IEEE 342-Node Low Voltage Networked Test System

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***Abstract*— The IEEE Distribution Test Feeders provide a benchmark for new algorithms to the distribution analysis community. The low voltage network test feeder represents a moderate size urban system that is unbalanced and highly networked. This is the first distribution test feeder developed by the IEEE that contains unbalanced networked components. The 342-node Low Voltage Networked Test System includes many elements that may be found in a networked system: multiple 13.2kV primary feeders, network protectors, a 120/208V grid network, and multiple 277/480V spot networks. This paper presents a brief review of the history of low voltage networks and how they evolved into the modern systems. This paper will then present a description of the 342-Node IEEE Low Voltage Network Test System and power flow results.**

***Index Terms*-- distribution, test feeder, unbalanced simulation model, power distribution system analysis**

I. Introduction

The majority of end-use customers in North America are served by radially operated distribution feeders that provide a high level of reliability for a moderate cost [1]. In areas where there is a high load density and a need for very high reliability, Low Voltage Networks (LVN) are sometimes built at a substantially higher cost. LVNs connect the end-use customers to an underground grid network that is supplied by multiple distribution feeders through step-down transformers. As a result of this design, the failure of one or more of the primary distribution feeders, or multiple transformers, will not generally result in the loss of service to any end-use customers. Because of the high cost of construction, and operation, of LVNs they have only been built in dense urban cores.

The Test Feeders Working Group (WG), under the Distribution System Analysis (DSA) Subcommittee and its parent Power Systems Analysis, Computing, and Economics (PSACE) Committee, has published numerous test systems and made these available [2]. Currently all of the published test systems are radial in operation and do not provide the distribution analysis community with a test system to evaluate new algorithms on networked unbalanced systems [3].

With the proliferation of many new smart grid technologies, new methods of distribution analysis are continually being developed. While some of these appear to work well for the radial test cases that exist, it is often difficult to judge whether new methods will extend to heavily meshed or networked systems. The purpose of the 342-node Low Voltage Networked Test System (LVNTS) is to provide a benchmark for researchers who want to evaluate if new algorithms generalize to non-radial distribution systems. The LVNTS has been designed to present challenges to distribution system analysis software in the following areas:

1. Heavily meshed and networked systems.
2. Systems with numerous parallel transformers
3. Modeling of parallel low voltage cables

The rest of this paper is organized as follows: Section II gives a brief history of LVNs and discusses how the early Direct Current (DC) Edison-type networks evolved into the modern Alternating Current (AC) networks. Section III presents the LVNTS in detail, including key pieces of equipment. Section IV gives the power flow solution for two operational cases and discusses simulation performance. Section V contains the summary remarks and future plans for distribution-level networked test systems.

II. Brief History of Low Voltage Networks

In the 1800s, the first applications for electricity were primarily in the areas of telegraphy and electroplating [4]. While both industries provided societal benefits, neither required a distribution system. It was not until the 1870's when arc lamps were used for street lighting that the first electrical distribution systems were developed. These early distribution systems were completely isolated and used dynamos to supply a single customer class: lighting. The first distribution system able to support multiple load types was not energized until 1882 when Thomas Edison's DC Pearl Street station went into operation [5].

A. Early DC Networks

At 257 Pearl Street, the Edison Electric Illuminating Company of New York had six 100kW dynamos driven by coal-fired steam reciprocating engines that supplied up to 7200 electric lamps [6]. Initially Pearl Street station distributed the 110V DC it generated through a two-wire system, but was soon upgraded to a 220V DC system to reduce costs associated with losses. The network area was able to reach nearly 1300 buildings and provide lighting to over 500 end-use customers [5]. Each of the components of

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the system had to be designed by Thomas Edison and his team because there was no existing commercial base. One invention that made commercial distribution possible was the electrochemical meter. A zinc solution was deposited from one plate to another in a precise electrolytic cell as current passed through it. The difference in weights was measured and the user was charged 1.2 cents per lamp-hour consumed. With this DC distribution system, Pearl Street station provided uninterrupted power to its end-use customers for all but three hours from September 4, 1882 up to January 2, 1890 when the station was damaged in a fire. This operating recorded showed the reliability of networked systems.

Soon after Pearl Street was operational, Edison's low-voltage DC system design was implemented in other cities [6]. The reliability of these networks was further increased when storage batteries were introduced into distribution systems to smooth out load and provide backup to the dynamos [7]. However, as DC networks grew they encountered many problems with regulation and overloading [8]. As more end-use electrical devices were invented, the load on the system grew tremendously. By the 1920's, many of the storage battery banks could only provide backup for 20 minutes which no longer provided a suitable backup for the dynamos. At the same time, alternating current systems were being advanced by the Westinghouse Electric and Manufacturing Company and its subsidiaries [9].

B. The First AC Networks

The first AC systems were radially constructed for the transmission of power over long distances. While these systems were ideal for long distance transmission, there were less suited for dense urban areas. The radial AC systems were only able to provide the voltage regulation of DC networks at a considerable expense and separate mains were required to supply both lighting and power loads [8]. Additionally, the AC systems did not have the reliability provided by batteries, and also had the added complication of reactive power considerations [9]. For these reasons, many believed that AC distribution would never be able to supply the dense load areas that were supplied by the DC networks [10]. However, the advantages of transformers and the potential savings in eliminating DC storage batteries drove many different companies across the United States to attempt an AC replacement.

Similar to the DC networks they would replace, the AC networks were placed in underground conduits beneath city streets [8]. Initially, primary distribution networks were experimented with and they achieved increased reliability, but they were not cost effective in most areas [8]. Low voltage networks were the ideal solution and National Electric Light Association declared in 1925 "any alternating-current installation should be called a network where transformers located on different premises have their secondaries tied together." [8]

One of the first attempts at a low voltage network was in Peoria, Illinois [8]. It was built around 1915 and was designed as three separate meshes, one for each phase. There is no indication that any protection equipment was included or needed. However, due to large voltage drops at the edges of the network, the system required additional primary feeder and transformers. Eventually the design proved not to be cost effective when scaled up to a larger network.

Other attempts at building networks were using banked transformers to address voltage drop issues [11]. Banking transformers had the advantage of minimizing voltage flickering due to motor starting currents and also prevented transformer overload by adding additional capacity to the circuit. In the Bronx, New York, a successful system used a primary mesh system with banked transformers [8]. However, banked transformers were abandoned by many cities due to fuse reliability. At the time, fuse construction was not consistent and were often considered a reliability issue in system designs.

C. Development of the Network Protector and Early AC Networks

None of the first AC systems were able to provide cost effective service that was as reliable as a DC network, or with equal voltage regulation. However, in 1921 the Puget Sound Power & Light Company designed a new AC system that was an underground network of transformers supplied from a secondary network. The secondary network was supplied by multiple primary feeders radially extending out from the substation. This design was possible because the Puget Sound Power & Electric had built the first three-phase combined light and power network that was protected with a new device called a network protector, instead of fuses [8]. This system was built in Seattle, Washington.

The Seattle network protector was a specially designed oil circuit breaker placed downstream of the primary feeder transformer secondary windings. The network protector would automatically isolate the transformer from the secondary network by opening on reverse power. Reverse flows as small as the charging of a transformer primary would cause the network protectors to operate. As a result, the network protectors would only operate if there was a fault on the primary feeders, not on the secondary systems. The upstream side of the primary feeder would then be isolated by a cutout fuse if a fault developed on a primary lateral or by the substation circuit breaker if the fault was on the main part of the feeder [8]. This allowed the system to have a secondary grid network that was supplied by multiple radial primary feeders. The secondary grid network was then protected by fuses at each service box where customer loads were connected.

By using multiple feeders, the Seattle network had significant advantages over all previous AC system designs. The Seattle system provided the voltage regulation using banked transformers and had the increased reliability of multiple feeders. The network also provided better efficiencies compared to a DC network [12]. However, there was still room for improvement. The network protectors needed to be manually closed after tripping open and there were still a large number of fuses in the system [8]. During major faults or repairs, significant time was spent to access each vault to reclose each of the network protectors. The requirement for manual closure also prevented the reliability of the network from reaching that of a DC network.

D. Modern Low Voltage Network Systems

In 1922, the United Electric Light & Power Company of New York energized the first modern AC low voltage network [13]. The network had 29 network protectors and was fed by four primary distribution feeders. The system took ten years to develop and was the only AC network design to compete with DC networks [8]. To be competitive, the team of engineers at United Electric Light & Power Company, led by Arthur Kehoe, had to build an AC network that was as reliable as DC networks with the same voltage regulation capabilities. At the same time they wanted to build an AC network that combined light and power loads on a single set of mains.

The New York network was different from all of the previous AC networks in several ways. First, the network protectors were a completely new design. The New York network used air circuit breakers instead of oil to make the network protectors smaller [8]. They still had reverse power relays like the Seattle network, but they also had the ability to automatically reclose when power was restored. The ability to automatically disconnect and reconnect transformers improved reliability, shortened the time for maintenance, and allowed for the utility to disconnect feeders during low load periods [13]. Automatic operation enabled, for the first time, an AC network that was as reliable as a DC network.

A second significant different of the New York System was in the protection of the secondary network. Like Seattle, the network protector served as the main protective device of the network, with a set of fuses serving only as a backup to network protector failures. For faults in the secondary network, it was calculated that cable faults would naturally burn-off the cable and self-isolate [13]. With the principle of burn-off, the team decided to not install any fuses in the secondary network. By removing fuses and their associated panels, the New York network became even more cost effective. The system they designed not only became the standard model for future AC networks, but it also earned Arthur Kehoe a Lamme Medal from the American institute of Electrical Engineer in 1943 [14].

Soon after the United Electric Power & Light Company completed its network in New York, other cities started to build similar AC networks. New Orleans became the first city to replace a DC network with an AC network modeled after the New York design [8]. This was largely in part due to W. R. Bullard, one of the lead engineers on the New Orleans network, being a former colleague of Arthur Kehoe [15]. The New Orleans network also displayed, for the first time, a direct cost comparison of various AC distribution designs. The calculations clearly showed that a higher medium voltage AC primary, with low voltage network secondary, would be the most cost effective system [16]. At the same time, in Philadelphia a different type of AC network was also being built, but was not complete until the 1930's [17]. Despite other attempts, it was the New York design that became the standard.

As other cities started to build AC networks, a new challenge occurred. There was no standard secondary voltage for the networks. One of the cost effective attributes of AC networks was the ability to have light and power loads on the same system. However, motors at the time were designed for 240V and lighting was designed for 120V. T The problem was that no three-phase system could provide both. Various voltages were championed by different engineers and some even had different numbers of phases in their designs [15]. The two most common voltage pairs, 208/120V and 199/115V could still be found as competing solutions in industry handbooks into the 1950's [16], [19]. However, at the time no industry handbooks were available that discussed low voltage networks. Instead, periodic journals of the era had detailed articles on the construction of AC networks, and they were the primary references for engineers [20]. Today, AC networks are known as grid or distributed networks and they have a standard voltages of 120/208V or 277/480V [8], [11].

By the 1970's, networks had become more standardized. In high density areas, 120/208V grid networks were used and 277/280V spot networks were constructed to power large load centers [18], [21]. Utilities such as Consolidated Edison in New York had also developed evaluation methods to determine the best design options for new customers [22]. In the 1980's, utilities explored installing new advanced sensors into low voltage networks [23]. With these new sensors, some utilities started to add more monitoring and control systems like Supervisory Control And Data Acquisition (SCADA) to their networks [24]. Present day networks use more advanced versions of the same technologies [25]. New network protectors perform the same operations as the original New York protectors, but now they use microprocessors instead of electromechanical relays and are usually attached directly to the transformer to minimize the distance between the network protector and the transformer [26]. Although many of these communication and sensing technologies are no longer new, as many as a third of network operating utilities still do not monitor their networks, in real time, downstream of the substation [27].

Currently in North America, approximately 80 cities operate LVNs of some form. Some of these are only 120/208V grids, while others are combinations of 120/208V grids and 277/480V spot networks. In either case, these systems are expensive to build and operate, but the reliability that they provide far exceeds that of radial distribution feeders.

III. The 342-Node Low Voltage Network Test System (LVNTS) Description

The computational challenges of LVNs are significantly different from the more common radial distribution feeder because the grid network is supplied by multiple radial distribution feeders. To provide a benchmark of analysis for LVNs, the LVNTS has been developed by the Test Feeder Working Group of the Distribution Analysis Subcommittee.

The 342-node LVNTS contains 150 delta-connected primary nodes and 192 grounded-wye secondary node. In contrast to existing test feeders, the LVNTS is a highly meshed system with unbalanced loads. The LVNTS is supplied by a 230kV substation containing two 50 MVA 230/13.2kV step-down transformers supplying eight radial 13.2 kV primary feeders. These eight primary feeders supply a single 120/208V grid system and eight 277/480V spot networks via 68 delta/grounded-wye transformers. The grid network and spot networks are grounded-wye systems. The total load on the system is approximately 50 MVA and is represented as both wye- and delta- connected constant power loads. Fig. 1 shows a one-line diagram of the LVNTS.

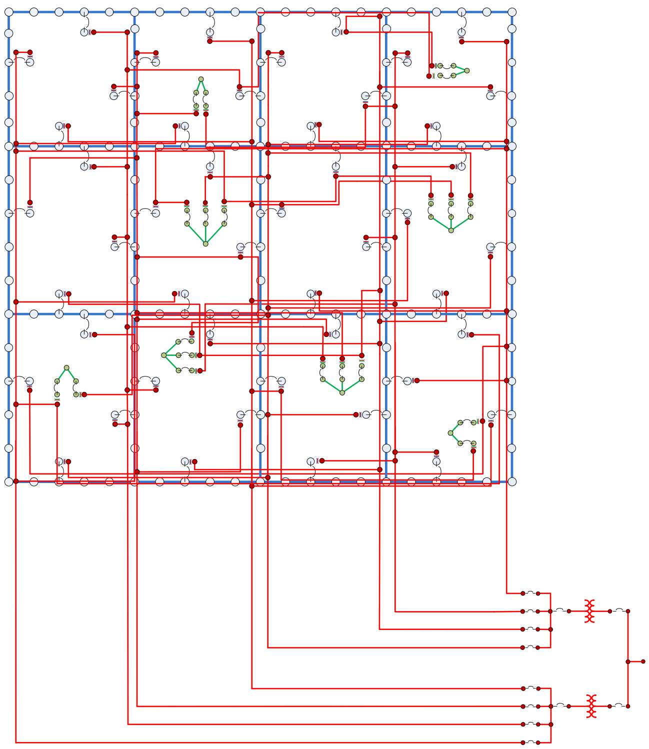

Fig. 1: One-Line Diagram of the 342-Node LVNTS

A. *Transmission 230 kV*

The LVNTS contains a small portion of the 230kV overhead transmission system that supplies the two 50 MVA delta-delta connected step-down transformers at the substation. Because there are no voltage control devices in the LVNTS, it is assumed that the voltage at the swing node will be on the high end of the allowable voltage range. The swing node voltage is assumed to be a balanced source with a line-to-neutral voltage of 139,429.97V, which corresponds to a line-to-line voltage of 241,499.84V.

B. *Primary Feeders*

The LVNTS contains eight radial primary distribution feeders supplied by two substation transformers on two buses. All eight feeders use a concentric neutral underground cable. The eight primary feeders are delta connected and their only loads are the 68 grid network and the 8 spot network transformers.

C. *Grid Network*

The LVNTS contains a single grounded-wye grid network operating at 120/208V. The Grid network is supplied by the eight primary distribution feeders through 48 1,000 kVA transformers. The eight primary feeders' feed the grid network, via 1,000 kVA transformers, though an interlaced pattern where no single primary feeder supplies adjacent transformers. This ensures that if a feeder is lost, the voltage in one region will not drop excessively. This will be examined in more detail in Section IV-B.

D. *Spot Networks*

The LVNTS contains eight grounded-wye spot networks operating at 277/480 V. The eight spot networks are supplied by the eight primary distribution feeders through 20 transformers. Each spot network is supplied by 2-3 transformers, each from a different primary feeder. The spot networks transformers range from 1,500 kVA to 2,500 kVA.

IV. Power Flow Solutions and Performance

One of the reasons that the reliability of networked systems is so high is that it is possible to lose one, or more, primary feeders without interrupting service to the end-use customers. For this reason the LVNTS will be examined under two cases.

A. *Case 1: Normal Operation-All Feeders in Service*

Under normal operation, all eight of the primary distribution feeders are in operation. With all eight of the feeders in operation, the voltage profile on the grid network can be seen in Fig 2. The voltages on the spot network nodes are similar.

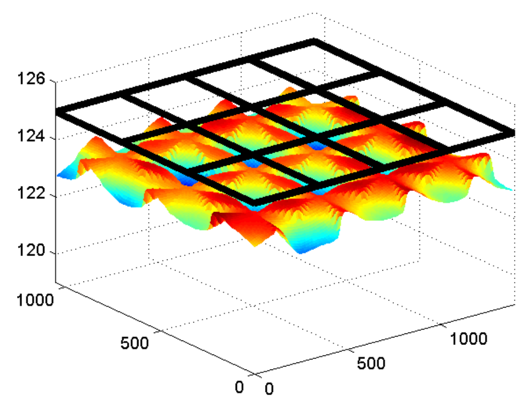

Fig. 2: Case 1 grid network voltage surface

B. *Case 2: Feeder 6 Out of Service*

If the supply breaker to any feeder is opened, reserve currents will cause all of the associated network protectors on that feeder to open on reverse current, and completely isolate the feeder. When feeder 6 is removed from operation, the grid network loses seven 1,000 kVA transformers and spot networks 1 and 6 each lose a single transformer. The loss of the seven network transformer causes greater voltage drops in the grid network, shown in Fig. 3. However due to the interlaced design, no voltages go below the ANSI C84.1 Range A guidelines [10]. Additionally, overloads are experienced in multiple locations on both transformers and cables. The maximum overloads do not exceed 126%.

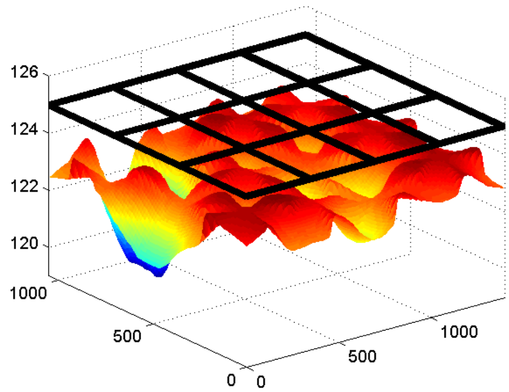

Fig. 3: Case 2 grid network voltage surface

C. Performance

Both Case 1 and Case 2 were initially modeled in the GridLAB-D simulation environment [28] and run on a Dell Latitude E6530 laptop. The complete simulation takes approximately 1 second using the Three-Phase Current Injection method with a Newton Raphson solver [29]; only 5 iterations are required from a flat start because there are no voltage control devices on the system. These results have been confirmed with a model run in CYMDIST [30], which also solves in approximately 1 second. The RMS voltage difference between the two simulations has a maximum value of 0.28% and an average value of 0.08%. The difference between the two simulations can be attributed to differences in modeling underground cable parameters.

V. SUMMARY

This panel paper has presented an overview of the 342-node IEEE Low Voltage Network Test System. Complete details of the LVNTS including the detailed model and power flow results will be posted to the Test Feeder Working Group web page [2]. This system provides a benchmark for new algorithms to test their ability to handle unbalanced networked systems with parallel transformers and parallel lines. An overview of results from two operational cases has been included: normal operation and a single feeder out of service. It is intended that the LVNTS is the first of two LVN test systems. The follow-up test system will include more complicated load configurations, protection equipment, and be larger in size.

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