Analytic Considerations and Design Basis for the IEEE Distribution Test Feeders

Report Prepared by the Test Feeder Working Group of the Distribution System Analysis Subcommittee

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***Abstract*—For nearly 20 years, the Test Feeder Working Group of the Distribution System Analysis Subcommittee has been developing openly available distribution test feeders for use by researchers. The purpose of these test feeders is to provide models of distribution systems that reflect the wide diversity in design and their various analytic challenges. Because of their utility and accessibility, the test feeders have been used for a wide range of research, some of which has been outside the original scope of intended uses. This paper provides an overview of the existing distribution feeder models and clarifies the specific analytic challenges that they were originally designed to examine. Additionally, this paper will provide guidance on which feeders are best suited for various types of analysis. The purpose of this paper is to provide the original intent of the Working Group and to provide the information necessary so that researchers may make an informed decision on which of the test feeders are most appropriate for their work.**

***Index Terms*—Distribution system analysis, power simulation, power modeling, smart grid, test systems.**

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I. Introduction

ELECTRICAL power infrastructures around the world are witnessing transformative changes, both in their design and their operations [1]–[4]. These changes are most evident in electric distribution systems where changes in generation, end-use loads, operations, and a desire for increased resiliency are redefining the way power is delivered at medium voltage levels [5]–[8]. Additionally, sustainability concerns are driving widespread integration of distributed renewable generation, plug-in hybrid electric vehicles, demand-response programs, and advanced metering infrastructure. These changes have propelled increasing R&D interest in the analysis, operations, and design of distribution feeders in the last decade, including the development of various sets of regional prototypical feeder [9]–[13].

The challenges with developing feeder models are that there exist regional differences in the structure and operation circuits across the world. The majority of modern power systems were constructed throughout the twentieth century, but despite their parallel development, there are fundamental differences in how they evolved. For example, a typical residential customer in North America receives single-phase power at 120/240 V at 60 Hz, while a typical residential customer in Europe receives three phase power at 400/240 V and 50 Hz [14], [15]. Similarly, in North America a secondary transformer with a rating of between 10 kVA and 50 kVA can serve between 1 and 10 customers through radial triplex cables, while in Europe a secondary transformer will be between 100 kVA and 1,000 kVA serving between 50 to over 250 customers through a networked secondary. Substantial differences in design and operation of feeders can be found within a single country, and even within a single utility, [9]–[13].

In 1991 the Test Feeder Working Group (TFWG), under the Power System Analysis Computing and Economics (PSACE), now the Analytic Methods for Power System (AMPS), Distribution System Analysis (DSA) subcommittee, released the first set of openly-available distribution test feeder models [16], [17]. This original set of five models was intended to provide researchers with models that included unbalanced loads and non-transposed distribution systems for the purposes of testing new power flow solution methods. Since that time, a number of additional models have been released by the TFWG that have been designed to examine specific computational challenges associated with distribution systems, and to reflect the changes in how they are operated [17]. When originally constructed, each of the test feeders was designed to address one or more specific analysis challenges; despite this, researchers have routinely used these models in research for which they were not originally intended. While this expanded use of the test feeders highlights their contributions to the industry, and is encouraged by the TFWG, researchers have not always been aware that many of the developed test feeders were not developed to represent a "typical" distribution system, but instead were designed to test the ability of new algorithms. For example, the IEEE 13 Node Test Feeder was originally intended to test the ability of power flow solvers to handle highly unbalanced systems, and is not meant to represent a "full-size" distribution circuit [18].

The purpose of this paper is to examine the existing test feeders that have been developed by the TFWG, including the analytic challenges that they were originally developed to address, and to provide guidance on which of these feeders is most suited to various common analysis. This information should be used by researchers to make an informed decision on which of the test feeders is most appropriate for the work that they are conducting, and provide a reference for reviewers about the applicability of new solutions on TFWG models.

The rest of this paper is organized as follows: Section II reviews a selection of power flow solution methods that have been applied to the test feeders, and their analytic performance. Section III provides descriptions and states the specific analytic challenge(s) for which the existing test feeders were developed. Section IV provides the same information as Section III, but for test feeders that are currently under consideration for development by the TFWG. Section V provides guidance on which test feeders are most appropriate for various types of common analysis, and Section VI contains concluding comments.

II. Power Flow Solutions

The intent of the original set of the test feeders was to provide researchers with a set of distribution system models to test new power flow methods [16]. Because the application of power flow solution methods is central to how the test feeders were originally intended to be used, it is important to review some of the more common power flow methods. The following sections will examine the distribution system elements that a power flow solution method must be able to model, and will provide a brief overview of some of the more common power flow solution methods. The following sections are included to support discussions on the analytic challenges of specific test systems, and not meant as a comprehensive review on the topic of powerflow.

A. Distribution Elements That Should Be Modeled

In order to conduct a power flow analysis of a system, it is necessary to have three key elements: a voltage source, a system model, and load models [19]. The voltage source for distribution systems is similar to those used for transmission systems, but can be unbalanced. It is the system elements in a distribution systems that present a greater degree of variation compared to transmission systems. The system model for a distribution system must be able to represent three-phase lines with or without neutrals, single- and double-phase lines, secondary triplex lines, and concentric neutral and tape shielded cables [19]. Additionally, it is necessary to support various conductor configurations that can exist, in both wye and delta-connected systems.

In addition to the lines and cables of a distribution system, there are numerous transformer types that must be supported. While the Delta-Gwye stepdown transform at the substation is commonly represented, there are many others that must be supported. For commercial loads, it is necessary to support wye-wye, Delta-wye, and Delta-Delta, where wye connections may be grounded to provide line-to-neutral voltages for single-phase loads. Additionally, for residential loads in North America it is necessary to model the single-phase center tap service transformer with a triplex secondary [19].

At the distribution level frequency is maintained by the transmission system when grid connected, with voltage often locally controlled. Therefore it is necessary to be able to model shunt capacitors and their various control schemes. These schemes can include timers, temperature, voltage, var, and volt-var set points [19]. Voltage regulation devices must also be modeled to properly represent distribution-level voltage control. These can be single- or three-phase autotransformers and are typically ± 16 taps [19]. The taps are controlled based on local voltage measurements, remote measurements, less frequently with line drop compensation (LDC).

The final element necessary for a power flow to be performed is a load model. Extensive work has been done on accurately representing the end-use load, and the full body of work is outside the scope of this paper. But some of the key methods include the ZIP model, induction motor models, multi-state load models, and composite load models [19]–[21]. With the three key elements modeled, it is possible to examine the various power flow methods that are commonly used for distribution system analysis.

B. Sweeping Methods

Special derivative-free iterative techniques, which are based on a ladder network, were some of the first solvers examined to model three-phase unbalanced distribution systems [22]. The fundamental equations for a ladder solver are given by (1) and (2), where the three phase voltages, V_{abc}, and phase currents, I_{abc}, are calculated as functions of voltages, currents, and matrices that represent the system model, A, B, c, and d.

$$[V_{abc}]_m = [A] \cdot [V_{abc}]_m - [B] \cdot [I_{abc}]_m \tag{1}$$

$$[I]_n = [c] \cdot [V_{abc}]_m + [d] \cdot [I_{abc}]_m \tag{2}$$

The modified form, i.e., Forward-Backwards Sweeping (FBS) methods, requires multiple iterations to converge even with linear load models, however the number of iterations will increase if nonlinear load models are used. One of the first attempts to apply a sweeping method to solving the unbalanced per-phase power flow solution was presented in [23]. Since it was originally presented, the sweeping method has advanced to include non-linear loads, triplex secondaries, and numerous transformer types [19]. Several attempts have been made to improve the convergence and computational speed of the sweeping methods [24]–[27]. Because sweeping methods are relatively easy to implement and robust to non-linear solutions they can still be found in commercial distribution analysis packages.

C. Impedance Methods

Direct impedance methods are another common means for solving unbalanced power flow solutions, often used in real-time applications due to the simplicity of forming the impedance matrix. The method exploits the radial or weakly meshed nature of the distribution system [28], [29]. The methods avoid the use of matrix inversions and reduce the need for LU decomposition. This leads to significant computational advantages under certain conditions, which was of upmost importance in the earliest implementations. These methods also have advantages in short-circuit and fault location algorithms, as the "new" ground impedance can simply be added to the matrix.

There are a number of different variations for how to directly solve the impedance-based solutions. Generally, the methods formulate the impedance matrix, Z, for each node in relation to the source node using Kirchhoff's Current Law. The solution is then found iteratively by solving (3) until the difference in voltage between iterations, $|V^{k+1} - V^{k}|$, reaches a pre-determined convergence criteria.

$$\left[V^{k+1}\right]_{abc} = \left[Z^{k}\right]_{abc} \cdot \left[I^{k}\right]_{abc} + \left[V^{k}\right]_{abc} \tag{3}$$

Direct impedance methods become more computationally burdensome when constant power, constant current, or time-varying load models are used. This is due to the fact that as the load changes, the Z-matrix must be continuously updated. Direct impedance solvers are relatively easy to implement and can be found in commercial power flow solvers.

D. Newton-Raphson Methods

While the sweeping methods and direct impedance solvers can require numerous iterations for highly non-linear loads, Newton-Raphson solvers require far fewer. Despite the computational requirements of forming a Jacobian matrix, Newton-Raphson solvers can solve in relative few iterations and are effective for highly meshed systems. In a Newton-Raphson solver, the set of nonlinear equations is linearized at a given initial solution point to form a set of sparse linear equations, which is solved iteratively. Assuming a power injection formulation, the iterative method for solving the power equations is shown in (4) [30].

$$\begin{bmatrix} \theta^{k+1} \\ \left|V^{k+1}\right| \end{bmatrix}_{abc} = \begin{bmatrix} \theta^{k} \\ \left|V^{k}\right| \end{bmatrix}_{abc} - \left[J\left(x^{k}\right)\right]^{-1}_{abc} \cdot \begin{bmatrix} \Delta P\left(x^{k}\right) \\ \Delta Q\left(x^{k}\right) \end{bmatrix}_{abc} \tag{4}$$

where:

θ Voltage angle
$|V|$ Voltage magnitude
J Jacobian matrix
x Vector of state variables
P Active power injections
Q Reactive power injections

For a Three-phase Current Injection Method (TCIM) formulation current injections are used instead of power injections. The iterative method for solving the power equations is shown in (5) [31]. The TCIM has a number of advantages over the power injection formulation, including not needing to update all of the elements of the Jacobian between iterations.

$$\begin{bmatrix} V_{\mathrm{Re}}^{k+1} \\ V_{\mathrm{Im}}^{k+1} \end{bmatrix}_{abc} = \begin{bmatrix} V_{\mathrm{Re}}^{k+1} \\ V_{\mathrm{Im}}^{k+1} \end{bmatrix}_{abc} - [J(x^{k})]^{-1}_{abc} \cdot \begin{bmatrix} \Delta I_{\mathrm{Im}}(x^{k}) \\ \Delta I_{\mathrm{Re}}(x^{k}) \end{bmatrix}_{abc} \tag{5}$$

where:

V_{Re} Real part of the voltage
V_{Im} Imaginary part of the voltage
I_{Re} Real part of the current
I_{Im} Imaginary part of the current

Fast decoupled load flow is not possible because of high R/X ratios that are typical in distribution systems.

E. Other Methods

In addition to the three methods discussed in the previous sections, many other methods have been developed. Methods that have been included in widely used simulation packages include Graph Trace Analysis (GTA) [32] and a fixed-point iteration method [33]. While the full scope of all power flow methods is beyond the scope of this paper, a non-comprehensive selection of other methods that have been developed by researchers for specific applications can be found in [34]–[40].

III. COMPLETED TEST FEEDER MODELS

As part of the TFWG, a number of test feeders have been developed over the past 25 years [17]. Some of these feeders were developed for academic purposes, while others were developed for more industrial needs. The feeders developed for academic purposes were created to test the large number of new power flow solution methods that were being proposed at the time. The industry-focused feeders were developed to highlight aspects of system construction or operation that were not widely known to the academic community.

Early work in the area of distribution analysis was often based on past industry experience with transmission analysis, with many of the solvers based on the balanced load assumptions. While this is no longer that case, there remains discrepancies on issues such as terminology. One such discrepancy is the definition of a "node". In a transmission system the definition is well defined, but at the distribution level the definition can vary because of the possibility of one-, two-, and three-phase nodes. In the original set of feeders developed by the TFWG, an electrical node was considered to encompass all electrical points at a single geographic point [16]. For example, at a two-phase location the single node would include phase *a*, phase *b,* and the neutral. In contrast, later test feeders such as the 8500 Node Test Feeder defined a node as any single electrical point; the same two-phase location would be considered as three separate nodes [41]. While there has been some discrepancies in the past, with the publishing of this paper the TFWG will now use the definition of a node as a single electrical point, while the term "bus" will include all electrical points at a geographic location; older test systems will not be renamed for consistency. The formal adoption of this terminology is consistent with IEEE std. 1729-2014 [42].

The following sections discuss the various feeders that have been developed by the TFWG, the purpose for which they were originally designed, and the specific analysis challenges that they provide. For each of the test feeders that have been published by the members of the TFWG, the solutions have been verified by at least two TFWG members, each using a separate simulation package, achieving voltage solution values within 0.01%. The simulation packages that have been used by the TFWG include OpenDSS [33], GridLAB-D [43], WindMil [44], CYME [45], RDAP [46], Synergi [47], and other independently developed solvers.

A. 4, 13, 34, 37, 123, and the Comprehensive Test Feeders

The first models developed by the TFWG were published in 1991 and they represented the type of unbalanced radial systems that are common in North America [16]. Because these feeders were the first released, they were relatively small in size and focused on representing the unbalanced system characteristics. The first five feeders were specifically designed to test new power flow algorithms [16], with a sixth later developed to test the ability to model a wide range of distribution system elements, especially transformers [48]; the original test feeders were not designed to represent the size or complexity of full size distribution feeders.

1) Description of Original Test Feeders: The original test feeders were small to medium radial systems that represent the type of feeders common to North America. These feeders were a combination of overhead lines and underground cables, included voltage regulators and shunt capacitors, with varying degrees of load unbalance. All of the end-use loads were placed on primary system nodes. The complete details of these feeders can be found in [16]–[18].

2) Specific Analytic Challenges for Original Test Feeders: Each feeder was constructed to highlight a specific analytic challenge:

1) 4 Node Test Feeder – tests the capability to represent all common three-phase transformer connections,
2) 13 Node Test Feeder – provided a good test of the convergence of a program for a very unbalanced system,
3) 34 Node Test Feeder – a very long feeder requiring the application of voltage regulators to satisfy ANSI C84.1 [49] voltage standards,
4) 37 Node Test Feeder – a three wire delta ungrounded underground system,
5) 123 Node Test Feeder – a medium size system with multiple voltage regulators and shunt capacitors,
6) Comprehensive Test Feeder – tests the capability of a program to model the majority of distribution system components and most connections of transformer banks and step-voltage regulators.

The first five of the above radial feeders should be readily solvable with any of the power flow solution methods described in Section II, or any newly proposed method. The comprehensive test feeder may be more challenging since it includes some uncommon transformer connection types.

B. 8500 Node Test Feeder

The 8500 Node Test Feeder was published in 2010 and represents an unbalanced radial system with a large number of line segments [41]. Similar to the original feeders, it is radial in construction, but also includes the secondary systems. This test feeder was specifically developed to address the fact that many researchers use the original test feeders, from the previous section, as representative of a full-size distribution system.

1) Description of 8500 Node Test Feeder: The 8500 Node Test Feeder is a 12.47 kV large radial system with 170 km of overhead lines and underground cables. The feeder has a substation Load Tap changers (LTC), three voltage regulators, and four shunt capacitors. The end-use loads are connected to the end of radial secondary systems served by 7200/120-240 V split-phase service transformers [19]. The complete details of this feeder can be found in [17] and [41].

2) Specific Analytic Challenges of the 8500 Node Test Feeder: The 8500 Node Test Feeder was developed specifically to provide a system that had a number of line segments consistent with a typical modern utility circuit model. The version with unbalanced load requires a center-tap transformer model for successful solution. In order to perform comprehensive voltage control studies, per-phase capacitor switching control is required, and users need to supply control settings and load profiles that were not specified in [41]. This system was designed specifically to provide a system of suitable complexity for researchers to prove the scalability of power flow, optimization, and search methods to a full-size distribution feeder.

Due to the size of this test feeder, the number of iterations required for sweeping type solvers, discussed in Section II-B, will be increased. Given the proper convergence criteria the solution of a sweeping method will be as accurate as a Newton method, Section II-D, but may take longer to converge. This is primarily due to the slow change in voltage during each sweep (1), and is overcome with Newton methods because of the quadratic converge that result from the use of a Jacobian (4) and (5).

C. Neutral-Earth-Voltage Test Feeder

The Neutral-Earth-Voltage (NEV) Test Feeder was published in 2008 and represents an unbalanced radial system where a Kron reduction is not used to reduce the neutral conductor [50], [51]. This test feeder was developed to examine the voltage rise that can occur on the neutral conductor when there is an impedance between the neutral and earth ground.

1) Description of NEV Test Feeder: The NEV Test Feeder is a 12.47 kV medium size radial system with a combination of overhead lines and underground cables where there is an impedance between the neutral conductor and earth ground; this impedance is what makes it different from previous test feeders. The end-use load are connected to the end of radial secondary systems served by 7200/240 V split-phase service transformers. The complete details of this feeder can be found in [17], [50], and [51].

2) Specific Analytic Challenges of the NEV Test Feeder: The original test feeder made the assumption that there is no impedance between the neutral conductor and the earth ground. This assumption allows for the use of a Kron reduction which reduces the 4×4 primitive impedance matrix of a line or cable to the 3×3 phase impedance matrix [19]. While this assumption is valid for many studies, it prevents an analysis of conditions where the impedance causes voltages on the neutral to rise above 0.0 V. The examination of this voltage rise phenomena is useful for systems where there are problems with broken ground connections, and certain studies examining harmonics. In addition to not reducing the representation of the neutral conductor with a Kron reduction, the NEV Test Feeder includes four individual feeders when calculating the impedance matrices for the segments leaving the substation.

While the NEV Test System could be solved with any of the power flow solution methods in Section II, the method must be able to accurately apply Carson's equations, without a Kron reduction, to account for the ground impedance value and for the mutual coupling of phase conductors on different feeders [52].

D. Low Voltage Network Test System

The Low Voltage Network (LVN) Test System was published in 2014 and represents the type of highly meshed low voltage systems that are seen in urban areas [53]. This is referred to as a test system, instead of a test feeder, because there are multiple feeders in the system serving a meshed system. This test system was designed specifically to test the ability of solvers to handle highly meshed systems and was the first test system published by the TFWG that was not radial.

1) Description of LVN Test System: The LVN Test System, also referred to as the 342-node LVNTS, represent a small portion of an urban core, or what is referred to in some areas as a sub-net [54]. In contrast to existing test feeders, this system includes multiple 13.2 kV feeders supplying a 120 V highly meshed work and multiple 480 V spot networks. The end-use loads are connected to either the 120 V meshed grid or the 480 V spot networks. The complete details of this feeder can be found in [17] and [53].

2) Specific Analytic Challenges of the LVN Test System: The computational challenges of LVNs are significantly different from the radial test feeders because the grid network is supplied by multiple radial distribution feeders supplying a meshed grid. While it is a meshed system, transmission solvers still cannot be used because the loads are unbalanced. The LVNTS was 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 LVN is typically not solvable with the sweeping methods of Section II-B, or any other method that requires a radially or weakly meshed system. Additionally, the method must be able to accurately apply Carson's equations to parallel low voltage cables that do not have a concentric or tape shielded neutral [53].

E. European Low Voltage Test Feeder

The European Low-Voltage Test Feeder is a 400 V (nominal voltage) radial system that represents a type of feeder found in the United Kingdom (some differences might exist in other parts of Europe). The voltage at the head of the feeder is set to 416 V to mimic typical operational values in the United Kingdom. The single-phase end-use loads are connected to one of the phases of the feeder. One-minute load shapes are provided for time-series simulations. This is the first test feeder to operate at 50 Hz. The complete details of this feeder can be found in [17].

1) Description of European Low Voltage Test Feeder: The European Low-Voltage Test Feeder is a 400 V (nominal voltage) radial system that represents a type of feeder found in the United Kingdom (some differences might exist in other parts of Europe). The voltage at the head of the feeder is set to 416 V to mimic typical operational values in the United Kingdom. The single-phase end-use loads are connected to one of the phases of the feeder. One-minute load shapes are provided for time-series simulations. This is the first test feeder to operate at 50 Hz. The complete details of this feeder can be found in [17].

2) Specific Analytic Challenges of the European Low Voltage Test Feeder: This feeder was specifically designed to address unbalanced low-voltage feeders which are commonly found in Europe. The computational challenges are not significantly different from previous test feeders, but the proper value of 50 Hz must be used when applying Carson's equations. Additionally, when applying the time-series data for the end-use loads it is necessary to run multiple power flow simulations. Because there are no state variables that are dependent on the state of the previous time-step it is possible to run these sequentially or in parallel.

IV. Test Feeders Under Consideration for Development

In addition to the test feeders, and the one test system, that have already been released, the TFWG is continually developing new test feeder models [55]. The following sections highlight some of the systems currently under consideration, and the specific analytic challenges that each is designed to evaluate.

A. Single Wire Earth Return

In some rural regions of the world, Single Wire Earth Return (SWER) systems are deployed where there is no metallic return conductor [56]. The same principle applied to monopolar High Voltage Direct Current (HVDC) circuits, which may allow earth return in emergencies, or even under extended-term normal conditions [57]. Because of the lack of a return conductor, the NEV

Test Case [50] does not accurately represent these systems, and a new case is being considered.

1) Description of SWER Systems: The SWER circuit would be radial, single-phase, single-wire, medium-voltage, relatively long, and lightly loaded. Only a small number of laterals and taps would be included because SWER is better suited to sparsely populated areas. Load-serving step-down transformers would be specified, along with primary and secondary grounding data.

2) Specific Analytic Challenges of SWER Systems: A program that already solves the single-circuit NEV test case should be able to solve a SWER test circuit, at least in principle. The transformers and secondary circuits have to be modeled in detail, including any winding unbalances and grounding connections. The solution should be able to show whether safety requirements are met on the secondary side. Voltage drops will be high due to the higher impedance of SWER circuits. To manage voltage drop, the program should allow series capacitors, in addition to the normal shunt capacitors and line voltage regulators.

B. Full Size LVN Test System

While the existing LVN Test System is currently available [53], a larger LVN Test System is needed to test the scalability of LVN analysis solutions.

1) Description of Full Size LVN Test System: This test system would consist of 100 or more individual low voltage feeders with 1000's of total nodes. The test system would represent an entire central business district of a large city, as opposed to a sub-net or individual radial low voltage feeder as in the LVN Test System.

2) Specific Analytic Challenges of the LVN Test System: This full-sized test system would test the scalability of analytical solutions and include additional complex connection types. For example, Gwye connected radial feeders served from unrounded Delta feeders where the ground is provided by a Zig-zag transformer [14].

C. Time-Series Test Feeder

Quasi-static time-series (QSTS), also called time-series, based distribution system analysis has increasingly been applied to distribution system analysis [58]–[60]. The time-series behavior of the system is fundamentally different from a static power flow solution.

1) Description of Time-Series Feeder: In order to support the development of a complete time-series test feeder, further development on the data needed to complete the analysis is required. Additionally, in order to verify comparable time-series analysis, specific operating points within a time-series analysis need to be identified and published as part of a test feeder. This will enable the capability to use the test feeders to benchmark their tools.

2) Specific Analytic Challenges of Time-Series Model: A full time-series analysis presents primary analytic challenges. First, it will be necessary for the solver to carry the state of time-varying equipment from one time-step to the next [20]. A good example of this is the time delays associated with voltage regulators. The solution method will need to carry the time since the last tap operation so that the next operation does not occur prior to the defined controller time-delay. Because of the coupling between states, it may not be possible to run the various time steps in parallel without an unacceptable decrease in accuracy. Second, a time-series analysis must look at not only power, but also energy. Because of the time-variant behavior of distributing systems it will be necessary to track integrated energy consumption for the time-variant power consumptions of end-use loads and system losses.

V. Applications

While there are many legitimate reasons why one of the test feeders could be used for a purpose other than those originally intended, as discussed in Section III, the following sections provide guidance on which feeders are typically more appropriate for various classes of commonly conducted analysis. If an author decides to use a test feeder in a way other than originally intended, they should provide an argument for the use.

A. New Power Flow Methods

The original set of test feeders developed by the working group were designed specifically to test the ability of power flow solvers [16]. Specifically, the ability to model one- and two-phase elements, unbalanced loads and the different configurations of overhead and underground distribution lines. These models were designed to test the functionality of algorithms and were not meant to represent the size and complexity of a full-size distribution feeder. The 8500 Node Test Feeder was developed to provide an example of the full size and complexity of a modern distribution utility planning model for a circuit [41].

As a result, a new power flow method at a minimum should be able to model all of the elements of the 4, 13, 34, and 123 Node Test Feeders, and be scalable to the 8500 Node Test Feeder. Additionally, it should be evaluated on a highly meshed system such as the LVN Test System to validate that is can work on non-radial systems. New power flow methods that require a radial topology, such as the original unmodified sweeping methods, do not represent an advancement in the state of the art.

B. Optimal Equipment Placement

One of the common places to see the test feeders used is in optimization studies. The objectives that are commonly seen include, capacitor placements, Distributed Energy Resource (DER) placement, and loss reduction; example publications include, but are not limited to [61]–[63]. In addition to being tested on the smaller test system, a new optimization should be tested on the 8500 Node Test Feeder to verify scalability; the number of nodes and links in the 8500 Test Feeder can reveal the non-linear computational challenges that can be experienced with optimization.

C. Islanded Operations

In recent years there has been an increased interested in islanded operations associated with microgrids [64]–[67]. Because of the wide range of what is considered a microgrid, almost any of the existing test feeders could be used as a basis for a study on islanded operations. However, for computationally intensive simulations the size of the test feeder should be considered.

D. Integration Studies

Studies of new or increasing amounts of DERs often use test feeders to compare alternative technologies or methods [68], [69]. For integration studies, voltage regulation is an important issue. For this reason, the 8500, 123, and 34 Node Test Feeders would be good candidates for most integration studies, in decreasing order of preference. Additionally, the 34-bus Test Feeder has a variant with induction generators, which could be used as the basis for integration studies [70]. The time-series test system under development would also be suitable for some integration studies.

E. State and Parameter Estimation

For state and parameter estimation studies, the 13 Node Test Feeder, and larger ones, would be suitable. It will be necessary to specify physical measurement locations and provide sample measurements, which can be a significant effort on the larger test feeders. The 37 Node Test Feeder could be helpful in showing a state estimator's performance with line-to-line voltage measurements. The 4 Node Test Feeder can be helpful in developing methods for a state estimator to handle different transformer connections. The effort in using the 8500 Node Test Feeder for this purpose is probably not worthwhile because it does not have the necessary data for state estimation studies. Researchers should focus on modeling full size operational feeders that have actual data sets, if they available to them. If a researcher does not have access to actual utility data, the 8500 Node Test Feeder with appropriately generated data could be used to show scalability.

F. Optimal Power Flow

The increasing presence of generation at the distribution voltage level has provided opportunities to optimize the operation of the system. The 8500 Node Test Feeder is suitable for testing and validating various optimization and control schemes because of its size and the inclusion of multiple voltage control devices.

G. New Control Schemes

The evaluation of newly developed control systems, whether they are new local autonomously controlled elements or circuit-wide control via new Distribution Management System (DMS) functionality, test feeders are often used as the underlying network being controlled [71]. For testing of locally controlled elements, such as new voltage regulator control methods or advanced photovoltaic inverter var functionality, a relatively small test feeder may be adequate for Power Hardware-in-the-Loop (PHIL) and Control-Hardware-in-the-Loop (CHIL) laboratory tests. For DMS testing or control methods that respond to circuit conditions at multiple points, a larger test feeders such as the 123 and 8500 Node Test Feeders should be used.

VI. Concluding Comments

In the past decade, there has been an increased interest in distribution system analysis, and an increased use of the test feeders developed by the TFWG. This paper has provided the research community with a detailed overview of the various test feeders that have been developed, the analytic challenges they each address, and guidance on how they could be used for research. This information is meant to be a resource for researchers, to enable them to make informed decisions when using the test feeders for their research. The final decision of which test feeder should be used is up to the researcher.

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