qquad (1)$$

Fig. 12 shows the equivalent circuit after the interruption of the PEN conductor. After the PEN conductor is broken, the potential on the enclosure is (before people contact).

$$P_E = V_s \frac{Z_{G1} + Z_{G2}}{Z_s + Z_L + Z_{Load} + Z_N + Z_{G1} + Z_{G2}} \qquad (2)$$

where

P_E : the potential on the enclosure of the equipment.
Z_N : impedance of the neutral conductor.
Z_{PE} : impedance of the PE conductor.
Z_{PEN} : the impedance of the PEN conductor.
Z_L : the impedance of the line conductor.
Z_s : the impedance of the source.
Z_H : the impedance of the body from hand to feet.
Z_{G1} : the grounding impedance at the source.
Z_{G2} : the grounding impedance of the grounding electrode at the user's premise.
Z_{G3} : the grounding impedance where the people stand.

Since the values of the grounding impedance Z_{G1} and Z_{G2} are much larger than the impedance of the conductor. The potential on the enclosure is very small if the system is healthy. However, after the interruption of the PEN conductor, the potential is largely affected by the impedance of the ground. Due to the high impedance of the ground, the potential of the enclosure rises significantly, thus people in the building are exposed to dangerous potential.

- *Absence of main and supplementary equipotential bonding:*

The main and supplementary equipotential bonding can limit the touch voltage between two conductive parts. Equipotential bonding is essential for TN systems. If the enclosure of the equipment, the reinforcing bars of the building and other extraneous conductive parts are connected to the main grounding bus bar, a significant reduction of touch voltage can be achieved [7]. The building of concern is a brick masonry structure without any main equipotential bonding and supplementary equipotential bonding. Therefore, when the

PEN is broken, persons in the building are subject to hazardous voltages.

- *No operation of protection devices:*

Protection devices have been already installed in the building, for example, RCDs for ground fault protection and CBs for overcurrent protection. The RCDs are designed to protect people from electric shock. The overcurrent protection can also interrupt the circuit during fault conditions. If one of the protection devices can trip in time，the accident could be avoided. Unfortunately, neither the RCDs nor the CBs in the building cut off the power supply when the electric shock accident happened. This is because when the PEN is broken, the fault current does not increase significantly, unlike the normal short circuit current. So the CBs can detect such a fault and would not trip at that time. It is known that the RCDs installed in the customer premise monitor the unbalanced current. Because the fault was not in the downstream circuit, the RCD would not be able to detect such a fault.

V. DISCUSSION

The accident presented in this paper is not a coincidence that rarely happened. In fact, similar incidents happened many times a year in urban villages. In the first half-year of 2018, there were 21 electric shock accidents happened in Shenzhen, leading to 21 deaths. It seems that the TN-C-S which has been widely used in China and other countries faces some difficulties in ensure electrical safety in Urban villages. According to our investigation, the reasons are listed as follow:

1) Compared to the TT system, a conductor for bonding PE and N conductors must be provided somewhere in the TN-C-S system. This conductor could be wrongly provided by a technician within the building. This leads to some difficulty for utilities to maintain electrical safety in the supply system, as the utility companies do not have a full record of such bonding information.

2) In case of a ground fault in the TN-C-S system, the potential rise of the PE can be transferred to other places along PE line. This makes all the metal parts in the building to be electrified, which is quite dangerous to occupants. To make matters worse, the buildings in urban villages are usually very dense, and some buildings are even less than one meter apart. Persons walking in alleys around the building, or persons even in other buildings could be subject to electric shock. This greatly increased the risk of electric shock. Therefore, in the TN-C-S system, equipotential bonding in the building as well as with adjacent buildings is indispensable.

3) Compared with commercial buildings the owners of the buildings in the urban villages often employ less qualified electrical engineers to carry out electrical work in order to reduce the operational costs. Therefore, the problematic wiring systems in the urban villages are quite common.

4) Because of the harsh environment and lack of regular inspection, the bare conductors are easily eroded. The breakage of the PEN conductor easily happens in the urban villages.

5) The local government has paid lots of attention to electrical safety in buildings and invested a lot of money to improve system performance, such as installing the RCDs free of charge. The effect, however, is not so significant. There are a variety of reasons for this. For instance, due to the incorrect wiring, many installed RCDs are frequently subject to nuisance tripping. So some of the users disassemble the RCDs to avoid nuisance tripping. In some cases, like the accident introduced in this paper, the RCDs will not trip through electric shock happened.

All these factors contribute to the electric shock hazard in the urban villages and areas or places with similar characteristics to the urban villages. According to the author's investigation, the TT system is more suitable for urban villages compared to the TN-C-S system. On the one hand, it is because of the shortcomings of TN-C-S stated above is hard to completely avoid in the environment like the urban villages. On the other hand, some disadvantages experienced in the traditional TT system will not be observed in urban villages. For example, due to the neutral conductor and the enclosure of the equipment are not connected, the ground potential rise caused by a lightning stroke can lead to the potential difference between the enclosure of equipment and neutral of equipment thus results in insulation failure. However, this situation unlikely happens in urban villages due to the surrounding high-rise commercial buildings. Another disadvantage of the TT system is that RCDs are needed to install in the circuits in order to guarantee electrical safety. Nowadays, since RCDs have been widely installed in urban villages, it is now no longer an obstacle to adopt the TT system in the urban village.

ACKNOWLEDGMENT

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