Processes for Investigating Elevated Voltage in the Urban Environment

David Kalokitis, *Senior Member, IEEE*, Anthony Cedrone, Stuart C. Hanebuth, *Members, IEEE*

***Abstract*— Utilities are often asked to investigate and determine the cause of elevated voltage in the urban environment. By understanding proper measurement techniques, how to interpret readings and the possible sources of the voltage, investigators can reach speedy and accurate conclusions and eliminate unwanted voltage.**

***Index Terms*—Contact Voltage, Electrical Safety, Power System harmonics, Stray Voltage**

I. Introduction

Utilities often investigate the cause of elevated voltage in the urban environment, and determine whether the condition is the result of stray or contact voltage. Stray voltage results from the normal delivery and/or use of electricity and generally does not require mitigation. Therefore it is not the focus of this paper.

Contact voltage results from abnormal power system conditions that may be present between two conductive surfaces that a person or animal can touch at the same time. Contact voltage is never related to normal system operation and is often from damaged insulation on phase conductors. Improperly connected customer or utility equipment can also cause contact voltage. Since contact voltage often involves phase conductors, it should be treated carefully because a low voltage level can rise to full-line voltage as the impedance of the conductive pathways changes.

These investigations are often straight forward, but at other times the cause of the elevated voltage is difficult to indentify. The process described herein is intended to help utility engineers quickly eliminate unlikely causes of elevated voltages and direct their troubleshooting to quickly determine the source.

It is important to remember that investigations of elevated voltage often do not directly involve street-level utility objects such as manholes or poles. In underground systems the vast majority of the events involve failures along the length of the cable that energizes other street-level assets such as sidewalks and fences. Investigators should understand that these events may energize multiple objects.

Some investigations may last several days, or be passed from one repair crew to another, or even between companies. That means utilities need a process that is repeatable between crews and organizations to maximize efficiency in troubleshooting. To streamline their investigative processes, organizations may develop their own investigative flow charts or modify those in the appendices and use them as the basis for their investigations. The authors recognize that every investigation is different and that not every step of the processes outlined will apply to every investigation.

II. Investigative Process

The objective of the investigation is to identify the source of the contact voltage, allowing the crew to repair the defective component as quickly as possible. Elevated voltage can be from a defect on either the line or neutral side of the circuit, so defects on both sides of the circuit should be considered suspect until measurements are taken to determine the exact cause. It is important to use proper measurement techniques to reach accurate conclusions.

A. Tools for Investigation of Elevated Voltage

1) Volt meter

A digital volt meter with an input impedance of greater than 1 Megaohm which is capable of making AC RMS measurements in the range of 0.1 volts to 600 volts is required for contact voltage investigations. Since volt meters measure only the difference in voltage between the two connections to the meter, it is important to understand exactly what is being measured. For example, connecting one lead to an object energized at 3 volts and the other lead to an object energized at 3.4 volts will result in the meter displaying a reading of 0.4 volts. Because of this method of operation, it is critical that one of the connections to the meter is made to a "ground" reference that is at zero potential. Connection to an energized reference will result in erroneous readings.

2) Shunt resistor

A resistor that is connected in parallel to the input of the volt meter, the shunt resistor is used primarily for eliminating induced or capacitively coupled voltage. This voltage may

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Stuart C. Hanebuth is with Power Survey Company, 25 Campus Drive, Kearny, NJ 07032 (phone: (973-474-4663; e-mail: shanebuth@powersurveyco.com)

David Kalokitis is with Power Survey Company, 25 Campus Drive, Kearny, NJ 07032

Anthony Cedrone is with Consolidated Edison Co. of NY, Inc., New York, NY 10003 USA

appear on an object but lacks the ability to source current and cause a shock. Common shunt resistor values include 500 Ohms, 3,000 Ohms and 10,000 Ohms. Higher impedance shunt resistors help minimize the impact of high-impedance contacts between probe tips and energized objects in the field. If induced voltage is not present, the shunt resistor provides little additional value in the investigation process and at times may make it more difficult to locate the source..

3) Pen-type tester, either contact or non-contact

Investigators use the pen tester to determine whether equipment is energized above a certain threshold. Pen testers have various "turn-on" voltage levels that should be characterized before introduction into a program. "Turn on" voltage levels range from 3 volts to greater than 100 volts. Pen type testers are not usable to confirm a ground reference is not energized. This is because the commonly used, and most sensitive, includes the technician's body in the measurement circuit. If the technician performing the test is standing on a surface that has an elevated voltage present the difference in voltage measured by the device is likely less than the "Turn on" voltage of the device.

4) Ground lead

A reliable ground lead of sufficient length is required to ensure that a suitable reference can be located and connected to the volt meter. Investigators commonly use leads of 50 to 150 feet during investigations in urban areas.

5) Handheld electric field detector

Handheld electric field detectors can measure electric fields that are radiated from energized objects. They often have displays that give a relative indication of field strength. During an investigation a handheld electric field detector helps a crew quickly find energized objects and can ensure that reference grounds are not energized.

6) Oscilloscope, power quality meter or other device capable of measuring total harmonic distortion

The total harmonic distortion (THD) of the voltage waveform of an energized object provides important information about the source of the voltage. A device that measures THD as a percentage of the fundamental operating frequency i.e. 60Hz in the U.S. is an important tool for investigators. Since the shunt resistors are linear loads, they have no impact on the harmonics content. Inserting the shunt resistor into the measurement circuit will only attenuate the signal and increase the measurement error. Therefore crews should take harmonics measurements without a shunt resistor in the circuit.

B. *Proper Measurements Techniques*

To confirm the finding, the crew must locate a reference ground with zero potential and low impedance to earth. That could be a fire hydrant, stand pipe, metal post or temporary driven ground or other object. The crew must confirm that the candidate ground has zero potential either by using an electric field meter, or by measuring with a high-impedance volt meter against additional candidate grounds. Next, investigators use the high- impedance volt meter to measure the voltage between the ground and the energized object. If the reading is greater than the predefined threshold, typically 1 V_{ac}, the crew repeats the measurement, using an appropriate value shunt resistor, ideally connected through a push button. The push button allows selective engagement of the shunt resistor without disturbing measurement contact points. If the reading is still greater than the predefined threshold, 1 V_{ac} for example, when the shunt is engaged, the object is recorded as detection. If the voltage drops significantly when the shunt is engaged, the crew should select an alternate ground and repeat the process. This step ensures a low-impedance ground reference and preserves measurement accuracy. Variations in technique in this process can cause significant errors. This is because selecting a ground that is energized or has high earth impedance could result in the failure to validate detection, since the volt meter is measuring the difference in potential between the object that is selected as the ground and the energized object [1].

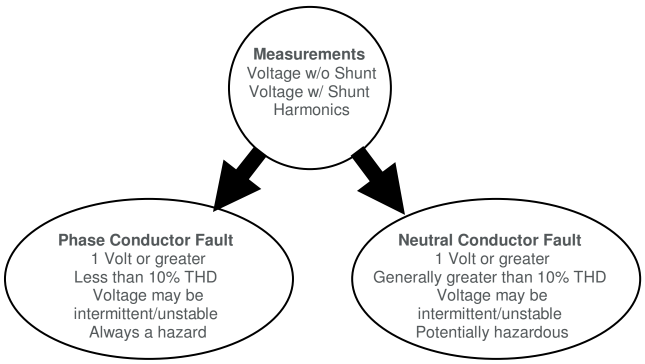
C. *General Investigative Process*

The investigative process begins with a report of elevated voltage. That report may have come from a crew conducting a periodic testing program, a crew that made a detection during routine work activities, or from a member of the public who reported a shock. The investigator's job is to determine the exact component on the power system that is causing the elevated voltage, whether it stray or contact voltage, and the right actions to take to eliminate the voltage.

Without the aid of advanced diagnostic tools such as an oscilloscope capable of analyzing total harmonic distortion, investigators may rely on basic information from a volt meter and shunt resistor. Prior to the development of techniques that use harmonics, investigators would begin their investigation by disconnecting the most likely source of the voltage and re-measuring the voltage on the object. They would repeat this process until the voltage was eliminated.

With the introduction of harmonics analysis, the investigative process begins with a measurement that often helps to eliminate one possible source of the elevated voltage. For objects with greater than 10 % total harmonic distortion investigators should look for defects associated with damaged or defective neutral conductors. For objects with less than 10% THD investigators should focus on defects associated with phase conductors. [2-3]

The voltage and harmonics measurements together can help investigators categorize the source of elevated voltage. The figure below relates the possible sources and their characteristics. An open or high-impedance neutral conductor is also labeled a fault.



D. Sources of Elevated Voltage

Contact voltage is sourced from either the line side (also known as the phase side), or the neutral side (also known as the return side) of a circuit. Investigators often focus on the line- side sources without considering possible sources on the neutral conductors and connections. It is important to consider and evaluate both to ensure cost-effective, timely repairs.

1) Line-side (Phase) sources

Most line-side sources, which normally have a total harmonic distortion of less than 10%, are easily identified by the isolation of a section of cable. Investigators often report finding abandoned cables with improperly sealed ends, improperly insulated split bolt connectors, defective cable insulation and reversed phase and neutral conductors as the causes of these contact voltage cases. These conditions can exist in utility-owned infrastructure such as manholes, vaults and conduits, municipally-owned infrastructure such as streetlights, or customer-owned equipment. Line-side sources of contact voltage are the most dangerous because even if voltage is detected at a low level the voltage has the potential to rise to full-line voltage.

2) Neutral (Return) sources

Open or high-impedance neutrals may be the source of elevated voltage and in some cases capable of sourcing enough current to cause harm. The voltage from high-impedance neutrals is a result of current flowing through that impedance. As a result the voltage that is measured is a function of the load on the cable. In addition to electric shock reports and contact voltage detections these defects may result in customer voltage complaints and reports by cable TV crews of current on their cables.

When troubleshooting cases where the THD is greater than 10% investigators should first inspect neutral connections and ensure that they are not loose or corroded and that the neutral is carrying the appropriate amount of current compared to the phase line.

Investigators should also be aware of the relationship between the current and voltage. Otherwise, they may accidently address the problem when they disconnect the service line, note that the voltage has been eliminated and order a replacement of the service. The replacement would likely fix the problem because it replaces both the phase and neutral conductors. But it also will result in the installation of new connections on both ends of the neutral line which may have been the cause of the elevated voltage. Thus, the elevated voltage could have been eliminated by simply remaking the connection and not replacing the cable.

E. Asset-Specific Troubleshooting

Since the troubleshooting process for each type of energized object varies the authors have divided the troubleshooting process into five main groups:

- Electric shock reports
- Objects other than streetlights that are directly fed by the utility
- Objects are not directly fed by utility supply
- Street and traffic lights
- Utility objects (i.e. manholes, service boxes and vaults)

For each group an investigative flow chart has been developed to aid in the elimination of defects that could be causing the elevated voltage.

1) Electric Shock Reports

The objective of the investigation into an electric shock report is to locate and categorize the energized object(s) so that further troubleshooting can eliminate the elevated voltage. These investigations can be difficult because of incomplete information from the public or first responders and delays in reporting. The general investigative strategy is shown in Appendix A.

The first step is to determine whether the shock was the result of an object that is normally energized, such as an overhead wire. Utilities receive shock reports from the public which were the result of customers making contact with overhead wires or other conductors that are normally energized. These reports are not cases of contact voltage, since most utilities have processes for investigating these reports, and since they are not the result of defective equipment this type of report is not covered in this document. After the elimination of normally energized sources, the next step is to validate the claim of the electric shock.

This process often involves testing the object or objects that caused the shock. Investigators can often accomplish this using a low-voltage pen-type tester or handheld electric field detector. If either device indicates the presence of voltage, investigators should use a multi-meter to make a voltage measurement, followed by a harmonics measurement, if available. When a specific object is cited as the source of a shock, investigators should use a volt meter to confirm voltage conditions on that object referenced to a qualified ground. Once the voltage on the object has been confirmed investigators can continue the troubleshooting process by following the appropriate flow chart.

The voltage reading may be below what is normally considered a level for human perception, and yet the object delivered a detectable shock. This is because the voltage level from a line-side fault can change as conditions around the fault change.

If the report cannot be confirmed, investigators should consider variables such as the time of day, the weather and the system load and retest, if appropriate. The authors discuss these variables in further detail in section IV.

2) Objects that are directly fed by the utility

For energized objects that are directly supplied by the utility, such as illuminated bus stops, kiosks, etc., the first step in the troubleshooting process is to measure the THD to help determine the possible source. The general investigative strategy is shown in Appendix B.

If the THD is greater than 10% the source of the elevated voltage is most likely associated with a neutral, either on the customer side of the meter or on the utility side of the meter. If a neutral issue is suspected current readings on the neutral and ground connections at the meter and at the service box may provide useful information. If there is more current on the customer side, then a high-impedance neutral or neutral connection is likely.

Disconnecting the load at the main circuit breaker is a simple and effective way to determine if line-side faults are the responsibility of the utility or the customer. But it's important to make sure that the elimination of the voltage is not due to the reduction in the load. If disconnecting the loads using a main breaker does not eliminate the voltage then the elevated voltage is likely being caused by a defective service wire. Continue by disconnecting the service wire and re-testing for voltage. If the voltage is eliminated, the service should be replaced. If this does not eliminate the voltage then the source is not associated with the service and other sources should be considered. They may include other nearby mains and services, current circulating on other utility lines such as cable TV shields, signaling systems for transit systems, etc.

3) Objects that are not directly fed by the utility

When voltage appears on objects such as sidewalks, roadways and fences, harmonics measurements can help determine a starting point for the investigation. Investigators may also choose to use a volt meter without a shunt resistor to determine where the highest voltage can be measured. They can then center their investigation on this location.

Investigators should consider facilities that cross under the energized object. Isolation of these facilities is helpful in determining their relationship to the source of the voltage.

Often the most difficult cases to resolve are those with harmonic content greater than 10% THD. These cases generally involve high-impedance neutrals in service or main conductors. As a result of the high-impedance conductor return currents flow through a variety of metallic and non-metallic objects including fences, sidewalks and cable television shields. In these instances it helps to search for points on the neutral system that are at the same potential as the energized object, or that have the same harmonic content as the energized object.

For example, if voltage on a cable TV shield measures 3 volts to a remote ground and zero volts to the service neutral inside of a nearby house, a logical next step would be to measure the current on the neutral at the house and the current flow at the point where the service connects to the system. If they are significantly different there may be high impedance in the service neutral. If there is not a significant difference the investigator would repeat this process until determining the cause of the elevated voltage.

4) Street and traffic lights

Investigations of elevated voltage on street and traffic lights are similar to investigations involving other objects that are directly fed by the utility. The slight difference is that often no circuit breaker is present at the interface between the light and the utility. The general investigative strategy is shown in Appendix D.

When investigating cases where the THD is greater than 10%, the investigator should also consider that the voltage may not be a result of a high-impedance streetlight neutral. Instead, it may be the result of a high-impedance neutral somewhere else in the electric distribution system. Metallic streetlighting standards are frequently connected to service neutrals. Because the standards are also grounded, either via driven grounds or through the mounting hardware, current from the system neutrals can flow to the streetlight ground. Investigators are often able to measure voltage as a result of this phenomenon. In this case the mitigation efforts will revolve around identifying the high- impedance component in the electrical system and making the repairs, which may be some distance from the light.

5) Utility objects (Manhole covers, etc.)

These investigations are often quite straight-forward. In many instances, a defective cable, or other piece of equipment is found inside a utility structure or on a pole and the event is quickly mitigated. The general investigative strategy for these types of objects is in Appendix E.

Using the voltage and harmonics measurements, investigators will generally find cable with defective insulation generating contact voltage with low harmonic distortion or high-impedance neutral connections generating contact voltage with high harmonic distortion. In cases where a detailed inspection does not reveal either of these types of defect, investigators should consider other conductive objects as the possible route of the voltage into the structure. Cases have been reported where the actual fault was in a structure more than 50 feet away and the metallic conduit connecting the two structures acted as the conductive pathway.

Investigators may also consider electric cables in conduits that are in the ground near the cover, but not routed through the structure. Since the metallic cover is often the only object that is tested it is possible that the ground surface around the structure has been energized from a nearby secondary cable fault, and measured on the metallic cover. Isolation of these cables may eliminate the elevated voltage.

III. Considerations when Previously Reported Voltage Cannot be Found

Sometimes investigators arriving at the location of a previously reported detection are unable to measure voltage at that location. Because of the nature of these events it is possible that the condition has temporarily eliminated itself. Before recording the event as unsubstantiated, investigators should evaluate the effect of factors such as system load, reference grounds, time of day, weather and other conditions that may be impacting the area.

A. Effects of Different References

As discussed previously, using different references as a ground can cause significant differences in voltage measurement, since volt meters measure the difference between the two inputs. When possible, investigators should use the same reference for the initial and subsequent voltage measurements. If investigators cannot use the same reference that was used for the initial reading and can't measure the previously reported voltage they should ensure that the new reference is not energized and consider repeating the measurement from other acceptable grounds before leaving the location.

B. Time of Day

When investigators cannot measure previously reported voltage, they should consider the time of day that the initial reading was taken. For example if the initial reading was taken when it was dark, investigators should inspect the area for lights or other equipment operated by photocells or timers. Investigators should also consider the current load at the time of the initial and subsequent readings, as discussed below.

C. Effects of System Load

The voltage associated with high-impedance neutrals is a function of the current that is traveling through the high-impedance portion of the circuit. If the initial readings are taken when the load on the neutral is high and subsequent readings are taken when the load is low, the voltage will be proportionally lower or even zero. If the investigators suspect a high-impedance neutral and are unable to measure a previously recorded voltage, they should consider changes in load between the time of the initial reading and the subsequent investigation.

D. Effects of Weather

Weather, particularly precipitation, can play a significant role in the voltage level. Precipitation can reduce the impedance of the conductive pathway to the surface, causing the voltage to increase. When that water evaporates or drains away, the impedance increases and the voltage may disappear. For this reason investigators should consider the weather conditions that existed during the initial detection. If they cannot detect the voltage, they should consider revisiting the location when the weather conditions are similar to those of the initial measurement.

IV. Recordkeeping

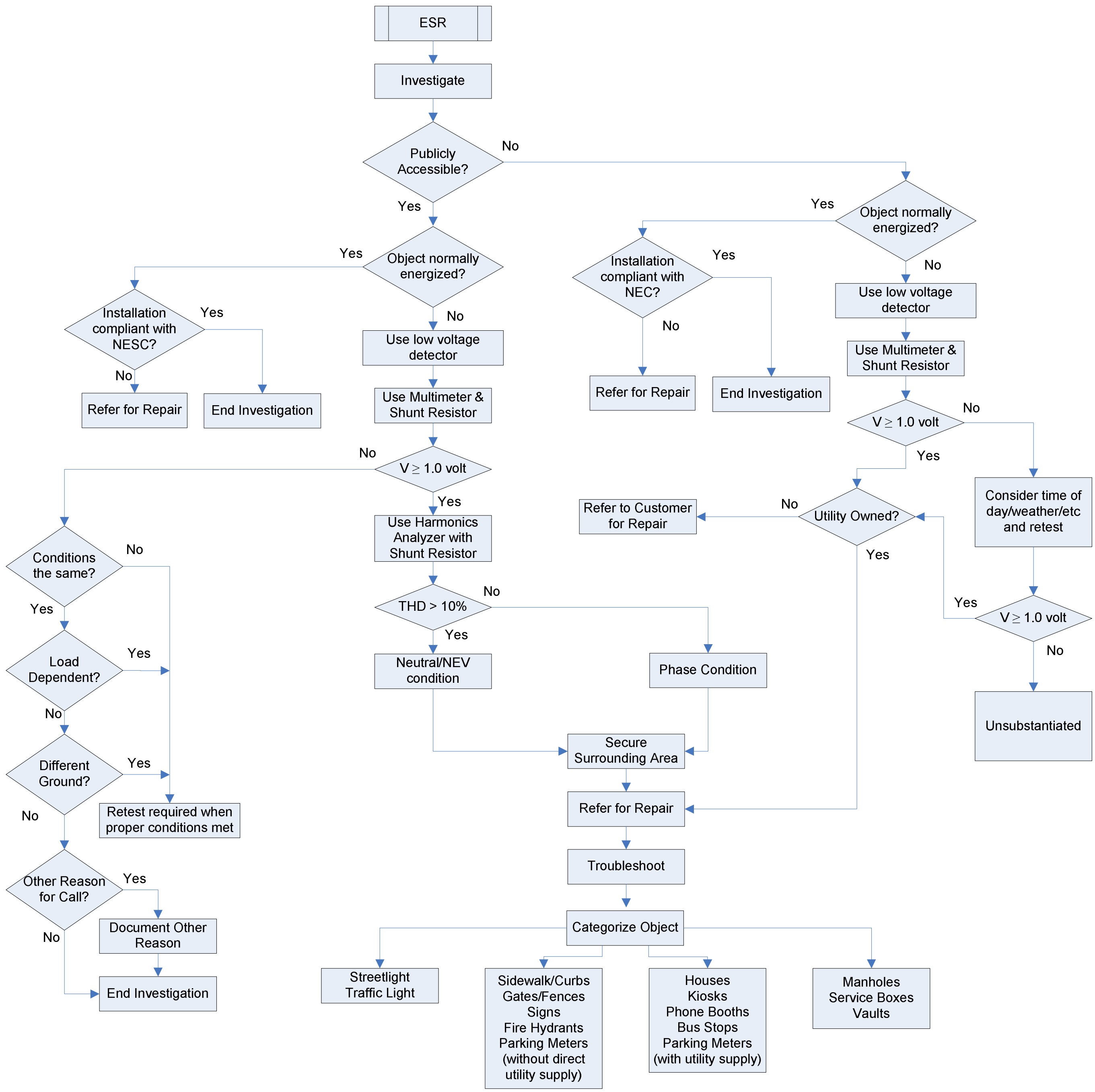
Each detection and subsequent mitigation offers insights into system performance, risk and repair practices. Collecting this data in a meaningful database can help utilities spot trends, improve processes and identify underperforming components. A standard collection of data across a number of organizations would enable a broader and more detailed analysis of the topic of contact voltage.

Some of the data fields that have proven useful in the development of the attached flowcharts and other analysis that have been previously published include: date, location, voltage and harmonic levels, ground connection point, shunt resistor value, etc.

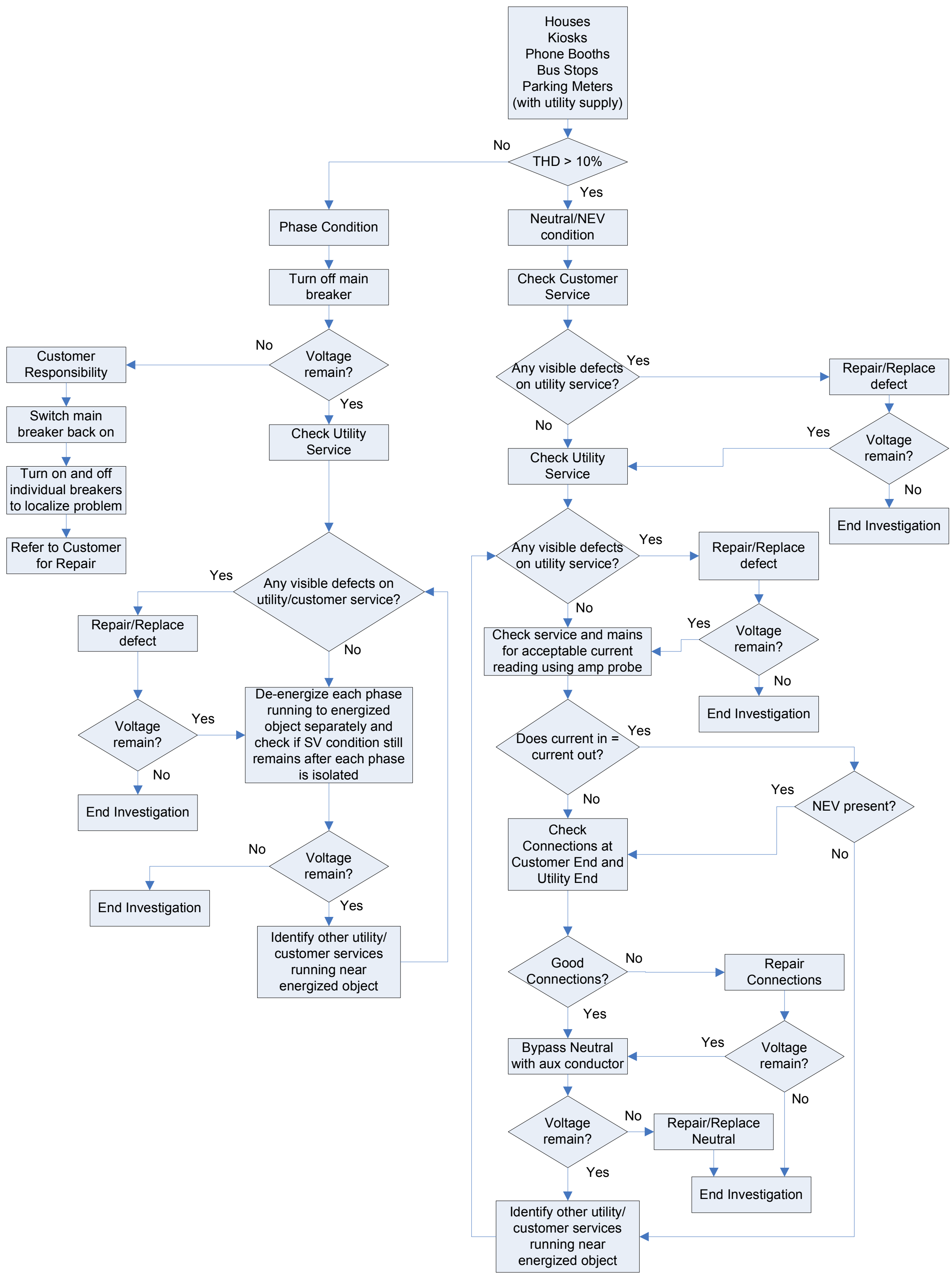
V. Conclusions

Mitigating contact voltage is challenging. Since many surfaces in the public landscape are conductive, isolating the exact source requires methodical troubleshooting. When proper steps are taken to perform accurate voltage and harmonic measurements against qualified ground references, the process is simplified. The flowcharts provided in the appendices will aid both the experienced and novice investigator achieve an accurate diagnosis.

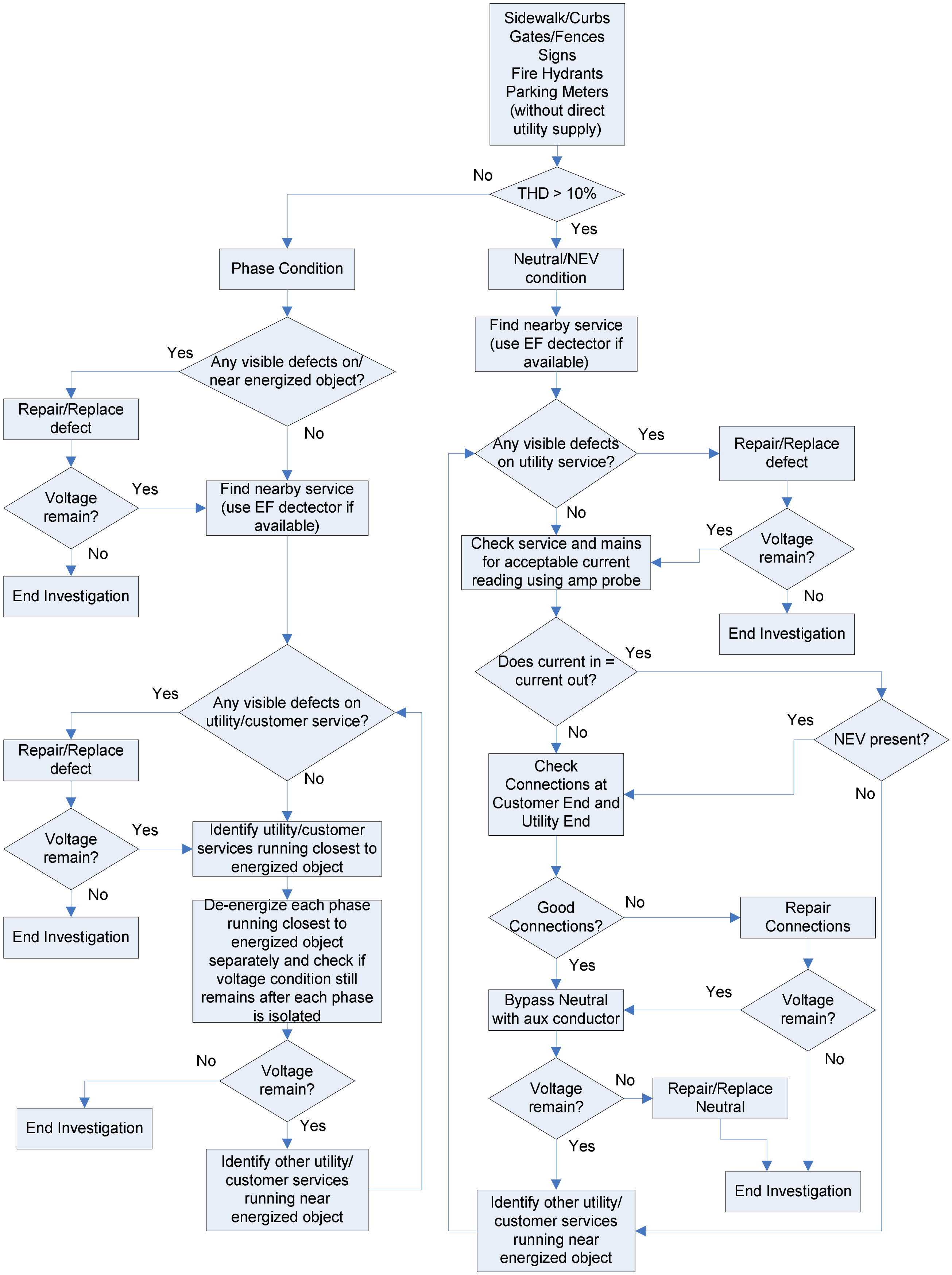
Appendix A – Electric Shock Report (ESR) Investigation Process



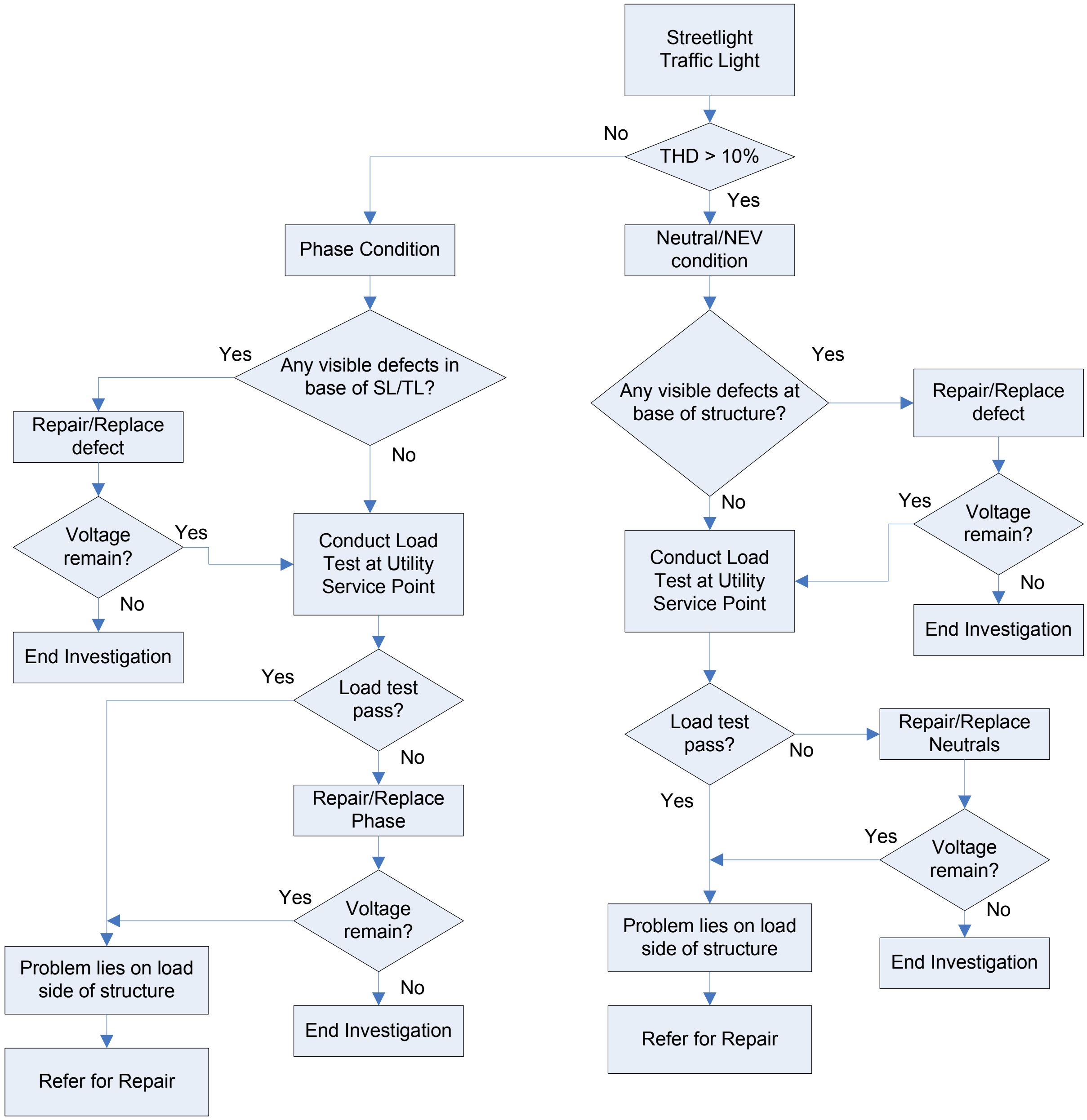
Appendix B – Investigation Process for Energized Objects which are Directly Fed by the Electric Utility



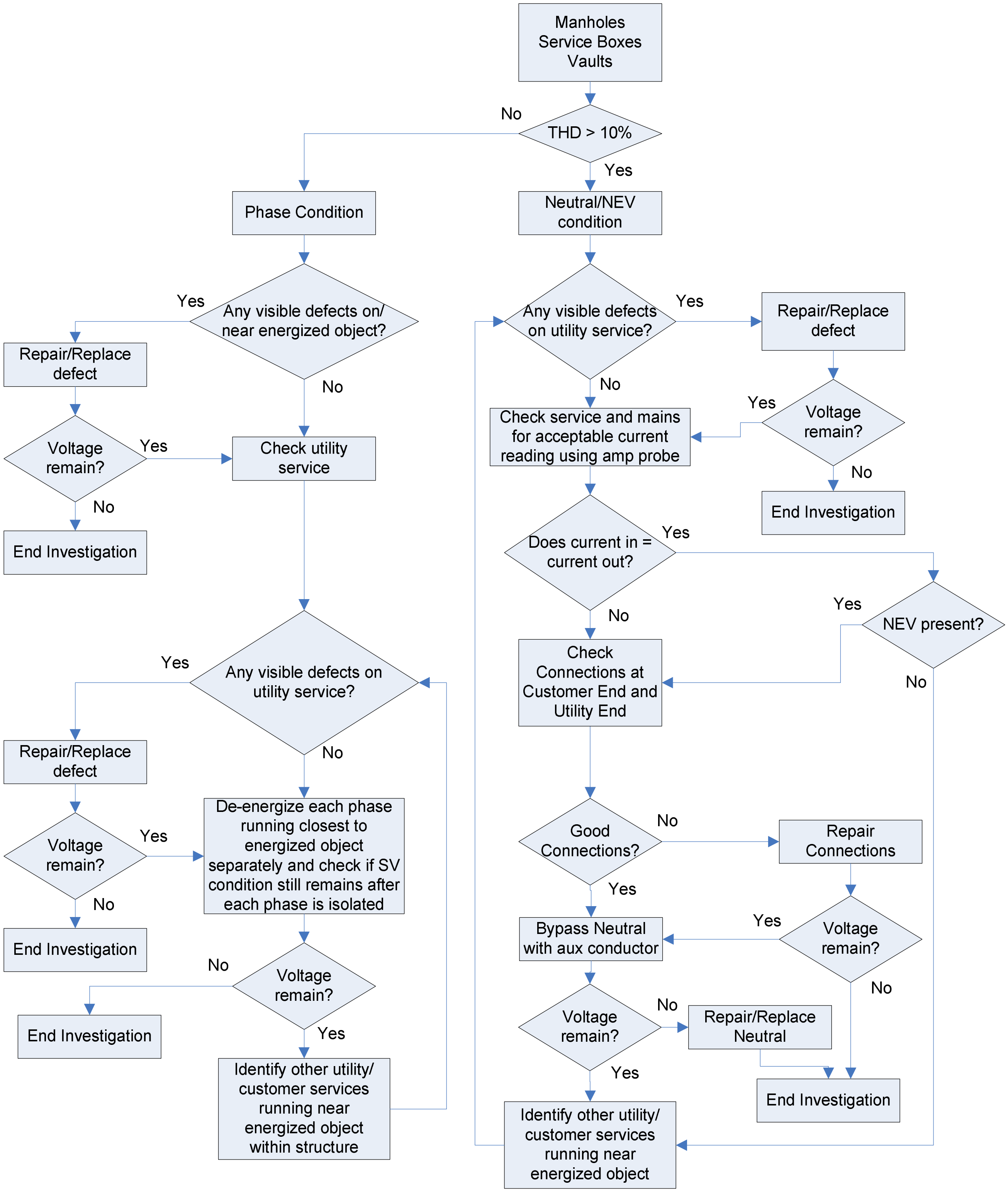
APPENDIX C – INVESTIGATION PROCESS FOR ENERGIZED OBJECTS WHICH ARE NOT DIRECTLY FED BY THE ELECTRIC UTILITY



APPENDIX D – INVESTIGATION PROCESS FOR STREET AND TRAFFIC LIGHTS



APPENDIX E – INVESTIGATION PROCESS FOR UTILITY STRUCTURES



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Stuart C. Hanebuth (M'2010) Stuart was born in St. Paul Minnesota and he earned a B.S. from Rutgers University, New Brunswick, NJ in 1996

He is currently the Vice President of Business Development at Power Survey Company in Kearny, NJ. He has worked in the utility industry for more than 15 years in a variety of positions. He was responsible for the oversight of the public safety programs at Consolidated Edison Co. of New York. He has also managed operations and maintenance in a wide variety of transmission and distributions areas.

Mr. Hanebuth is an active member of the IEEE P-1695 Working Group on Voltages at Publically and Privately Accessible Locations and has written several papers on topics associated with Contact Voltage and Public Safety. He has been recognized several times for his innovative contributions in the utility field, including twice by EPRI for moving R&D projects into operational programs.

Anthony Cedrone (M'2010) Anthony was born in The Bronx, N.Y. and earned a B.E. from Steven's Institute in Hoboken, N.J. in 2001 and an MSEE from Manhattan College, in the Bronx in 2011.

He is the Manager of the Public Safety Programs Group at Consolidated Edison Co. of New York where he is responsible for the execution of many of the Company's public safety programs.

Mr. Cedrone is an active member of the IEEE P-1695 Working Group on Voltages at Publically and Privately Accessible Locations

David Kalokitis (M'83 – SM'04) David was born in Paterson N.J. and earned the BS degree in Electronics Eng. Tech. from Trenton State College, Trenton, N.J. in 1983 and the MSEE degree from Monmouth University, West Long Branch, N.J. in 1990.

He is Chief Technology Officer at Power Survey LLC in Kearny N.J. Prior to forming Power Survey, he spent 25 years in Microwave research and development at Sarnoff Corporation (formerly RCA Laboratories) in Princeton N.J.

Mr. Kalokitis is an active member of the IEEE P-1695 Working Group on Voltages at Publically and Privately Accessible Locations, and a frequent lecturer on the topic of Contact voltage at various conferences and symposia.

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