

REPRESENTATIVE TEST SYSTEMS FOR SWEDISH DISTRIBUTION NETWORKS

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ABSTRACT

This paper describes two electrical distribution systems, Swedish Urban Reliability Test System (SURTS) and Swedish Rural Reliability Test System (SRRTS), which are representative of actual Swedish distribution networks. These test systems aim to serve as a basis for reliability and cost analyses of Swedish distribution networks and for studies of regulation policies. The project was conducted within a research programme of Elforsk, a Swedish industry research association. The challenge has been to make the test systems representative in terms of load, component and customer data as well as network topology. To ensure the similarity of the test systems to actual networks, industry representatives of major Swedish power distribution companies have been an integral part of the development process. This paper shows the result of a validation of the test systems against data compiled by the Swedish Energy Markets Inspectorate. The validation was performed for the reliability indices SAIDI and SAIFI. It was confirmed that the developed test systems are good representatives of actual distribution networks, and thus suitable for further research of distribution networks and for studies of regulation policies.

INTRODUCTION

Models of electrical power systems, often called test systems, are valuable tools in reliability evaluation. As they usually contain a consistent set of data, this kind of test systems provides a good basis for many types of power system studies. The Reliability Test System (RTS), presented in an IEEE publication in 1979 [1], was later followed by Roy Billinton's Test System (RBTs) [2]. These international test systems have extensively been used as references for comparing alternative technical solutions to distribution reliability problems [3].

However, to apply international test systems in studies of national distribution networks is not always suitable, as network data vary much between different countries. In Ref. [4], the need to review available test systems is acknowledged and a close collaboration with power distribution companies during the development of future test systems is recommended. Another identified aspect for further development is to include customer interruption costs in the test systems.

The test systems described in this paper have been created

to meet the requirements in Ref. [4]. Firstly, in order to represent the diversity of actual Swedish distribution networks two different test systems have been developed. The Swedish Urban Reliability Test System (SURTS) and the Swedish Rural Reliability Test System (SRRTS) have the characteristics of urban and rural distribution networks, respectively. Secondly, representatives of major Swedish power distribution companies have been an integral part in the development of the test systems. Finally, customer interruption costs have been included.

All calculations of system reliability and interruption costs in this paper are based on time sequential Monte Carlo simulations of component failures in the test systems.

DESCRIPTION OF THE DISTRIBUTION NETWORKS: SURTS AND SRRTS

SURTS is intended to represent an actual urban distribution network with more than 20 customers per km feeder. Correspondingly, SRRTS represents rural networks with less than 10 customers per km feeder. These classifications of urban and rural distribution networks are defined by the electric utility organization Swedenergy. The test systems are based on data from all Swedish distribution companies compiled by the Swedish Energy Markets Inspectorate (EI).

The main characteristic of urban distribution networks is the cable-loop design. SURTS is a 10 kV system with 10 identical loops, as shown in Figure 1. Each loop has approximately 1100 customers and 10 km cable. It is possible to connect or disconnect each section in the loops. This design is simple, yet it sufficiently reflects the system redundancy in urban networks.

In rural distribution networks line length, redundancy and the proportion of uninsulated line are crucial for reliability evaluation. SRRTS consists of two modules, Module A and Module B, as shown in Figure 2. A typical feature of rural distribution networks is the radial structure, especially at some distance from the primary substation, and SRRTS has a partially radial structure. The most important simplification made for SRRTS is that there are only one or two feeders, respectively, from the substations (40/10 kV). Disconnectors are placed as shown in Figure 2.

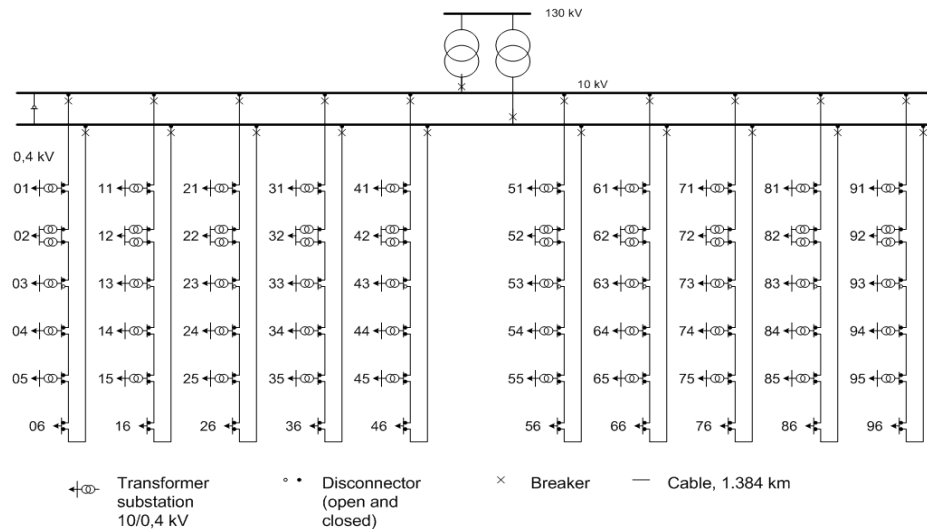


FIGURE 1. System layout of the Swedish Urban Reliability Test System (SURTS). Ten identical loops with approximately 1100 customers and 10 km feeder cable each.

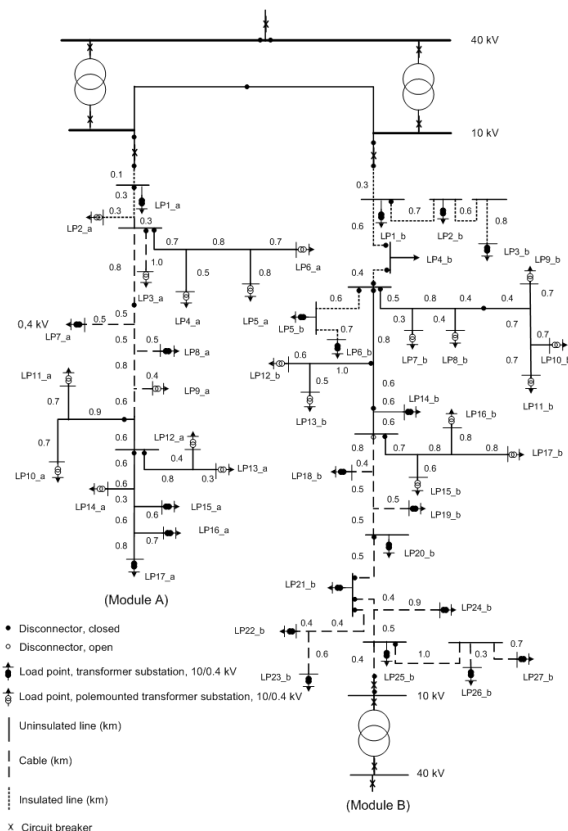


FIGURE 2. System layout of the Swedish Rural Reliability Test System (SRRTS).

The design of these distribution networks followed utility principles in Refs. [3] and [5] regarding component failures and their consequences. The following comments relate to the function of the test systems:

- The feeders are operated as radial feeders even though they in some cases are connected as a loop. As shown in Figure 1 and 2, open disconnectors serve as normally open sectionalizing points.
- Load points without transformers indicate high voltage customers, for example an industry. For those load points, no transformers are included in the analysis.
- It is assumed that sufficient capacity is installed and that no component will be overloaded neither during normal operation nor when switching to a faulted mode.
- All breakers and disconnectors used in the analysis are identified in the figures.
- Feeder types and lengths are shown in the figures.

CUSTOMER AND LOAD DATA

The customer load data is based on statistics from Fortum Distribution. Six different customer categories were identified: urban residential, rural residential, industry, commercial, agriculture and public sector. Table 1 shows the average of aggregate load for each customer category at the load points in the test systems. Customers in the same customer category have a common average load. When a fault occurs in the time sequential simulation, these customer averages are multiplied with an index number from a load curve that represents the time-varying power consumption. Each customer category has a set of different load curves to represent seasonal, daily and hourly variations in power demand. The load curves used in the test systems are presented in Ref. [6].

Load Point	Res. (kW)	Ind. (kW)	Comm. (kW)	Agr. (kW)	Pub. sect. (kW)	Nr. of Cust.
SURTS						
x1,x3, x4,x5	147.42	0.00	149.22	0.00	16.20	212
x2	147.42	0.00	215.54	0.00	16.20	220
x6	0.00	232.39	149.22	0.00	16.20	40
x=0,1,...,9						
SRRTS, Mod. A						
1	3.03	41.01	33.16	0.00	0.00	10
2,5-10, 13,15,17	14.14	13.67	8.29	2.08	3.24	19
3,4,11, 12,14,16	11.11	0.00	8.29	7.28	0.00	19
SRRTS, Mod. B						
1, 5,10, 22,25	16.16	0.00	24.87	7.28	0.00	26
2,3,6-9, 11-21,23	16.16	13.67	8.29	4.16	3.24	23
24,26	0.00	68.35	24.87	0.00	0.00	8
4	18.18	0.00	24.87	10.40	0.00	31
27						

Res.= Residential power demand (kW)

Ind.= Industry power demand (kW)

Comm.= Commercial power demand (kW)

Agr.= Agriculture power demand (kW)

Pub. Sect.= Public Sector power demand (kW)

Nr. of Cust.= Number of customers

TABLE 1. Average load per customer category and number of customers for each load point. Load points of SURTS are found in Figure 1 (replacing x with a digit), and load points of SRRTS are found in Figure 2.

FAILURE RATES, SWITCHING TIMES AND REPAIR OR REPLACEMENT TIMES

The test systems are assumed not to be affected by temporary failures and also to be in normal operation mode when faults occur. The effects of failures that occur on higher or lower distribution levels are neglected. Disconnectors are considered to be 100 % reliable. The reliability data in Tables 2 and 3 include failure rates (λ), repair times (r/r_p) and switching times (s), and are mainly based on Refs. [3], [5] and [7]. Representatives from power distribution companies have also contributed with data. In the simulation, λ is assumed to be exponentially distributed and r/r_p and s are assumed to be log-normally distributed, why the tables also include the standard deviations (Std).

Component	λ_r SURTS/ SRRTS	r or r_p SURTS/ SRRTS	Std for r/r_p SURTS/ SRRTS	s	Std for s
Cable	0.025/ 0.019	690	138	60	24
Insulated lines	0.03	300	60	60	24
Uninsulated lines	0.123	300	60	60	24
Breakers (MV)	0.006	240	24	60	24
Breakers (HV)	0.0058	480	48	60	24
Transformer substations	0.0155	150/600	30/60	60	24

Polemounted transformers	0.02	600	60	60	24
Transformers (40/10 kV or 130/10 kV)	0.003	-	-	60	24
Busbars (40 or 130 kV)	0.001	120	24	60	24
Busbars (10 kV)	0.001	120	24	60	24

 λ_r = total failure rate (f/yr) [for lines/cables (f/yr.km)] r = repair time (min) r_p = replacement time (min) s = switching time (min)

TABLE 2. Reliability and component data.

In the analysis, an active failure in a breaker causes also the next breaker on the feeding side to trigger. This is not the case with the more contained passive failures.

Component	λ_a	λ_p	r/r_p	Std for r/r_p
Breakers (MV)	0,004	0,002	240	24
Breakers (HV)	0,0035	0,0023	480	48

 λ_a = active failure rate (f/yr) r = repair time (min) λ_p = passive failure rate (f/yr) r_p = replacement time (min)

TABLE 3. Active and passive failure rates for breakers.

CUSTOMER INTERRUPTION COSTS

The outage costs for the customers in the test systems are based on a survey study [8]. The interruption costs are shown in Table 4. The costs for the public sector include external costs (waiting times etc.) for the public.

Outage length (h)	Res.	Ind.	Comm.	Agr.	Pub. sect.
1	2,1	61	170	8	228
2	3,6	97	284	12	256
3	5,7	134	405	16	285
4	8,4	173	535	21	316
5	11,4	194	605	24	327
6	14,7	213	668	27	339
7	19,3	231	726	30	351
8	24,5	248	779	34	361
9	27,1	264	828	37	372
10	29,9	280	894	41	384
11	32,6	295	916	44	394
12	35,3	310	955	48	405
13	37,9	325	992	52	416
14	40,4	339	1025	56	427
15	42,7	353	1057	60	438
16	44,8	367	1086	64	449
17	46,7	381	1112	68	459
18	48,3	394	1136	72	471
19	49,7	407	1159	77	482
20	50,8	421	1179	81	493
21	51,2	434	1197	86	504
22	51,5	447	1213	90	516
23	51,5	459	1227	95	526
24	51,5	472	1240	100	538

Res.= Residential (SEK/kW)

Ind.= Industry (SEK/kW)

Comm.= Commercial (SEK/kW)

Agr.= Agriculture (SEK/kW)

Pub. sect.= Public Sector (SEK/kW)

TABLE 4. Interruption costs for each customer category in SEK/kW.

RELIABILITY RESULTS

To verify the accuracy of the models, reliability calculations were performed. All the calculations are based on time sequential Monte Carlo simulations. Reliability indices calculated for the simulations are:

- SAIFI (System Avg. Interruption Freq. Index)
- SAIDI (System Avg. Interruption Duration Index)
- ASUI (Avg. System Unavailability Index)
- ENS (Energy Not Supplied)
- Outage Cost (average annual customer cost)

Tables 5 and 6 present the aggregated results for both test systems.

	SURTS	EI
SAIFI (f/cust.yr)	0,210	0,325
SAIDI (h/cust.yr)	0,232	0,306
ASUI (% of time)	0,0025	-
ENS (kWh/cust.yr)	0,410	-
Outage Cost (SEK/cust.yr)	36,38	-

TABLE 5. Results for SURTS and a comparison with EI statistics.

Generally, the reliability results for SURTS in Table 5 correspond well to actual networks. SAIFI and SAIDI for the test system are somewhat lower than the EI statistics. However, the statistics compiled by EI include data from all distribution companies with an average of more than 20 customers per km feeder, and is likely to include occasional rural networks with higher failure rates. The EI statistics also include outages caused by the underlying low-voltage system.

	SRRTS (Total)	SRRTS (A)	SRRTS (B)	EI
SAIFI (f/cust.yr)	1,638	1,960	1,477	1,45
SAIDI (h/cust.yr)	3,673	5,018	3,002	2,75
ASUI (% of time)	0,042	0,057	0,034	-
ENS (kWh/cust.yr)	7,041	9,401	5,854	-
Outage Cost (SEK/cust.yr)	342,6	430,48	297,85	-

TABLE 6. Results for SRRTS and a comparison with EI statistics.

The EI data in Table 6 are based on data from distribution companies with an average of less than 10 customers per km feeder. In consequence, the EI statistics are not based on data for rural networks exclusively. Therefore, even though SAIFI and SAIDI for SRRTS are slightly higher than corresponding system indices in the EI statistics, SRRTS is representative of Swedish rural distribution networks. It should also be noted that the EI statistics for outages in rural networks vary substantially between different years because of great variance in the frequency of weather-caused failures. Due to the radial structure the outage time for

Module A is longer than it is for Module B. The high portion of uninsulated lines in Module A results in a high SAIFI.

Overall, rural customers suffer almost ten times higher annual outage costs than urban customers because of much more frequent outages. However, the higher density of commercial customers in the urban system results in larger average outage cost per kWh.

CONCLUSIONS

The validations of system reliability indices SAIFI and SAIDI confirm that the developed test systems are good representatives for actual distribution networks. Hence, the test systems are applicable in many types of studies of electrical distribution systems. The resemblance of the test systems to actual networks has also been confirmed by representatives of major Swedish power distribution companies regarding for instance load, customers and network topology. Each test system provides a consistent set of data which enables calculations for reliability analyses and for the assessment of customer interruption costs. Finally all data for the test systems are available at the website of Elforsk [6], which makes it easy for industry and researchers to use them.

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