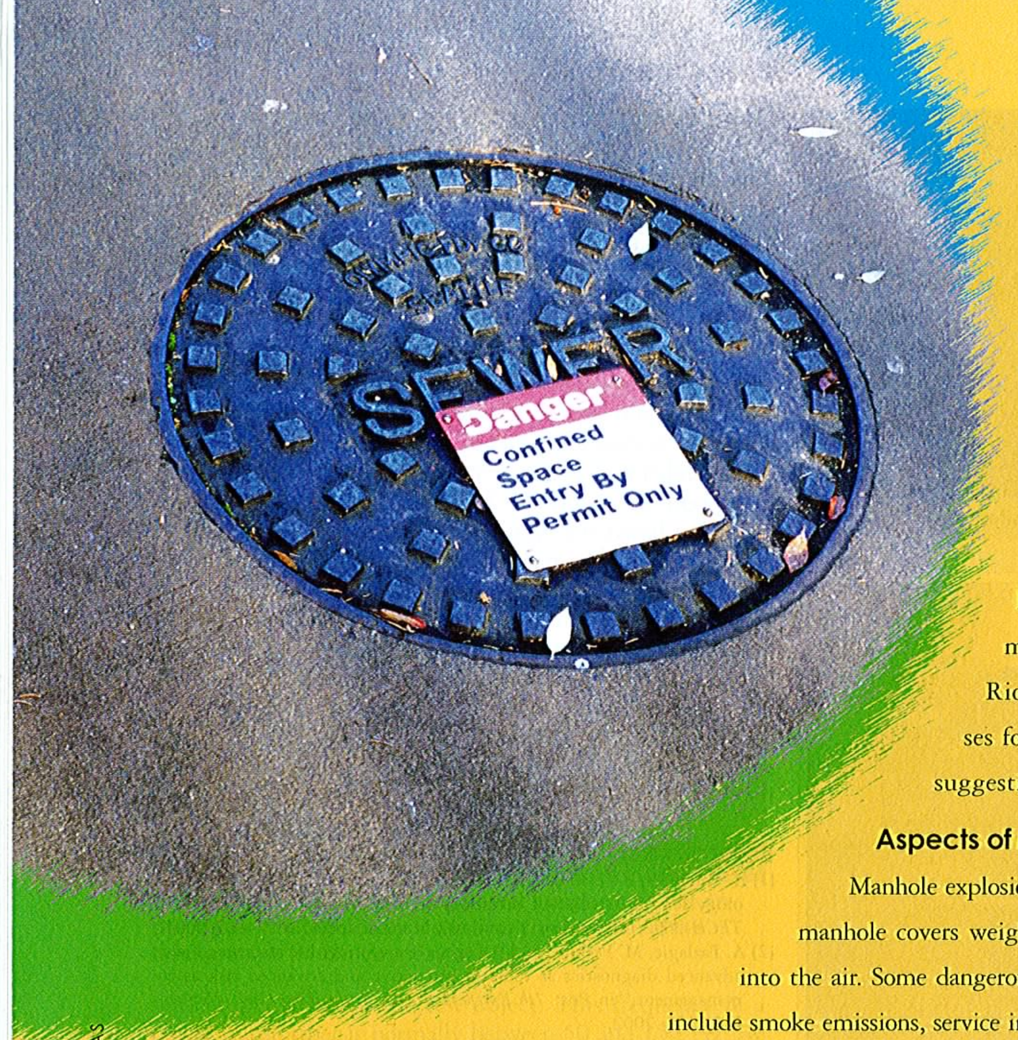


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BY ESTELLITO RANGEL Jr.

# EXPLOSION RISK IN UNDERGROUND NETWORKS

Measures for preventing manhole explosion events

MANHOLE EXPLOSIONS have occurred in many cities and are concerning to citizens. This article cites some manhole explosion events, shows the measures taken so far by authorities in Rio de Janeiro, analyzes some hypotheses for the root causes, and provides some suggestions to solve this dangerous problem.

## Aspects of Manhole Explosions

Manhole explosions have been known to cause cast iron manhole covers weighing about 300 lb to be thrown 4 m into the air. Some dangerous consequences of manhole explosions include smoke emissions, service interruptions affecting many consumers, interdiction of roads, deaths, and pedestrians suffering serious burns.

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On 29 June 2010, a female tourist from Ohio spent 68 days in the hospital, with 80% of her body burned as a result of a manhole explosion that occurred in a pedestrian crosswalk in Rio de Janeiro. Her husband spent 30 days in the hospital with 35% of his body burned [1]. It is noteworthy that they were able to leave the hospital, but they had many scars and were not able to function as well as before the accident. Their medical treatments, which may take several months and include physical therapy, plastic surgeries, and psychological counseling, will be continued at home.

Many professionals are exposed to such risks, such as the following.

- Electricity utility workers—In New York, 9 October 2008, a utility employee died while making repair services in a manhole [2]. A buzzing sound was noticed, black smoke issued from the hole, and, in sequence, the explosion occurred, killing the worker inside the manhole.
- Police officers—On 13 September 2008, two police officers approached a manhole that exploded on Raul Pompeia Street in Rio de Janeiro when, suddenly, a second explosion occurred, throwing one of them against a metal fence [3].
- Firefighters—On 26 February 2010 on Domingos Ferreira Street in Rio de Janeiro, when firefighters opened an electric manhole's cover after an explosion, a second one exploded across the street. On 24 April 2012 on Yorba Linda Boulevard, Orange County, California, a firefighter and a captain approached a manhole that had already popped off to take a peek inside, when a second explosion occurred and tossed the captain about 10 ft onto a bush. Two explosions occurred a few seconds after these two in the same manhole [4].

## Measures Taken in Rio de Janeiro

### *By The Local Electricity Distribution Company*

Around ten manhole explosions were recorded by the press in Rio de Janeiro in 2000 [5]. An average of three explosions per year was recorded in the following years, and a new cycle of frequent explosions occurred, nearly 20, in 2010. On 20 September 2010, the local electricity distribution company announced that it would make some structural improvements in the southern districts, including the installation of 6 mi of medium-voltage (MV) cables (nine feeders) and the replacement of eight transformers, which would be concluded in December 2010. The main focus was on minimizing the risks of equipment failures and improving the supply service quality. Such improvements were not announced as the solution for removing the causes of manhole explosion events. In 2011, another 20 explosions in the underground network were recorded, and it became clear that those measures were ineffective.

The local electricity distribution company signed a legal agreement with the Rio de Janeiro state prosecutor on 18 July 2011 that stipulated fines of US$50,000 for each manhole explosion that causes injuries to victims or damage to public or private property [6]. The agreement also stipulated the modernization of 4,000 vaults to be completed by December 2012; among them, 1,170 would be modernized by December 2011.

As part of the modernization plan, it was announced that gas, flood, and intrusion sensors would be installed in 1,170 vaults connected to a wireless communication system to send real-time information to a dedicated supervisory room, allowing for the identification of the entry of gas, water, or unauthorized persons into vaults.

Considering that, in the following years, new manhole explosions were recorded, it is clear that the installation of gas sensors in the vaults was not enough to prevent explosions. Another concern is related to the gas sensors specifications, as it was not confirmed which gases are expected to be present in the underground system. In the "A Deeper Look" section, this topic will be discussed in detail.

Another questionable measure was the drilling of holes on the manhole covers to ensure the release of accumulated gas inside the underground system. However, this is not considered efficient because the gas dissipation inside the underground ducts is not smooth, and gas accumulation in some points can occur. Figure 1 shows such holes (four) completed in 6,478 manhole covers.

It seems that the local electricity distribution company is aware of these drawbacks, as it pointed out that "the investment does not guarantee the end of further incidents" (i.e., explosions, smoke, and fire in manholes) [7].

### *By City Hall*

The Rio de Janeiro City Hall, through its Conservation and Public Services Secretary (Seconserva), in August 2011, hired a private company for an independent measuring of flammable gas concentrations in the underground network, aiming for a total of 10,000 inspections in manholes and vaults per month, on a six-month schedule, costing US$2.121 million.

Inspections were done using gas detectors (explosimeters) to verify the concentration of $CH_4$, $O_2$, and CO. In addition, the service also included inspections in vaults to measure the external temperature of distribution transformers using infrared thermometers. The objective was to compare the current equipment temperatures to those recommended by the manufacturers. When inspections demonstrated the presence of gases above 80% of its lower explosive limit (LEL), it was necessary to immediately inform the Seconserva. Then, the

**1** These holes cut into manhole covers are intended to aid in the release of gas buildup.

An isolated and signalized manhole with a considered high flammable gas concentration, waiting for repairs.


An excavation of the damaged terracotta ducts of the street lighting circuits: 1) new polyethylene gas piping and 2) damaged terracota ducts exposing the street lighting cables.

manhole was isolated and signalized for an expected immediate repair under the responsible utility company.

Figure 2 shows an isolated manhole, with the cover partially open, waiting for repairs. Once the first measuring values were issued, newspapers published headlines such as "A Manhole with 80–100% Explosion Risk Was Found," based on the gas concentration indicated on the explosimeter display. This is a misconception because when the explosimeter indicates "80," it means that the gas that passed through the sensor has a concentration corresponding to 80% of the calibration gas LEL, e.g., methane. Therefore, if the real gas in the manhole was methane, there was not an explosive atmosphere since its LEL was not achieved.

The explosion risk can only be mathematically estimated after the knowledge of the frequency and duration of an ignition source, which could appear at the same time that the flammable gas concentration surpasses its LEL. This estimate should be a result of a quantitative risk analysis, a specialized service not provided by explosimeters. As manhole explosions continued to happen after the end of this service, it became clear that gas measuring activities did not solve the problem.

Another requirement made by city hall was that all utility companies, such as gas, water, and sewage, provide a complete digital location map of their underground systems, aiming to avoid explosions during service repairs, notably when excavations made by one company damage the gas piping.

Figure 3 shows terracotta ducts with wires inside that were damaged after an excavation made by the gas utility company when replacing the cast iron pipes with polyethylene ones (yellow and black piping). Until now, no manhole explosions had occurred due to the excavations required for repairing services by other companies.

### By the Gas Utility

The gas utility signed a legal agreement with the Rio de Janeiro state prosecutor on 28 July 2011, pledging to replace 31 mi of old cast iron piping with new polyethylene pipes in one year in the districts of Copacabana and downtown, which were the most affected by manhole explosions. If any further manhole explosion causes harm to victims or damage to property, and the gas utility is considered guilty, it would be required to pay a fine of US$50,000 [8]. The cost of these modernizations was estimated to be US$12.5 million.

### By the Regulatory Agency

The Brazilian Electricity Regulatory Agency (ANEEL) establishes all legal and technical requirements for electricity distribution companies. The main evaluation factors applied by ANEEL to the electricity distribution companies are the system average interruption duration index (DEC) and the system average interruption frequency index (FEC), which reflect the operational continuity but not the safety level of the service. Due to the characteristics of the network system (the secondary grid with no cable protection), the load of one faulty transformer can be taken by those located in adjacent vaults, issuing a high operational continuity, i.e., low DEC and FEC values.

This explains why electricity distribution companies, even with numerous events of fire, smoke, and manhole explosions, can be evaluated by ANEEL as efficient. No fines have been applied by ANEEL to electric utilities due to manhole explosions. Thus, it is strongly recommended that manhole events be included in the evaluation of electricity distribution companies as service continuity alone is a precarious index.

### The Police Investigations

Each manhole explosion that caused injuries to victims or property damage was investigated by the police department. Usually, the reports made by the police department did not show sufficient details, limiting the analysis to the particular interior of the manhole that had an incident. The inspectors had no independent equipment to detect and analyze gases, and they had no temperature meters, so they asked the utility companies to perform these measurements.

If information about the underground connected ducts, system load, previous maintenance activities, and eyewitness declarations were added to the police reports, they could contribute to point out the incidents' root causes.



## Conditions for an Explosion

To have an explosion, it is necessary to have the simultaneous presence of an explosive atmosphere and an ignition source with the required energy. An atmosphere acquires explosive characteristics when the flammable gas reaches its LEL [9].

Although the gas supplied to homes by the gas utility company was at first listed as the main suspect of a supposed flammable atmosphere inside the electricity distribution companies' ducts, some studies revealed that flammable gases can be also generated by the electrical cables themselves if they operate at temperatures above those recommended by the manufacturers.

As flammable gases have evolved and accumulated in the ducts, the decomposition of the cable insulation also allows for the occurrence of a short circuit, which will be the ignition source promoting an explosion.

The phenomenon that occurs in an underground distribution network can be illustrated using the typical topology shown in Figure 4. Depending on the geometry of the underground system ducts, the "pressure piling effect" propagates the explosion through the ducts until the adjacent manholes.

## A Deeper Look

The concerns about manhole explosions are not new. In 1948, the Los Angeles Sewage Department issued a plan very similar to the measures adopted in Rio de Janeiro, 63 years later, consisting of flammable gas concentration measuring in manholes, to stop the manhole explosions [10]. As the explosions still happen today, it is clear that those measures are not effective.

When a manhole explosion occurs, the first declaration given by the utility is that an investigation is under way to find the causes. Unfortunately, the causes of the previous explosions are never announced. Only after identifying the root causes of a problem is it possible to implement an action plan to solve it.

In Washington, D.C., the Public Service Commission of the District of Columbia hired a consulting firm to conduct an independent analysis of the electrical utility underground system in 2001. The main cause was identified as circuit overloads, which caused the deterioration of cable insulation and led to fire, smoke, and explosions in the manholes [11]. This removed the popular suspicion of leakage from the gas utility piping as the sole cause of manhole explosions.

Even if an explosive atmosphere can be formed inside the electrical underground system due to a leakage of nearby gas piping, why, at that same moment, should a spark occur? If the underground system is well designed and maintained, no sparking points are expected.

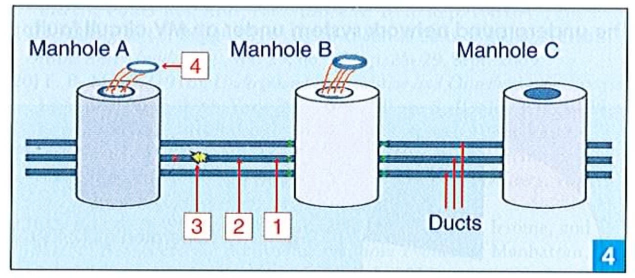
One common design requirement for the electrical underground system is that customers will remain powered after one "contingency," i.e., one primary MV feeder out of service. If a second contingency occurs, it is expected that the operators will shut down part of the system because overloads will start to happen on the remaining feeders. This decision, which is up to the utility operator, is based solely on readings of the load monitors of the remaining primary feeders located at the area substation because the secondary grid is not usually provided with metering systems. It was not uncommon for the underground system to be subjected to up to four contingencies, as in Rio de Janeiro [12], and even six contingencies, as in New York [13], which leads us to estimate that the remaining feeders and the secondary grid were subjected to severe overloads [11].

> EXPLOSIONS IN UNDERGROUND DISTRIBUTION SYSTEMS ARE A REAL CONCERN OF BIG CITIES.

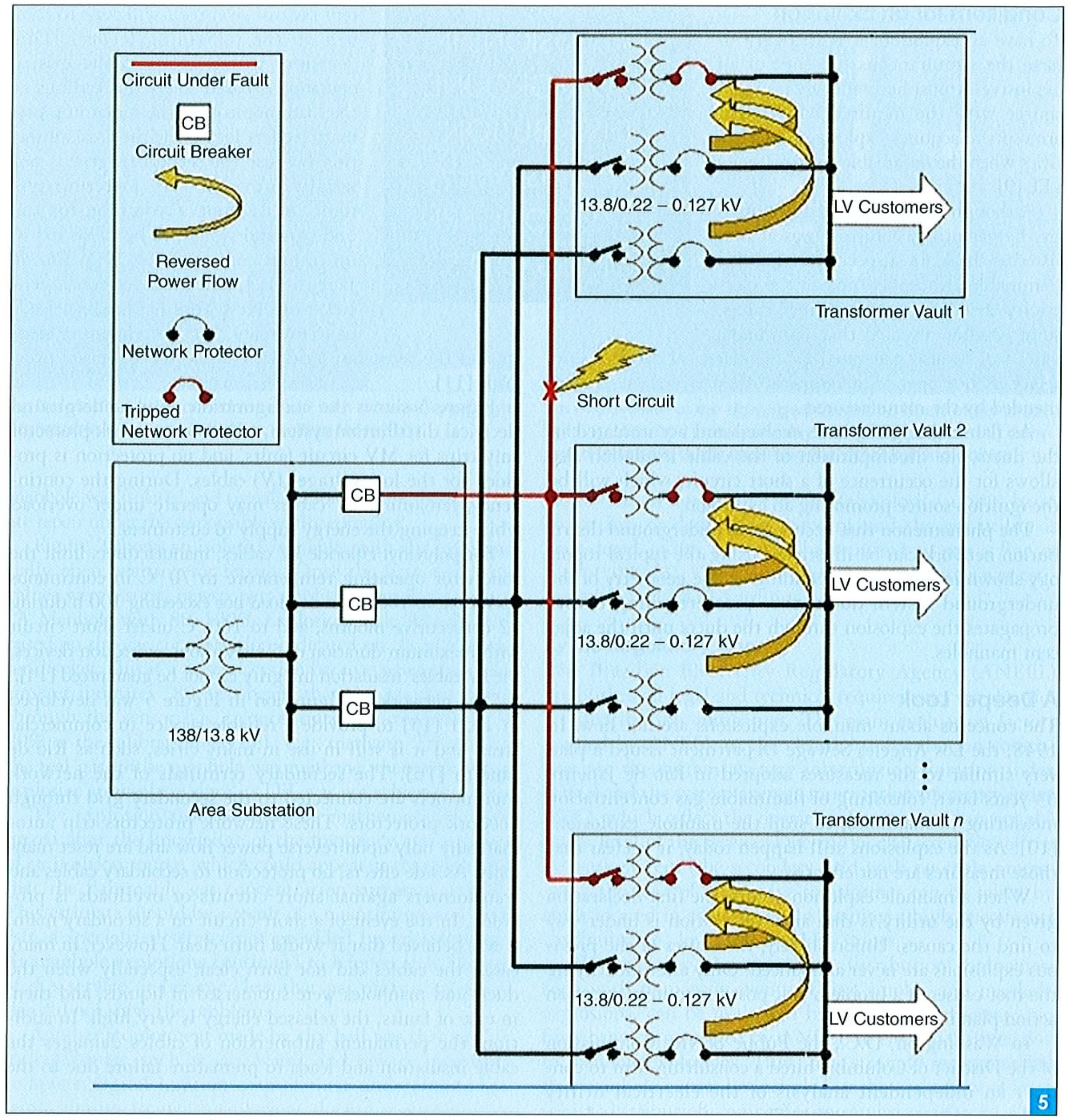
Figure 5 shows the configuration of an underground electrical distribution system, where the network protector only trips for MV circuit faults, and no protection is provided for the low-voltage (LV) cables. During the contingency, remaining LV cables may operate under overload while keeping the energy supply to customers.

For polyvinyl chloride LV cables, manufacturers limit the conductor operating temperature to 70 °C in continuous operation, to 100 °C on overload not exceeding 100 h during 12 consecutive months, and to 160 °C under short circuit with maximum duration of 5 s. Without protection devices, the LV cables' insulation integrity cannot be guaranteed [14].

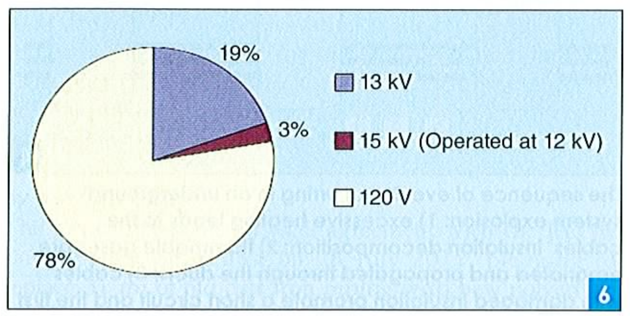
The network configuration in Figure 5 was developed in 1921 [15] to provide a reliable service to commercial areas, and it is still in use in many cities, such as Rio de Janeiro [16]. The secondary terminals of the network transformers are connected to the secondary grid through network protectors. These network protectors trip automatically only upon reverse power flow and are reset manually. As side effects, no protection to secondary cables and transformers against short circuits or overloads is provided. In the event of a short circuit on a secondary main, it was believed that it would burn clear. However, in many cases, the cables did not burn clear, especially when the ducts and manholes were submersed in liquids, and then, in case of faults, the released energy is very high. In addition, the permanent submersion of cables damages the cable insulation and leads to premature failure due to the




The sequence of events occurring in an underground system explosion: 1) excessive heating leads to the cables' insulation decomposition; 2) flammable gases are emanated and propagated through the ducts; 3) cables with damaged insulation promote a short circuit and the first explosion; and 4) the gas is ignited and the explosion propagates throughout the ducts, blowing up the manhole covers.




The underground network system under an MV circuit fault.




The majority of manhole explosions occur in LV systems with burn clear configuration.

water tree aging phenomenon [17]. All of these conditions led to the statistics shown in Figure 6, where 36 manhole explosions were considered [18].

As shown in Figure 5, faults on the secondary grid will not usually result in outages to any customers due to the multiplicity of paths from the area substation to the customer loads. This is why this configuration offers the highest reliability level, and it is still extensively used in many metropolitan areas.

The decomposition of a styrene-butadiene rubber (SBR) cable insulation due to thermal aging is shown in Table 1 in the air and in anaerobic conditions; the latter was simulated using argon with 1% $O_2$. In the air, CO could not be identified due to an interference from $N_2$ [19]. It is notable that the main detected component was hydrogen, a highly flammable gas.

**TABLE 1. THE COMPOSITION OF DETECTABLE PRODUCTS FROM SBR CABLE DECOMPOSITION BY OVERHEATING AT 500 °C.**

| | Composition (%) | |
|---|---|---|
| Component | In Air | In an Anaerobic Environment |
| Hydrogen | 27.98 | 57.35 |
| Carbon monoxide | — | 18.63 |
| Water | 26.08 | 15.84 |
| Carbon dioxide | 41.78 | 6.75 |
| Methane | 3.84 | 1.76 |
| Acetylene | 0.14 | 0.16 |
| Ethane | 0.17 | 0.01 |

## Conclusions

Explosions in underground distribution systems are a real concern of big cities, considering the registered incidents in Baltimore, Boston, Cincinnati, Detroit, Hong Kong, Indianapolis, London, Los Angeles, New York, Philadelphia, Pittsburgh, Rio de Janeiro, San Francisco, São Paulo, Washington, D.C., and many others with the "burn clear" concept. Surprisingly, this problem is not new, as explosions occurred in underground systems in the early 20th century [20]. Service reliability has been the main objective of electricity distribution companies, especially in the central business districts of large cities, but the citizens' safety must be paramount.

The concept of no protection to the secondary grid cables is the oldest and cheapest method to achieve reliability, but this alternative allows for overloads that deteriorate the cables' insulation and generate flammable gases, which can be ignited by the short circuits due to the damaged insulation. Considering the widespread heavy use of electronics today, the modern urban electrical load has more harmonics, which also contributes to the insulation stress in cables. The old concept for the secondary grid can be considered outdated and unsafe, and, thus, the implementation of an effective protection system that is properly designed to the new faults' characteristics [21] is imperative.

Some researchers show that it is possible to create mathematical models to evaluate the underground networks according to their vulnerability. The ranking results can be used to prioritize preventive repair work on the underground network, avoiding the insulation deterioration that leads to manhole events such as explosions, fire, and smoke [22].

A policy of operating the electrical system components strictly under their manufacturers' specifications is the key to ensuring the electrical distribution service without jeopardizing the citizens' safety.

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