Radial Distribution Test Feeders

Distribution System Analysis Subcommittee Report

Abstract: **Many computer programs are available for the analysis of radial distribution feeders. In 1992 a paper was published [1] that presented the complete data for three four-wire wye and one three-wire delta radial distribution test feeders. The purpose of publishing the data was to make available a common set of data that could be used by program developers and users to verify the correctness of their solutions.**

This paper presents an updated version of the same test feeders along with a simple system that can be used to test three-phase transformer models.

Keywords: distribution system analysis, test systems, computer programs, transformer models

I. Introduction

In recent years many digital computer programs have been developed for the analysis of unbalanced three-phase radial distribution feeders. The programs use a wide variety of iterative techniques and range from very simple with many simplifying assumptions made for line and load models to very sophisticated with little if any simplifying assumptions. With so many different programs available there is a need for benchmark test feeders so that the results of various programs can be compared.

This paper presents the complete data for three four-wire wye, one three-wire delta test feeders and a simple feeder for testing three-phase transformer models. Only the data for the 13 node test feeder will be presented in this paper. The complete data and solutions for all of the test feeders can be downloaded from the Internet at **http://ewh.ieee.org/soc/pes/dsacom/testfeeders.html.**

II. Basic Data

The following data will be common for all systems:

Load Models:

Loads can be connected at a node (spot load) or assumed to be uniformly distributed along a line section (distributed load). Loads can be three-phase (balanced or unbalanced) or single-phase. Three-phase loads can be connected in wye or delta while single-phase loads can be connected line-to-ground or line-to-line. All loads can be modeled as constant kW and kVAr (PQ), constant impedance (Z) or constant current (I).
Table 1 lists the codes that will be used to describe the various loads.

Table 1
Load Model Codes

Code	Connection	Model
Y-PQ	Wye	Constant kW and kVAr
Y-I	Wye	Constant Current
Y-Z	Wye	Constant Impedance
D-PQ	Delta	Constant kW and kVAr
D-I	Delta	Constant Current
D-Z	Delta	Constant Impedance

Single-phase loads connected line-to-line will be assigned delta connection codes regardless of whether the feeder is a four-wire wye or three-wire delta.

All of the load data will be specified in kW and kVAr or kW and power factor per phase. For constant current and constant impedance loads the kW and kVAr should be converted by assuming rated voltage (1.0 per-unit). For wye connected loads, phases 1, 2 and 3 will be connected a-g, b-g and c-g respectively and delta connected loads will be connected a-b, b-c and c-a respectively. Only non-zero loads will be given in the various feeder load tables. All other loads are assumed to be zero.

Shunt Capacitors:

Shunt capacitor banks may be three-phase wye or delta connected and single-phase connected line-to-ground or line-to-line. The capacitors are modeled as constant susceptance and specified at nameplate rated kVAr.

Overhead Spacing Models:
The spacing ID numbers and type for overhead lines are summarized in Table 2.

Table 2
Overhead Line Spacings

Spacing ID	Type
500	Three-Phase, 4 wire
505	Two-Phase, 3 wire
510	Single-Phase, 2 wire

Figure 1 shows the spacing distances between the phase conductors and the neutral conductor for Spacing ID numbers used for the overhead lines.
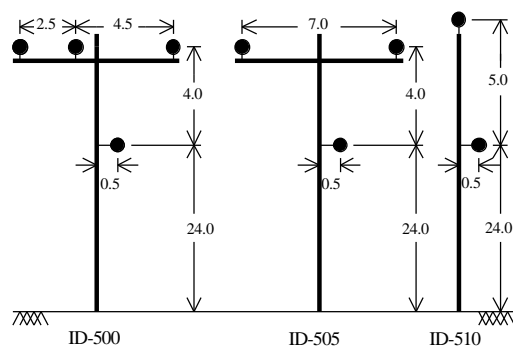

Figure 1 – Overhead Line Spacings

Conductor Data

Table 3 lists the characteristics of the various conductors that are used for the overhead configurations in the test feeders[2,3]. The columns correspond to:

1 – Conductor size in AWG or kcmil
2 – Type of conductor
 AA = All Aluminum
 ACSR = Aluminum Conductor Steel Reinforced
 CU = Copper
3 – 60 Hz resistance at 50 degrees C (ohms/mile)
4 – Conductor outside diameter (inches)
5 – Geometric Mean Radius (ft.)
6 – Ampacity at 50 degrees C   (amps)

Table 3
Conductor Data

1	2	3	4	5	6
1,000	AA	0.105	1.15	0.0368	698
556.5	ACSR	0.1859	0.927	0.0313	730
500	AA	0.206	0.813	0.026	483
336.4	ACSR	0.306	0.721	0.0244	530
250	AA	0.410	0.567	0.0171	329
# 4/0	ACSR	0.592	0.563	0.00814	340
# 2/0	AA	0.769	0.414	0.0125	230
# 1/0	ACSR	1.12	0.398	0.00446	230
# 1/0	AA	0.970	0.368	0.0111	310
# 2	AA	1.54	0.292	0.00883	156
# 2	ACSR	1.69	0.316	0.00418	180
# 4	ACSR	2.55	0.257	0.00452	140
# 10	CU	5.903	0.102	0.00331	80
# 12	CU	9.375	0.081	0.00262	75
# 14	CU	14.872	0.064	0.00208	20

Underground Spacing Models:

The spacing ID numbers and type for underground lines are summarized in Table 4.

Table 4
Underground Line Spacings

Spacing ID	Type
515	Three-Phase, 3 Cable
520	Single-Phase, 2 Cable

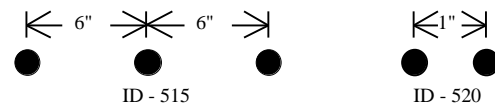Figure 2 shows the spacing distances between cables for underground lines:

Figure 2 – Underground Line Spacings

Cable Data:

Table 5 lists the characteristics of the various concentric neutral cables [4] that are used in the test feeders. The column numbers correspond to:

1 – Conductor size in AWG or kcmil
2 – Diameter over insulation (inches)
3 – Diameter over screen (inches)
4 – Outside diameter (inches)
5 – Copper 1/3 neutral (No. x AWG)
6 – Ampacity in 4 inch duct

Table 5
Concentric Neutral 15 kV All Aluminum (AA) Cable

1	2	3	4	5	6
2(7x)	0.78	0.85	0.98	6 x 14	135
1/0(19x)	0.85	0.93	1.06	6 x 14	175
2/0(19x)	0.90	0.97	1.10	7 x 14	200
250(37x)	1.06	1.16	1.29	13 x 14	260
500(37x)	1.29	1.39	1.56	16 x 12	385
1000(61x)	1.64	1.77	1.98	20 x 10	550

Table 6 lists the characteristics of a tape shielded conductor used in the test feeders. The column numbers correspond to:

1 – Conductor size in AWG
2 – Diameter over insulation (inches)
3 – Diameter over the shield
4 – Jacket thickness (mils)

5 – Outside diameter (inches)
6 – Ampacity in 4 inch duct (amps)

Table 6
Tape Shielded 15 kV All Aluminum (AA) Cable
Tape Thickness = 5 mils

1	2	3	4	5	6
1/0	0.82	0.88	80	1.06	165

Configuration Codes:

Each test feeder will have a table of "Configuration Codes". The configuration code is a unique number assigned to describe the spacing model (Tables 2 and 4), the phasing (left to right) and the phase and neutral conductors used.

Line Segment Data:

Each test feeder will have a table of "Line Segment Data". The data will consist of the node terminations of each line segment (Node A and Node B), the length of the line segment and a configuration code (Config.). There is no significance in the order in which the data appears or whether node A or node B is closer to the source.

Voltage Regulators:

Voltage regulators are assumed to be "step-type" and can be connected in the substation and/or to a specified line segment. The regulators can be three-phase or single-phase. Tap positions will be determined by the compensator circuit settings described by:

1. Voltage Level – desired voltage (on a 120 volt base) to be held at the regulating point.
2. Bandwidth – the voltage level tolerance usually assumed to be 2 volts.
3. Compensator – resistance (R) and reactance (X) settings – the equivalent resistance and reactance between the regulator and the regulating point calibrated in volts.
4. PT Ratio – turns ratio of the potential transformer feeding the compensator circuit.
5. CT Rating – the current rating on the primary of the current transformer feeding the compensator circuit.

III. The Test Feeders

The data for the feeders is so extensive that only the data for the 13 node feeder will be given in this paper. Data for all of the test feeders can be downloaded from: **http://ewh.ieee.org/soc/pes/dsacom/testfeeders.html**.
The data is in a spreadsheet format. In addition to the data a solution for each of the feeders can be downloaded. The solution consists of:
1. Listing of the per mile phase impedance and admittance matrices for each of the configurations

used in the feeder. The impedance matrix assumes a resistivity of 100 Ohm-meters and the admittance matrix assumes a relative permittivity of 2.3.
2. Radial Flow Summary –a summary of the system input, total load, total losses and total shunt capacitors by phase and total three-phase.
3. Voltage Profile – voltage magnitudes and angles by phase at each node. Voltage magnitudes are given in per-unit.
4. Voltage Regulator Data – for each regulator in the system a summary of the settings and the final tap settings.
5. Radial Power Flow – complete node data including line flows in amps and degrees by phase. Line power losses by phase and total three-phase are also given.

The IEEE 13 Node Test Feeder

This feeder is very small and yet displays some very interesting characteristics.

1. Short and relatively highly loaded for a 4.16 kV feeder
2. One substation voltage regulator consisting of three single-phase units connected in wye
3. Overhead and underground lines with variety of phasing
4. Shunt capacitor banks
5. In-line transformer
6. Unbalanced spot and distributed loads

For a small feeder this will provide a good test for the most common features of distribution analysis software.

The complete data for this system is given below to illustrate the form of the data for all of the test feeders.

One Line Diagram
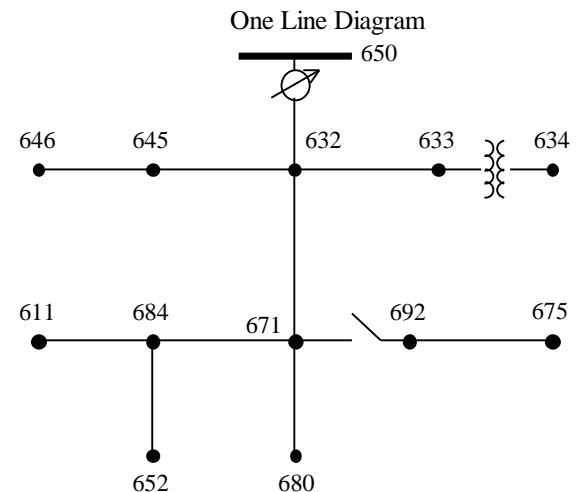
Underground Line Configuration Data:

Config.	Phasing	Cable	Neutral	Space ID
606	A B C N	250,000 AA, CN	None	515
607	A N	1/0 AA, TS	1/0 Cu	520

Overhead Line Configuration Data:

Config.	Phasing	Phase	Neutral	Spacing
		ACSR	ACSR	ID
601	B A C N	556,500 26/7	4/0 6/1	500
602	C A B N	4/0 6/1	4/0 6/1	500
603	C B N	1/0	1/0	505
604	A C N	1/0	1/0	505
605	C N	1/0	1/0	510

Line Segment Data:

Node A	Node B	Length(ft.)	Config.
632	645	500	603
632	633	500	602
633	634	0	XFM-1
645	646	300	603
650	632	2000	601
684	652	800	607
632	671	2000	601
671	684	300	604
671	680	1000	601
671	692	0	Switch
684	611	300	605
692	675	500	606

Capacitor Data:

Node	Ph-A	Ph-B	Ph-C
	kVAr	kVAr	kVAr
675	200	200	200
611			100
Total	200	200	300

Regulator Data:

Regulator ID:	1		
Line Segment:	650 - 632		
Location:	650		
Phases:	A - B -C		
Connection:	3-Ph,LG		
Monitoring Phase:	A-B-C		
Bandwidth:	2.0 volts		
PT Ratio:	20		
Primary CT Rating:	700		
Compensator Settings:	Ph-A	Ph-B	Ph-C
R - Setting:	3	3	3
X - Setting:	9	9	9
Volltage Level:	122	122	122

Transformer Data:

	kVA	kV-high	kV-low	R - %	X - %
Substation:	5,000	115 - D	4.16 Gr. Y	1	8
XFM -1	500	4.16 – Gr.W	0.48 – Gr.W	1.1	2

Spot Load Data:

Node	Load	Ph-1	Ph-1	Ph-2	Ph-2	Ph-3	Ph-3
	Model	kW	kVAr	kW	kVAr	kW	kVAr
634	Y-PQ	160	110	120	90	120	90
645	Y-PQ	0	0	170	125	0	0
646	D-Z	0	0	230	132	0	0
652	Y-Z	128	86	0	0	0	0
671	D-PQ	385	220	385	220	385	220
675	Y-PQ	485	190	68	60	290	212
692	D-I	0	0	0	0	170	151
611	Y-I	0	0	0	0	170	80
	TOTAL	1158	606	973	627	1135	753

Distributed Load Data:

Node A	Node B	Load	Ph-1	Ph-1	Ph-2	Ph-2	Ph-3	Ph-3
		Model	kW	kVAr	kW	kVAr	kW	kVAr
632	671	Y-PQ	17	10	66	38	117	68

IEEE 123 Node Test Feeder

The IEEE 123 node test feeder operates at a nominal voltage of 4.16 kV. While this is not a popular voltage level it does provide voltage drop problems that must be solved with the application of voltage regulators and shunt capacitors. For programs that can "allocate" load, this will be a good test feeder to use. There are enough switches in the feeder so that "optimal" configuration procedures can be tested.

This is the most comprehensive feeder and is characterized by:

1. Overhead and underground line segments with various phasing.
2. Unbalanced loading with all combinations of load types (PQ, constant I, constant Z)
3. All loads are "spot loads" located at a node
4. Four step-type voltage regulators
5. Shunt capacitor banks
6. Switching to provide alternate paths of power-flow

This feeder is well behaved and does not have a convergence problem. It provides a test of the modeling of the phasing of the lines. The four voltage regulators provide a good test to assure that the changing of

individual regulator taps is coordinated with the other regulators.

The IEEE 34 Node Test Feeder

This feeder is an actual feeder located in Arizona. The feeder's nominal voltage is 24.9 kV. It is characterized by:

1. Very long and lightly loaded
2. Two in-line regulators required to maintain a good voltage profile
3. An in-line transformer reducing the voltage to 4.16 kV for a short section of the feeder
4. Unbalanced loading with both "spot" and "distributed" loads. Distributed loads are assumed to be connected at the center of the line segment
5. Shunt capacitors

Because of the length of the feeder and the unbalanced loading it can have a convergence problem.

The IEEE 37 Node Test Feeder

This feeder is an actual feeder located in California. The characteristics of the feeder are:

1. Three-wire delta operating at a nominal voltage of 4.8 kV
2. All line segments are underground
3. Substation voltage regulator consisting of two single-phase units connected in open delta
4. All loads are "spot" loads and consist of constant PQ, constant current and constant impedance
5. The loading is very unbalanced

Although there are very few three-wire delta systems in use, there is a need to test software to assure that it can handle this type of feeder.

The IEEE Four Node Test Feeder

This feeder was not part of the original set of test systems published in 1992. The primary purpose of this test feeder is to provide a simple system for the testing of all possible three-phase transformer connections. Characteristics of the feeder are:

1. Two line segments with a three-phase transformer bank connected between the two segments
2. Data is specified for "closed" three-phase transformer connections and for two transformer "open" connections
3. Transformer data is specified for step-up and step-down testing. The primary voltage is always 12.47 kV while the secondary voltage can be either 4.16 kV or 24.9 kV.
4. Data is specified for balanced and unbalanced loading at the most remote node

Test results for this feeder include the following transformer connections for step-down and step-up operations and for balanced and unbalanced loading.

1. Grounded Wye – Grounded Wye
2. Grounded Wye – Delta
3. Ungrounded Wye – Delta
4. Delta – Grounded Wye
5. Delta – Delta
6. Open Wye – Open Delta

IV. Summary

Data for five different test feeders has been developed. Data appearing in this paper are "common" to all of the feeders. The total data for the 13 node test feeder is included to illustrate the form of the data for the other test feeders. The data and one-line diagrams for the other test feeders are too extensive to be included in the paper. The data for all five test feeders are in spreadsheet format and can be downloaded from the Web at:

http://ewh.ieee.org/soc/pes/dsacom/testfeeders.html

The test feeders have been studied using the Radial Distribution Analysis Package of WH Power Consultants, Las Cruces, New Mexico and/or Windmil developed by Milsoft Integrated Solutions, Abilene, Texas. The results of these tests are included with the data for each feeder.

Software developers are encouraged to test their software using these test feeders and to publish the results. The hope is that in time there will be agreement on the results in the same way that there is agreement on the various test systems used by network power-flow programs.

V. References:

1. IEEE Distribution Planning Working Group Report, "Radial distribution test feeders", *IEEE Transactioins on Power Systems,*, August 1991, Volume 6, Number 3, pp 975-985.
2. J.D. Glover and M. Sarma, "*Power system analysis and design*", 2nd Edition, PWS Publishing Company, Boston, MA, 1994.
3. "*Overhead conductor manual*", Southwire Company, Carrollton, GA, 1994.
4. "Product data", Section 2, Sheets 10 and 30., The Okonite Company, www.okonite.com